EPA/600/R-17/027 | February 2017
www.epa.gov/homeland-security-research

United States
Environmental Protection
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Exposure Assessment of Livestock Carcass Management Options During Natural Disasters

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Homeland Security Research Program

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EPA/600/R-17/027
February 2017

Exposure Assessment of Livestock Carcass Management Options During Natural Disasters

U.S. Environmental Protection Agency
Office of Research and Development
National Homeland Security Research Center
Cincinnati, Ohio 45268

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Disclaimer

The U.S. Department of Homeland Security, in collaboration with the U.S. Environmental Protection Agency (EPA) and the U.S. Department of Agriculture, funded and managed the research described herein under Interagency Agreement RW7095854501 and contract EP-C-14-01 WA-24 to ICF International. It has been subjected to the Agency's review and has been approved for publication. Numeric results in this assessment should not be interpreted as "actual" risks. Note that approval does not signify that the contents necessarily reflect the views of EPA. Mention of trade names, products, or services does not convey official EPA approval, endorsement, or recommendation.

Questions concerning this document or its application should be addressed to:

Sandip Chattopadhyay, Ph.D.
National Homeland Security Research Center
Office of Research and Development
U.S. Environmental Protection Agency
26 West Martin Luther King Drive, NG-16
Cincinnati, Ohio 45268
(513) 569-7549
Chattopadhyay.Sandip@epa.gov

Sarah C. Taft, Ph.D.
National Homeland Security Research Center
Office of Research and Development
U.S. Environmental Protection Agency
26 West Martin Luther King Drive, NG-16
Cincinnati, Ohio 45268
(513) 569-7037
Taft.Sarah@epa.gov

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Acknowledgements

The authors wish to acknowledge the contributions of experts who participated in a workshop held during the 5th International Symposium on Animal Mortality Management on October 1, 2015, in Lancaster, Pennsylvania. The workshop participants reviewed and discussed data and assumptions used to develop carcass management scenarios and to estimate potential exposures. Information obtained at the workshop and in follow up communications has been helpful in refining the exposure assessment approach. Acknowledgements also are due to the following workshop attendees and other experts who provided follow-up information and support: Dr. Robert DeOtte, West Texas A&M University; Gary Flory, Virginia Department of Environmental Quality; Mark Hutchinson, University of Maine Extension; Mark King, Maine Department of Environmental Protection; Dr. Mike Brown, West Texas A&M University; and Dr. Andy Cole, United States Department of Agriculture (USDA). Dr. Sandip Chattopadhyay served as task order contracting officer representative and Dr. Sarah C. Taft served as alternate contracting officer representative.

Acknowledgements also are extended to reviewers who provided many helpful comments on the report, including: Lori P. Miller, P.E., USDA, Animal and Plant Health Inspection Service (APHIS); Dr. Scott Wesselkemper, USEPA; Dr. Randy Bruins, USEPA; Dr. Paul Lemieux, USEPA; Dr. Kevin Garrahan, USEPA; Anna Tschursin, USEPA; Dr. Eileen Sutker, USDA; Dr. Craig Ramsey, USDA; and Samantha Bates, USDA.

Executive Summary

Proper management of livestock carcasses following large-scale mortalities protects humans, livestock, and wildlife from chemical and biological hazards; maintains air, water, and soil resources; protects ecological resources and services; and enhances food and agricultural security. In support of the National Response Framework, the U.S. Department of Homeland Security (DHS) Science and Technology Directorate funds research in collaboration the U.S. Environmental Protection Agency's (USEPA's) Office of Research and Development (ORD), Homeland Security Research Program (HSRP) and the U.S. Department of Agriculture's (USDA's) Animal and Plant Health Inspection Service (APHIS) to support the proper management of animal carcasses following major environmental incidents. Mass livestock mortalities can result from a natural disaster, foreign animal disease (FAD) outbreak, chemical or radiological incident, or other large-scale emergencies. As a product of the collaborative research between USEPA and USDA, this report evaluates livestock carcass management options following a natural disaster through a comparative exposure assessment. This assessment helps to inform a scientifically-based selection of environmentally protective methods in times of emergency. Future phases of this project will examine a FAD outbreak and chemical or radiological incidents.

The livestock carcass management options included in this exposure assessment are seven well-established methods with sufficient capacity for large-scale carcass management: on-site open burning (pyre), on-site air-curtain burning, on-site unlined burial, on-site composting, off-site fixed-facility incineration, off-site landfilling, and off-site carcass rendering.

With the three off-site options, all releases to the environment (e.g., incinerator emissions to air, rendering facility discharge to surface water) are restricted by, and are assumed to comply with, applicable U.S. federal regulations. Therefore, chemical and microbial releases from off-site commercial facilities are assumed to be adequately controlled. The number of potential chemical and microbial exposure pathways in conceptual models for the three off-site management options are lower than for the four on-site options. These differences are the basis of a Tier 1 ranking shown in Table ES.1.

Table ES.1. Tier 1 Ranking of Livestock Carcass Management Options

Tier 1 Ranking	Management Options	Chemical Exposure Pathways	Microbial Exposure Pathways	Controls and Limits to Environmental Releases
Rank 1: Negligible to minimal exposure — releases regulated to levels safe for human health and the environment	Incineration	6	6	Air emissions regulated under the Clean Air Act (CAA), including pollution control equipment (e.g., scrubbers, filters), with tall stacks to prevent localized deposition; residuals (i.e., ash) managed under the Resource Conservation and Recovery Act (RCRA); wastewater managed under the Clean Water Act (CWA).
	Rendering	3	2	Releases to air and to water regulated under the CAA and CWA, respectively.
	Landfilling	2	2	Landfill design and operation regulated under RCRA; controls include leachate collection and management and methane recovery.
Rank 2: Higher exposure potential— uncontained releases to the environment	Open Burning	10	10	Uncontrolled and unregulated combustion emissions; possible releases from combustion ash if managed on site
	Air-curtain Burning	10	10	Partially controlled but unregulated combustion emissions, possible releases from combustion ash if managed on site
	Composting	8	7	Partially controlled releases from compost windrow (minor leaching, runoff, and gas release to air); where finished compost is tilled into soils, potential runoff and erosion from amended soil
	Burial	6	6	Uncontrolled leaching from unlined burial; slow gas release to air.

Note: higher number (10) indicates potential for higher exposure and risk and a low number indicates less potential for exposure.

The top section of Table ES.2 shows that the Tier 1 assessment for chemicals did not rank the off-site options relative to each other. In a Tier 2 assessment for the on-site management options, potential exposures are ranked relative to one another for a hypothetical site, using a standardized set of environmental conditions (e.g., meteorology), assumptions about the scale of mortality, and how the carcass management options are designed and implemented. Chemical and microbial exposures are assessed independently due to fundamental differences in characteristics influencing transport and fate and in their effects on human health and the environment.

For chemicals, Tier 2 rankings are based on a quantitative assessment in which different methods are applied to estimate combustion releases to air and subsequent deposition to ground level and

to assess fate and transport in surface and subsurface soils, groundwater, and an on-site lake. Exposures were assessed for humans breathing airborne chemicals and ingesting chemicals in drinking water, home grown foods, and fish caught in the on-site lake. Some options (e.g., air-curtain burning and open burning) were not distinguishable from each other given data gaps and uncertainty in modeling. Those options have, therefore, the same relative rank. The findings for the Tier 2 chemical assessment are summarized in the bottom section of Table ES.2.

Table ES.2. Ranking of Livestock Carcass Management Options for Chemicals

Tier 1 Description	Management Option		Principal Rationale
The qualitative Tier 1 assessment distinguishes the off-site options from the on-site options based on level of regulatory control. The off-site options are considered to pose lower risk than the on-site options, which have uncontrolled environmental releases. The off-site options are not ranked relative to each other.	Off-site Rendering		Carcasses processed into useful products; wastes released under permits; availability decreasing
	Off-site Landfill		Carcass leachate contained and methane captured; landfills at capacity are closed and new ones built
	Off-site Incinerator		Destruction of materials; air emissions are regulated; ash is landfilled
Tier 2 Description	**Rank [a]**	**Management Option**	**Principal Rationale**
The quantitative Tier 2 assessment ranks the on-site options relative to each other by comparing ratio of estimated exposures (from data on source emissions and fate and transport modeling) with toxicity reference values (TRVs).	1	Compost Windrow	Bulking material retains most chemicals
	1	Burial	Soils filter out chemicals traveling toward groundwater
	2	Air-curtain burning	Similar release profiles; emissions sensitive to type and quantity of fuels used and burn temperature
	2	Open Pyre burning	
	3	Compost Application	If no offset from lake; mitigate with offset and erosion controls

[a] Rank 1 poses the lowest relative risk and higher numbers indicate higher relative risk.

In the Tier 2 assessment for microbes, three pathogenic microbes were evaluated to represent prions, bacterial spores, and bacterial cells. For these microbes, all estimated exposures were below available exposure benchmark values. However, because of significant uncertainty about the initial concentration of the pathogenic microbes in healthy livestock killed by a natural disaster, the Tier 2 rankings for microbes are based on the degree of thermal destruction and containment provided by the carcass management options. These rankings assume prions could survive more management options than spores, and bacteria that do not form spores were most susceptible to thermal inactivation. Thermal destruction can be applied as a criterion for both the on-site and off-site options. Tables ES.3 and ES.4 show the microbial exposure rankings for Tier

1 and Tier 2, respectively. Although the on-site options are not ranked relative to the off-site options, some will offer thermal destruction comparable to or greater than off-site options.

Table ES.3. Tier 1 Ranking of Off-site Livestock Carcass Management Options for Microbes

Tier 1 Description	Rank[a]	Management Option	Principal Rationale
The qualitative Tier 1 assessment distinguishes the off-site options from the on-site options based on level of regulatory control. Among the off-site options, rankings are based qualitatively on the level of thermal destruction. Off-site options are not ranked relative to on-site options, although some will offer thermal destruction comparable to or greater than off-site options.	H	Off-site Incinerator	Thermal destruction of all microbes, ash is landfilled
	M	Off-site Rendering	Thermal inactivation of all microbes except prions, workers protected from prion exposure with the use of PPE
	L	Off-site Landfill	Containment, including liner, leachate collection, cover material, but no thermal destruction; when capacity is reached, landfill is closed and new ones built

Abbreviations: H = Highest rank; M = Middle rank; L = Lowest rank.

[a] Relative and absolute risks from microbial pathogens depends on initial concentrations in healthy cattle, which is unknown.

Table ES.4. Tier 2 Ranking of On-site Livestock Carcass Management Options for Microbes

Tier 2 Description	Rank[a,b]	Management Option	Principal Rationale
Rankings in the Tier 2 assessment are based on quantitative exposure dose estimates for a limited number of exposure pathways. For those pathways and the microbes assessed, all estimated exposure doses were below the available ID_{50} values for each representative microbe (<7, 3–4, and ~ 1 order of magnitude lower than the ID_{50} for *Escherichia coli*, *Bacillus anthracis*, and prions, respectively). Therefore, the rankings reflect the extent of thermal destruction.	1	Air-curtain	Thermal destruction of all microbes
	2	Open Pyre	Thermal destruction of all microbes except prions
	3	Compost: -Windrow -Soil application	Thermal inactivation of most microbes during windrow decomposition phase, incomplete activation of spore-forming microbes and prions with some decay/inactivation expected before the application of finished compost
	4	Burial	No thermal inactivation of any microbes, some decay expected

Abbreviations: ID_{50} = infectious dose for 50 percent of the exposed population.

[a] Rank 1 poses the lowest relative risk and higher numbers indicate higher relative risk.

[b] Relative and absolute risks from microbial pathogens depends on initial concentrations in healthy cattle, which is unknown; qualitative ranking is based on thermal destruction and containment.

Off-site options, including incineration, landfilling, and rendering, are subject to air, water, and solid waste regulations designed for adequate health and environmental protection. This

assessment finds that, when properly designed and implemented, the four on-site carcass management options are unlikely to cause adverse health or environmental effects.

The Tier 2 assessment provides a scientifically based understanding of the relative contribution of specific exposure pathways, hazardous agents, and steps in carcass management processes. These insights can assist selection of environmentally protective livestock carcass management methods in the event of a natural disaster. The assessment also can aid selection and priority setting for mitigation and best management practices.

In actual natural disasters, many site-specific factors contribute to potential chemical and microbial exposures from carcass management options. The exposure estimates presented in this report should not be interpreted as “actual” exposures associated with the management options. However, site managers can use the findings of this report, in conjunction with site-specific factors, to make informed decisions about which carcass management options would minimize risks to human health and the environment for specific locations.

Acronyms and Abbreviations

Acronym / Abbreviation	Stands For (Country or Agency Affiliation)
µg	microgram(s)
µm	micrometer(s)
ADD	average daily (ingestion) dose
AEGL	Acute Exposure Guideline Level
AERMET	pre-processor for meteorological data for AERMOD
AERMOD	AMS/USEPA Regulatory Model air dispersion model
Al	aluminum
AMS	American Meteorological Society
APHIS	Animal and Plant Health Inspection Service (USDA)
As	arsenic
AT	averaging time
ATSDR	Agency for Toxic Substances and Disease Registry (CDC)
BAF	bioaccumulation factor
BaP	benzo(a)pyrene
BOD	biological oxygen demand
BSE	bovine spongiform encephalopathy
°C	degrees Celsius
Ca (Ca^{2+})	calcium (cation)
CAA	Clean Air Act (U.S.)
CAFO	concentrated animal feeding operation
Cd	cadmium
CDC	Centers for Disease Control and Prevention (U.S.)
CDD	chlorinated dibenzo-p-dioxin
CFR	Code of Federal Regulations (U.S.)
CFU	colony forming unit(s)
CJD	Creutzfeldt–Jakob disease
Cl	chlorine
Cl^-	chloride (anion)
cm	centimeter(s)
CO	carbon monoxide
COD	chemical oxygen demand
CO_2	carbon dioxide
Cr	chromium

Acronym / Abbreviation	Stands For (Country or Agency Affiliation)
Cu	copper
CWD	chronic wasting disease
DHS	Department of Homeland Security (U.S.)
DNR	Department of Natural Resources (Iowa)
dw	dry weight
ED	exposure duration
EF	exposure factor
EFH	Exposure Factors Handbook
°F	degrees Fahrenheit
FAD	foreign animal disease
FC	fraction contaminated
FDA	Food and Drug Administration (U.S.)
Fe	iron
FFI	fatal familial insomnia
ft	foot (feet)
ft^2	square foot (feet)
ft^3	cubic foot (feet)
FMD	foot-and-mouth disease
g	gram(s)
gal	gallon(s)
GSS	Gerstmann-Sträussler-Scheinker syndrome
H_2O	water
HAPs	hazardous air pollutants
HCO_3^-	biocarbonate (anion)
Hg	mercury
HOWI	hog farm waste incinerator
HLC	Henry's Law Constant
hr	hour(s)
HHRAP	Human Health Risk Assessment Protocol (USEPA)
HPAI	highly pathogenic avian influenza
HSE	Health and Safety Executive (of the United Kingdom)
HSRP	Homeland Security Research Program
ID	infectious dose
ID_{50}	infectious dose causing illness in 50 percent of the exposed population

Acronym / Abbreviation	Stands For (Country or Agency Affiliation)
IPCS	International Programme on Chemical Safety (WHO)
IRIS	Integrated Risk Information System (USEPA)
IR	ingestion rate
K (K^+)	potassium (cation)
Kd	soil/liquid partition coefficient
kg	kilogram(s)
km	kilometer(s)
Kow	octanol-water partitioning coefficient
L	liter(s)
lb	pound(s) (weight)
LEL	lower explosive limit
LIWI	livestock disease control incinerator
m	meter(s)
m^2	square meter(s)
m^3	cubic meter(s)
MCL	Maximum Contaminant Level (USEPA)
MCLG	Maximum Contaminant Level Goal (USEPA)
mg	milligram(s)
Mg	magnesium
MIRC	Multimedia Ingestion Risk Calculator
mL	milliliter(s)
mm	millimeters(s)
Mn	manganese
N	nitrogen
Na (Na^+)	sodium (cation)
NABCC	National Agricultural Biosecurity Center Consortium (Kansas State University)
NAWQC	National Ambient Water Quality Criteria
NAWQC-AL	National Ambient Water Quality Criteria for the Protection of Aquatic Life
ng	nanogram(s)
NH_3	ammonia
NH_3-N	nitrogen measured as ammonia
NH^{4+}	ammonium
NHSRC	National Homeland Security Research Center (USEPA)
NIST	National Institute of Standards and Technology (US Department of Commerce)
Ni	nickel

Acronym / Abbreviation	Stands For (Country or Agency Affiliation)
nm	nanometer
NOx	nitrogen oxides
NRC	National Research Council (of the National Academy of Sciences)
NRF	National Response Framework
NSAID	non-steroidal anti-inflammatory drugs
nv-CJD	New variant Creutzfeldt-Jakob disease
OAQPS	Office of Air Quality Planning and Standards (USEPA)
OLEM	Office of Land and Emergency Management (USEPA)
ORD	Office of Research and Development (USEPA)
OW	Office of Water (USEPA)
P	phosphorus
PAHs	polycyclic aromatic hydrocarbons
PAL	Provisional Advisory Levels (USEPA)
Pb	lead
PCDD	polychlorinated dibenzo-p-dioxins
PCDF	polychlorinated dibenzofurans
PeCDD	pentachlorodibenzo-p-dioxin
$PM_{2.5}$	particulate matter ≤ 2.5 microns (μm) in diameter
PM_{10}	particulate matter ≤ 10 microns (μm) in diameter
PO_4^{3-}	phosphate (ion)
PPE	personal protective equipment
PrP^{Sc}	prion causing Scrapie
QA	quality assurance
RCRA	Resource Conservation and Recovery Act (U.S.)
RfD	reference dose
RPF	relative potency factor
S	sulfur
SI	International System of Units
Si	silicon
SO_2	sulfur dioxide
SO_4^{2-}	sulfate (ion)
SSW	Soil and Surface Water (Screening Model)
TCDD	tetrachlorodibenzo-p-dioxin
TEF	toxicity equivalency factor
TEQ	toxic equivalency factor

Acronym / Abbreviation	Stands For (Country or Agency Affiliation)
TKN-N	nitrogen measured as total Kjeldahl nitrogen;
TOC	total organic carbon
ton	U.S. ton(s) (2,000 lb)
tonne	metric tonne(s) (1,000 kg)
TRV	toxicity reference value
TSE	transmissible spongiform encephalopathy
UEL	upper explosive limit
U.S.	United States (adjective)
USDA	United States Department of Agriculture
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey
vCJD	variant Creutzfeldt-Jacob disease
WBAN	Weather-Bureau-Army-Navy
WHO	World Health Organization
ww	wet weight
yd	yard
Zn	zinc

1. Introduction

Established by the U.S. Department of Homeland Security (DHS), the National Response Framework (NRF) is a single comprehensive approach to domestic incident management. The NRF provides a context for DHS and other federal departments and agencies to work with communities to prevent, prepare for, respond to, and recover from hazards such as natural disasters, acts of terrorism, and pandemics.

In support of the NRF, the DHS Science and Technology Directorate is funding research in collaboration with the U.S. Environmental Protection Agency's (USEPA's) Office of Research and Development (ORD), National Homeland Security Research Center (NHSRC) and the U.S. Department of Agriculture's (USDA's) Animal and Plant Health Inspection Service (APHIS) to assure the proper management of animal carcasses following major environmental incidents such as a natural disaster, foreign animal disease (FAD) outbreak, chemical or radiological incident, or other large-scale emergencies. Proper management, including disposal, of livestock carcasses following large-scale mortalities is needed to protect humans, livestock, wildlife, and the environment from chemical and biological hazards; to maintain air, water, and soil resources; to protect ecological resources and services; and to enhance food and agricultural security.

Exposure Assessment Objective

The objective of this exposure assessment is to support selection of environmentally protective livestock carcass management methods in times of emergency by providing scientifically-based information on potential hazards posed by management methods to human health, livestock, wildlife, and the environment.

1.1. Purpose and Scope

This Report focuses on relative exposures and hazards for different livestock carcass management options in the event of a *natural disaster*. Future phases of this research will rank management options in the event of introduction of a FAD, a chemical emergency, and a radiological emergency.

Previous studies (e.g., Gwyther et al. 2011; CAST 2009; NABCC 2004) discussed possible environmental and public health outcomes of mass livestock mortalities following specific natural disasters or animal disease outbreak emergencies. At least three studies (i.e., Gwyther et al. 2011; Pollard et al. 2008; UKDH 2001) also provided comparative analyses to rank carcass

management options (e.g., on-site burial, incineration). Past research relied primarily on qualitative methods or observations based on incident-specific circumstances, which limits its predictive value.

This Report presents a quantitative exposure assessment by which livestock carcass management options are ranked relative to one another for a hypothetical site setting, a standardized set of environmental conditions (e.g., meteorology), and following a single set of assumptions about how the carcass management options are designed and implemented. These settings, conditions, and assumptions are not necessarily representative of site-specific carcass management efforts. Therefore, the exposure assessment should not be interpreted as estimating levels of chemical and microbial exposure that can be expected to result from the management options evaluated. The intent of the relative rankings is to support scientifically-based livestock carcass management decisions that consider potential hazards to human health, livestock, and the environment. This exposure assessment also provides information to support choices about mitigation measures to minimize or eliminate specific exposure pathways.

1.2. Report Organization

The remainder of this Report is organized in seven sections. Section 2 explains the basic conclusions of problem formulation, while Section 3 describes the conceptual models in more detail for each livestock carcass management option, including carcass transportation and handling. The analyses for chemicals are included in Sections 4 and 5. Section 4 focuses on environmental releases, transport, and fate of chemicals from each carcass management option, and Section 5 presents estimated human exposures to chemicals via inhalation from air and total ingestion exposures from all sources (e.g., drinking water, eating fish, consuming crops) for each livestock carcass management option. For chemicals, Section 5 also discusses possible environmental consequences of each carcass management option. Microbial releases, transport, and fate in the environment are described more qualitatively than for chemicals. Section 6 focuses on microbial exposure pathways for humans, other livestock, and terrestrial and aquatic habitats. Potential exposures among the livestock carcass management options are compared in Section 7. In particular, exposures estimated the livestock carcass management options are compared with health benchmarks and the results are used to rank the management options in terms of their potential for adverse health effects. Section 7 also summarizes uncertainties in the

assessment data and methods, and discusses how different scenarios or assumptions would affect potential exposures. In addition, Section 7 discusses mitigation measures and best management practices to address potential exposures, and identifies research needs that would support further understanding of exposures and other potential impacts of the management options. The Report concludes with quality assurance documentation in Section 8 and references cited in Section 9. All appendices are included at the end of this Report.

1.3. Unit Conventions

Calculations for the exposure assessment were performed using metric system units consistent with the International System of Units (SI) as described by the National Institute of Standards and Technology (NIST 2008). Many of the information sources for the exposure assessment used U.S. customary units (e.g., feet, pounds). Quantitative information from these sources is introduced in their original units followed by metric system equivalents in parentheses. The metric equivalents are used thereafter in the Report.

2. Problem Formulation

Problem formulation for the exposure assessment defines the scope of the assessment, including the natural disaster scenario and scale of mortality, the livestock carcass management options and associated activities to be evaluated, and the hazardous materials that could be released to the environment for each option. It also defines a set of standardized environmental conditions and specifies the initial mass of livestock carcasses as 50 U.S. tons (45,359 kg) for all management options. The livestock are assumed to be healthy at the time of death and intact when collected for management. Implementation of carcass management is assumed to be prompt (i.e., not delayed or otherwise affected by disaster conditions, e.g., flooding, damage to roads or structures).

To establish an exposure scenario that encompasses all of the possible exposures and that might reasonably be expected from the livestock carcass management options, livestock mortality is assumed to occur at a hypothetical farm. The location and regional factors do not preclude the availability or feasibility of any carcass management option (e.g., no shallow water tables). Humans potentially exposed include adult and child residents and workers participating in carcass management. The farm includes agricultural fields and a home garden that supplies the farm residents' fruits and vegetables. The residents also produce their own livestock food products at home, including beef, dairy, pork, poultry, and eggs; fish for consumption are caught in an on-site lake. Farm residents obtain drinking water from an on-site groundwater well.

A large number of chemicals and microbes are potentially released to the environment from carcass management options, some of which are more likely than others to be hazardous at estimated or likely environmental concentrations; some of the chemicals and microbes might pose negligible risks from any management option. Included in the exposure assessment are chemicals identified in scientific literature as being present in carcass management wastes and by-products (e.g., leachate, incineration emissions), including chemicals formed from fuels used in the combustion of carcasses. Microbes included in the exposure assessment were ones that could be present in cattle not exhibiting signs or symptoms of illness and considered to be free of disease. The list of assessed microbes was narrowed to a subset expected to remain viable during and after the carcass management process.

This section summarizes the assumptions that apply to the entire assessment, including selection of management options, hazardous agents, and standardized environmental settings and scenarios. The assumptions for specific livestock carcass management options are identified in Section 2 with discussion of the management-specific conceptual models.

2.1. Livestock Carcass Management Options

The management options considered for the exposure assessment are those with documented use following natural disasters or that are likely to have sufficient capacity for large-scale carcass management. These include seven well-established methods, which can be categorized into three groups:

Table 2.1.1. Livestock Carcass Management Options Considered for the Exposure Assessment

Management Type	Specific Management Option
Combustion-based Management	▪ On-site Open Burning (Pyre) ▪ On-site Air-Curtain Burning ▪ Off-site Fixed-facility Incineration
Land-based Management	▪ On-site Unlined Burial ▪ On-site Composting ▪ Off-site Lined Landfill
Materials Processing	▪ Off-site Rendering

The carcass management options can also be categorized as *on-site* or *off-site*. The on-site management methods (open burning, air-curtain combustion, burial, and composting) typically are performed on the livestock owner's property if a suitable location is available. Therefore, residues from the management method could remain in compost windrows, burial trenches, or ash buried at the combustion site. In addition to the biomass residues, there also will be remnants of any additional materials used for the management process, such as woodchips or straw from composting, residual ash from wood or coal used to burn carcasses, and chemical byproducts from accelerants such as petroleum products. For composting, two phases are evaluated: the compost windrow for one year and application of finished compost to farm soils at the end of that year.

Finally, the carcass management options can be categorized by degree of containment. Open pyres and unlined burial do not include constructed barriers to prevent the movement of

substances away from the carcass management site (Table 2.1.2). For air-curtain combustion and composting, there are some constructed barriers inhibiting movement of chemicals and microbes from the carcass management location to the environment. For off-site commercial landfills, commercial incinerators, and rendering facilities, releases from the facility are restricted by regulations designed to protect human health and the environment. For this comparative exposure assessment, all management options are assumed to operate in compliance with applicable regulations and best practices so that releases from commercial off-site facilities are within permitted limits. Thus, exposures from permitted releases from the three regulated off-site management options (i.e., rendering, commercial incineration, placement in lined landfills) are not evaluated, although exposure from transporting the animal carcasses from the farm to the off-site facility is assessed.

Table 2.1.2. Containment of Releases from Management Options

Combustion		Land Based		Material Processing	
On-Site	Off-Site	On-Site	Off-Site	On-Site	Off-Site
Air Curtain	Incineration	Composting	Landfill	Not Evaluated	Rendering
Open Burning (Pyre)		Burial			

= Releases restricted by regulation
= Releases partially restricted by physical barriers
= No barrier to releases

The two on-site combustion options (air curtain and open burning) release gases and particles to air during the few days of active burning. Combustion products released to air, primarily those in particle-phase, will deposit back to ground-level (i.e., surface soils, crop and grass surfaces, and surface water), with more deposited closer to the source than farther away and with heavier particles deposited closer to the source than lighter particles. Dry deposition of particles in the vicinity of the site would occur over roughly the same time as the active combustion.

After combustion ceases, the materials deposited to soils can move over months to years due to precipitation. On the hypothetical farm, chemicals and microbes deposited to surface soils (and plants) move downgradient via runoff and erosion toward the lake, where aquatic plants and animals, including fish, could be exposed.

Leaching of chemicals and microbes from buried ash (remaining from combustion options), from buried carcasses, from compost windrows, and from compost applied to soils also could occur slowly over months and years. Soils would filter some materials out of the leachate, but some might reach groundwater used for the on-site well or reach the lake through groundwater recharge.

This report uses a standardized scenario and set of environmental conditions to estimate the relative exposure potential among the seven carcass management options as discussed in Section 2.2.

2.2. Standardized Conditions

For all carcass management options, the exposure assessment evaluates the management of 50 U.S. tons (45,359 kg) of carcasses. For cattle, that mass would equal 100 animals if they each weighed 454 kg (1,000 lb). For swine, that mass would equal 565 hogs if they each weighed 80 kg (177 lb). For broiler chickens, the mass would include 25,000 birds averaging 4 lb (1.9 kg)[1] each. For turkeys, 5,000 birds averaging 20 lb (9.1 kg)[2] each would constitute 45.4 tonnes (50 U.S. tons) of carcasses. Based on criteria discussed in Section 3.1, carcass management is assumed to take place at hypothetical farm in Iowa.

Mass livestock losses can result from extreme storms, floods, extreme cold and severe winter weather, extreme heat and drought, and fire (USDA 2002; NABCC 2004). From 1998 through 2000, federally-declared natural disasters in the United States included 29% thunderstorms, 22% floods, 15% tornadoes, 12% winter storms, 10% hurricanes, 8% tropical storms, 2% mudslides, 2% wildfires, and 1% earthquakes (USDA 2002). Other disasters that could cause livestock losses are much less frequent in the United States (e.g., avalanche or landslides, tsunamis, volcanic eruption).

Different types of natural disasters can affect the potential for chemical and biological exposures, as well as the feasibility of using specific carcass management options. Storms, hurricanes, tornadoes, and floods can leave the landscape inundated with water, precluding use of some

[1] http://jcea.agr.hr/articles/500_Comparison_of_slaughter_yield_and_carcass_tissue_compisition_in_broiler_chickens_of_various_origin_en.pdf

[2] Turkeys sold for human consumption weigh from 12 to 22 pounds when packaged (USDA 2013a). Whole carcasses would weigh more; therefore 20 pounds per turkey is assumed.

types of carcass management methods (e.g., on-site burial, combustion) and hampering transport of carcasses across flooded areas to off-site carcass management locations. This assessment is limited to releases of hazardous substances from livestock carcass management; it does not address other problems that might accompany specific natural disasters (e.g., blocked roadways, overflow from manure settling lagoons, increased mosquito populations). Hazards and exposures to hazardous materials from carcasses remaining in place for many days or weeks differ from those expected if carcass collection and management occurs within one or two days. To standardize conditions across disaster types, physical effects of the disaster are not considered and are assumed not to impede timely implementation of any of the carcass management options.

Other assumptions to standardize conditions across livestock carcass management options are listed in Table 2.2.1. Readers are cautioned that several of the assumptions would not apply to any given actual emergency mass mortality from a natural disaster in a given area of the country.

2.3. Site Setting and Environmental Conditions

The hypothetical farm establishes an exposure scenario that encompasses possible exposure pathways to humans. A hypothetical location in Iowa was chosen as the site setting because of the predominance and diversity of agricultural activities in the central Midwest and because this region generally is not characterized by extreme weather conditions (e.g., aridity).

The farm includes agricultural fields for fruits and vegetables, a lake, a groundwater well providing water for household uses, irrigation, and raising livestock, and grazing/feeding areas for livestock. For each option, the farmer must manage 45,359 kg (50 U.S. tons) of livestock carcasses killed by the natural disaster on the farm.

1.1.1. Site Location and Meteorology

Multimedia exposure modeling requires assumptions about topographical, hydrogeological, and meteorological conditions in the modeling domain. Land cover near a farm can affect atmospheric stability and moisture availability. Meteorological parameters such as wind, temperature, atmospheric mixing height, atmospheric stability, and precipitation directly affect air dispersion and subsequent deposition of emissions from on-site combustion. Precipitation affects the rates of runoff and erosion from soil and leaching to groundwater.

Table 2.2.1. Standardized Conditions and Assumptions

Issue	Assumptions
Carcass Management and Post-Management Assumptions	▪ Carcass management options include those with documented use following natural disasters or believed to have sufficient capacity for large-scale carcass management. ▪ The exposure assessment begins with collection of carcasses from where animals died and their placement in a single above-ground storage pile on-site. ▪ Workers move the carcasses from the storage pile to the management location (e.g., placement in a burial trench, trucking off-site to a landfill) within 48 hr. ▪ Exposures to hazardous materials released from management units and from post-management processes (e.g., residuals disposal) are both assessed. ▪ On-site management options are designed and operated in compliance with applicable state and federal guidance and regulations. ▪ Off-site commercial management options include containment technologies that should restrict emissions to permitted levels. Moreover, the releases of particles and chemicals at or below regulatory limits are assumed to be health protective. Therefore, the three regulated, off-site carcass management options (i.e., placement in landfills, commercial incineration, and rendering) are not assessed for chemical releases.
Disaster Type and Disaster-Related Effects	▪ The initial mass livestock loss is a result of a natural disaster (type unspecified) and not a disease or culling of livestock to prevent disease. ▪ Carcasses are distributed across the farm for all management options (i.e., not comparing mass mortalities in rangelands to those in concentrated animal feeding operations [CAFOs]). ▪ Carcasses are not damaged by the disaster and are intact (Willis 2003) when collected and placed in the storage pile[2]. Upon placement in the storage pile, carcasses begin to decompose and release liquid. ▪ Disaster conditions (e.g., flooding, road damage, extreme weather incidents) do not impede collection, movement, or handling of the carcasses or implementation of any of the carcass management options.
Livestock Types	▪ The exposure assessment focuses on the management of cattle carcasses. Other livestock categories (e.g., swine and poultry) are discussed where relevant. Category-specific livestock characteristics (e.g., body size) influence handling and management of carcasses (e.g., poultry and juvenile pigs can be moved by hand, movement of cattle and hogs requires heavy equipment), whereas other characteristics are similar across categories (e.g., basic elemental composition of terrestrial vertebrate animals).
Hazard Types	▪ Hazardous agents of concern include chemical and biological agents released directly from decomposing carcasses or from carcass management (including any added materials) and post-management processes. ▪ Prior to death, all livestock are healthy and are asymptomatic even if virulent strains of pathogenic microbes are present in their gut flora. ▪ Other types of hazards caused by natural disaster conditions (e.g., flooding, extreme temperature) are not evaluated. ▪ Accidents (e.g., transport vehicle turnover, rainstorm on open pyre that could end blaze and result in substantial smoldering, road washout) that could affect implementation of a carcass management option do not occur.

Issue	Assumptions
Scale of Livestock Mortality	▪ For all carcass management options, 45,359 kg (50 U.S. tons) of carcasses are managed.
Geographic and Spatial Issues	▪ All carcass management activities take place at a hypothetical site in Iowa. ▪ All carcass management options are evaluated with identical on-site spatial and geographic assumptions (e.g., same size watershed, nearby water bodies, precipitation, land gradient, depth to aquifers). ▪ The site location and regional factors do not preclude the availability or feasibility of any carcass management option (e.g., no shallow water tables). ▪ A single set of values are used for meteorological and other environmental parameters (e.g., wind speed, air mixing height, soil porosity, soil fraction organic carbon, slope and erosion rates, rainfall-related soil percolation and runoff rates). The values are based on data from a representative agricultural region, nationally representative values (if available and vetted as such by USDA or USEPA), and/or health protective values.
Human Health	▪ Farm residents consume farm products as part of their regular diet. ▪ Farm residents are not exposed to other chemicals or other sources of the chemicals analyzed in this report (that is, all doses are directly from the carcass management option). ▪ Worker exposures arise solely from the carcass management option.
Legal Requirements	▪ All federal requirements must be met. ▪ The hypothetical setting as a farm in Iowa does not mean that State of Iowa requirements for carcass management[1] would necessarily be met because that would limit the general applicability of the assessment for emergency mass livestock mortalities.

Abbreviations: hr = hours.

[1] Examples of State of Iowa requirements include that those disposing of dead animals must have a license from the department (Iowa Code §167.2); transporters must be licensed (167.15); disposal must be within 24 hours (167.12(7)), burial must be more than 4 feet deep in the soil and the use of quicklime is required during burial (167.12(6)); disposal must be within a reasonable time after death by composting, cooking, burying, or burning (167.18); open-air burning must be within 24 hours if the animal dies of anthrax or hog cholera (Iowa Administrative Code Chapter 61 21—61.29(167), 61.30(167)).
Iowa Administrative Code § 567-100.4(2)(b)(2): A maximum loading rate of 7 cattle, 44 swine, 73 sheep or lambs or 400 poultry carcasses on any given acre per year. All other species will be limited to 2 carcasses per acre. Animals that die within two months of birth may be buried without regard to number.

[2] There is a short window of time for proper disposal of animal carcasses following their death. Within 7-10 days of death, dependent upon the outside ambient temperatures, animal carcasses become too decomposed/fragile to handle easily with disposal equipment.

To compare the livestock carcass management options for their relative exposure potentials, environmental characteristics must be the same across options. For this project, one year of meteorological data from the National Oceanic and Atmospheric Administration (NOAA) provides a reasonable (i.e., realistic) combination of hourly temperatures, wind speeds and direction, and precipitation frequency and intensity. To realistically represent daily temperature fluctuations and precipitation on an hourly basis for air dispersion modeling, ground-level

meteorological data for the year 2014 were obtained from a station in Iowa City, Iowa (call sign KIOW; Weather-Bureau-Army-Navy [WBAN] identifier 14937). To estimate air mixing height, twice-daily upper-air data for the same year were obtained for Davenport, Iowa (call sign KDVN; WBAN identifier 94982). Sub-hourly wind data were available from Iowa City.

2.3.3. Soils, Crops, and Grazing Lands

The hypothetical farm is located in a predominantly agricultural setting and includes both livestock and crop agriculture on site. Grazing pastures for cattle receive contaminants deposited from the air. Crops grown on site include fruits and vegetables that are consumed by the farm residents. On-site crop agriculture is assumed to supply livestock feed and food for the residents, including beef, pork, poultry, eggs, and dairy products.

As stated above, the two combustion-based carcass management options release gases and particles to air (e.g., the smoke). Airborne particulates can deposit to soils, crops, and grazing land via wet and dry deposition.

Compost windrows are localized; however, finished compost applied to fields spreads the remaining materials, and possibly viable prions and spore-forming microbes over surface soils. Precipitation can move chemical or microbial contaminants in the top few cm of soil to the on-site lake via runoff or erosion.

2.3.4. Lake and Aquatic Food Web

The residents also consume fish caught in an on-site lake. For sustainable populations of game and pan fish (e.g., largemouth bass and sunfish, respectively), the lake must be more than a few acres in size. A 40.5 ha (100 ac or 404,700 m^2) lake could support sustainable populations of game fish (i.e., top carnivores in the food chain), which could accumulate relatively high concentrations of any bioaccumulative chemicals loaded to the lake. Smaller lakes (e.g., 4.05 ha or 10 ac) could support sustainable populations of pan fish. Based on a database for lakes in Minnesota, an average "maximum" depth for a 40.5 ha (100 ac) lake is 7.62 m (25 ft). An average maximum depth for a 4.05 ha (10 ac) lake is 4.57 m (15 ft). Using an empirical formula to estimate average lake depth from maximum lake depth,[3] the average depth of a 40.5 ha lake

[3] The equation, Average Lake Depth = e^(0.727*ln(Maximum Lake Depth), was developed by ICF International in support of a previous application of HHRAP.

would be 4.38 m (14.4 ft) and the average depth for a 4.05 ha (10 ac) lake would be 3.02 m (9.9 ft). The volume of a 40.4 ha lake would therefore be 1.8E+06 m^3 or 1.8E+09 L, and the volume of a 4.04 ha lake would be 1.2E+05 m^3 or 1.2E+08 L, i.e., the product of surface area and average depth.

The lake includes the water column and a bottom sediment layer. The water column can receive chemicals released from carcass management locations via deposition from the air, overland runoff and erosion from soil, and/or groundwater recharge.

For combustion-based carcass management options, the combustion location is assumed to be 30.5 m (100 ft) upwind of the lake. Thus, air deposition of gases and particles would occur primarily in the direction of the lake, with some fraction depositing directly to the lake and the remaining particles depositing to soil and plant surfaces. Following the actual combustion over a few days, the chemicals and microbes deposited to soils would be subject to erosion, runoff, and leaching from the surface soils. Assuming that the lake is the lowest area within a 202 ha (500 ac) watershed (for both lakes), with a slope of 5%, the direction of erosion and runoff would be toward the lake. Groundwater is assumed to intersect the lake bed and to contribute to the contaminant load in the lake water column. The distance of groundwater travel between the location of combustion and the lake is assumed to be 30.5 m (100 ft) (Freedman and Fleming 2003, NABCC 2004).

2.3.5. Groundwater Well

A groundwater well is located on the farm. Considering the four on-site livestock carcass management options, state-recommended off-sets for private groundwater wells were identified only for on-site burial and composting. For those two management options, 100 ft (30.4 m) is the minimum offset identified to date (e.g., Iowa Department of Natural Resources [DNR] 2013, California WRCB 2015, Freedman and Fleming 2003, NABCC 2004). A longer distance is required between a burial site and a public groundwater well (e.g., Iowa DNR recommends 200 ft).

1.4. Hazardous Agents

A large number of different types of chemicals and microbes might be released to the environment from each of the on-site carcass management options. Chemicals include all those

derived from biotic and abiotic degradation of animal carcasses (e.g., carbon dioxide, ammonia, phosphate, sulphate, elemental cations and anions, intermediate degradation products). For combustion-based management options, additional chemical products of pyrolysis include polycyclic aromatic hydrocarbons (PAHs) and dioxins and furans produced by combustion of the carcasses and added fuels. Microbes include those present in the gastrointestinal tract of healthy animals (e.g., *Escherichia coli* O157:H7), including the microbial fauna that assists ungulates digest plant materials, and other microbes frequently found in livestock feces (e.g., *Escherichia coli* O157:H7, *Salmonella* spp., *Shigella* spp.). Several selection criteria focused the exposure assessment on a subset of chemicals and microbes, as described in Sections 2.4.1 and 2.4.2, respectively.

1.4.1. Chemical Agents

Considering all the chemicals in livestock carcasses, the quantities released cannot exceed the total content of the fresh carcasses. Young et al. (2001; based on Forbes 1987) estimated the total content of a cattle carcass weighing 454 kg (1,000 lb) for four elements as:

- Carbon (C): 355 kg (35.5% by mass)
- Nitrogen (N): 40 kg (4%)
- Chlorine (Cl): 0.13 kg (0.13%)
- Potassium (K): 3.0 kg (0.30%)

Releases of those elements in various compounds or forms (e.g., carbon dioxide, ammonia, chloride anions, potassium cations) are not likely to exceed the quantities listed above for each 454 kg of livestock carcasses. Most of the chemical mass in mammalian and avian carcasses is water (H_2O, 55–60%) (Young et al. 2001). Some scientists estimate or assume higher water content and lower carbon content for cattle carcasses (e.g., 75% water, 18% carbon, 3% nitrogen, and 3% hydrogen; SKM 2005).

Three criteria were used for selecting/identifying chemicals for an initial list. The chemicals are:

1) Naturally present in carcasses
2) Created from combustion or decomposition of carcasses
3) For the combustion-based management options, present or created by the fuels used to burn carcasses

The list of chemicals and their sources as analyzed in this report are summarized in Table 2.4.1. Additional criteria allowed elimination of a subset of the chemicals or their potential exposures in particular media or for particular time-frames from further consideration, as explained in Table 2.4.2.

Two types of organic chemicals are not naturally found in livestock, but are formed during combustion of carcasses and fuels used to burn them: PAHs and dioxins/furans. Those two chemical groups include many different congeners. PAHs are formed during incomplete combustion of most organic materials, including coal, gas, oil, wood, garbage, and other materials originating from plants and animals. In nature, PAHs are created by forest and brush fires and from volcanic eruptions. There are more than 100 different PAHs identified, and mixtures of multiple PAHs generally result from combustion (ATSDR 1995). Various mixtures of PAHs also occur in substances such as crude oil, coal, coal tar pitch, creosote, and roofing tar (ATSDR 1995).

Table 2.4.1. Chemicals/Agents Retained for Exposure Assessment for Management Options

Chemical	Medium, Duration	Reason Retained for Assessment
CO, NH_3, CO_2, NOx, SO_2 (gas) from combustion-based management options	Air, short-term	Gases possibly of concern for acute toxicity if air concentrations sufficiently high at receptor location; dilution, dispersion, and advection in open air once the emissions leave the management option might reduce concentrations to nontoxic levels at relatively short distances.
Methane	Soils, long-term	From anaerobic decomposition; risk of explosion if methane accumulations occur in closed buildings and if ignited.
$PM_{2.5}$, PM_{10}	Air, short-term	Hazardous via inhalation; can carry and deposit sorbed hazardous chemicals, can impair visibility.
PAHs	Air and leachate, long-term	Both vapor-phase and particle-phase PAHs are produced during combustion of carcasses and fuels; some are carcinogenic. Particle-phase PAHs can deposit onto plants, soils, and surface waters. Naphthalene is the most abundant PAH produced by carcass combustion (~ 50%; Chen et al. 2003; USEPA 2013a), but it is highly volatile and is expected to remain in vapor-phase.
Dioxins and furans	Air, long term	Produced from combustion of fossil fuels, wood, and other auxiliary fuels used in combustion-based management options. Although primary release is through air, primary exposure is indirect through the food chain after transport and subsequent deposition. Currently there are no data directly evaluating amounts of dioxin or furan release from carcass burning.
NH_3 and NH_4^+	Leachate, long-term	From decomposition of proteins in buried or composted carcasses. Changes nutrient status of surface soils and surface waters. In aerobic environments (e.g., compost windrows), can be converted to nitrates or nitrites, which are toxic to infants.
Cl^-, Na^+, Ca^{2+}, K^+	Leachate first 2.5 months	Included in monitoring data for leachate contamination; most will leach out of carcasses and buried ash over first 2.5 months. Chloride is highly mobile in soils because it is a low molecular weight anion; cations exchange with other cations loosely bound to soil particles. Chloride often used as an indicator of water movement (Glanville et al. 2006).
Fe, Cd, Cr, Cu, Mn, Ni, Pb, Zn	Air (in fly ash) and Leachate, long-term	Cu added to livestock feed to promote growth, Fe to improve hemoglobin levels, Zn to improve skin and fur condition, Mn as a nutrient supplement (although concentrations in carcass leachate measured by Pratt and Fonstad 2009 < 1 mg/L). Elevated levels of Pb and Ni identified in pig excrement from unknown sources, possibly from soil amendments (see Chen et al. 2004).
Phosphate (PO_4^{3-}), sulfate (SO_4^{2-})	Leachate, long-term	Can change nutrient status of surface soils and surface waters.
Biological oxygen demand (BOD)	Leachate, long-term	Can reduce oxygen content in soils and surface waters.
Chemical oxygen demand (COD)	Leachate, long-term	Can reduce oxygen content in soils and surface waters.
As	Leachate	Highly toxic, naturally exceeds USEPA's drinking water criterion (10 µg/L) in groundwater in some areas of the United States. In 2013, the U.S. Food and Drug Administration (FDA) banned use of most organic arsenical drugs (98 of 101 arsenic-based animal drugs) from poultry and pig feeds. In 2014, FDA withdrew approval for roxarsone and two new drugs: arsanilic acid and carbasone. In 2015, FDA withdrew approval of nitarsone, the only remaining arsenic-based drug used in poultry feeds. It could be used through the end of 2015. Thus, as of January 1, 2016, there are no arsenic-based drugs registered for use in livestock feed.

Abbreviations: $PM_{2.5}$ = particulate matter 2.5 micrometers diameter or smaller; PM_{10} = particulate matter 10 micrometers diameter or smaller; PAHs = polycyclic aromatic hydrocarbons; BOD =biological oxygen demand; COD = chemical oxygen demand.

Table 2.4.2. Justifications to Eliminate Chemicals or Their Exposure Sources or Durations from Exposure Assessment for Carcass Management Options

Chemical	Medium, Duration	Reason Eliminated
CO_2, NOx, SO_2 from combustion-based management options	Air, long-term	Gases eliminated from concern for chronic toxicity or long-term adverse environmental effects (e.g., greenhouse gases, acid rain), because they are released in much greater quantities by other point and non-point sources and disperse quickly in air from a single source.
CO, NH_3 from ground-based management options	Air long-term	Gases eliminated because long-term releases from ground-based management options will be at low concentrations.
H_2S, mercaptans from ground-based management options	Air long-term	Odor-causing gases resulting from anaerobic decomposition of carcasses underground; should not be a concern for properly buried or composted carcasses or at landfills with gas recovery technology.
Cl^-, Na^+, Ca^{2+}, K^+	Leachate after 2.5 months	Although these ions contribute to salinity and ionic strength of water, they are not toxic per se at low concentrations.
HCO_3^-	Leachate, long-term	Bicarbonate complexes with some proportion of cations in leachate and buffers pH in soils. Although of low toxicity, the presence of bicarbonate can affect pH and the mobility of other chemicals.
Hg	Air and leachate, long-term	Mercuric compounds are no longer used as fungicides in animal feeds. Although ubiquitous in the environment, most investigators of carcass management options do not analyze samples for Hg. The purpose of this report is to generate comparable environmental assessments of disposal options and not to generate applicable human health assessment numbers. In the absence of the mercury pathway, this assessment constitutes an important first step.
Al	Leachate, long-term	Concentration in leachate is low (<1 mg/L) relative to toxicity (Pratt and Fonstad 2009).
Si, Mg	Leachate, long-term	Soluble silicon and magnesium concentrations in leachate are low (e.g., 20 to 40 mg/L, Pratt and Fonstad 2009) compared with toxic concentrations via ingestion.

In the early 1980s, USEPA identified 16 PAHs as potentially hazardous to humans based on both toxicity and occurrence in the environment (ATSDR 1995):

- naphthalene,
- acenaphthene,
- acenaphthylene,
- anthracene,
- benz(a)anthracene,
- benzo[a]pyrene,
- benzo[b]fluoranthene,
- benzo[g,h,i]perylene,

- benzo[k]fluoranthene,
- chrysene,
- dibenz[a,h]anthracene,
- fluoranthene,
- fluorene,
- indeno[1,2,3-c,d]pyrene,
- phenanthrene, and
- pyrene.

Those 16 PAHs are suspected to be the most harmful, and they have been identified at Superfund sites at higher concentrations that most other PAHs (ATSDR 1995). Naphthalene, a two-ringed PAH, often is the predominant product (e.g., almost 50%) of the combustion of the organic materials including carcasses and auxiliary fuels noted above (Black et al. 2012a,b; Chen et al. 2003; Choi 2014; Johansson and Bavel 2003; USEPA 2013b). More than 98% of naphthalene, however, remains in vapor phase rather than sorbing to particulates. Cyclopenta(c,d)pyrene and perylene (5 rings), benzo(b)chrysene (6 rings), and coronene (7 rings) also are frequently measured in emissions from combustion of organic materials including carcasses and woody fuels for open pyre and air-curtain burning (Black et al. 2012b; Chen et al. 2003; Choi 2014).

Appendix A lists the physicochemical and toxicological properties of the 21 PAHs identified above.

Dioxins, unless separately identified in this report, include polychlorinated dibenzo-*p*-dioxin (PCDD) compounds and polychlorinated dibenzofurans (PCDFs). Dioxins can bioaccumulate in the fatty tissues of fish and other animals and can be of concern in milk products from exposed cattle and goats because of the high lipid content of milk. Dioxins are hydrophobic (also called lipophilic), resistant to metabolism, and persistent in the environment (USEPA 1994, 2012). Their toxicity depends on the degree of chlorination and which functional sites on the molecule are substituted with chlorine (i.e., the congeners with chlorine substituted at the 2,3,7, and 8 positions are the toxic isomers), and 2,3,7,8-tetrachlorinated dibenzo-*p*-dioxin (2,3,7,8-tetrachlorodibenzo-*p*-dioxin [TCDD]) serves as the index chemical for relative toxicity factors (USEPA 2010). Dioxins are expected as a product from the combustion of fossil fuels and woody products. Unfortunately, data on dioxin and furan releases measured from combustion of

carcasses are currently not available. Section 3 describes the data and assumptions used to estimate chemical emissions from combustion of carcasses and fuels.

The dioxins analyzed for this report include dioxin and furan congeners with chlorine substitutions in the 2, 3,7, and 8 positions, which USEPA considers to be the most toxic (USEPA 2010). Appendix B lists the chemical/physical and toxicological properties of the dioxins listed below:

- octaCDD, 1,2,3,4,6,7,8,9-
- octaCDF, 1,2,3,4,6,7,8,9-
- heptaCDD, 1,2,3,4,6,7,8-
- heptaCDF, 1,2,3,4,6,7,8-
- heptaCDF, 1,2,3,4,7,8,9-
- hexaCDD, 1,2,3,4,7,8-
- hexaCDF, 1,2,3,4,7,8-
- hexaCDD, 1,2,3,6,7,8-
- hexaCDF, 1,2,3,6,7,8-
- hexaCDD, 1,2,3,7,8,9-
- hexaCDF, 1,2,3,7,8,9-
- pentaCDD, 1,2,3,7,8-
- pentaCDF, 1,2,3,7,8-
- hexaCDF, 2,3,4,6,7,8-
- pentaCDF, 2,3,4,7,8-
- tetraCDD, 2,3,7,8-
- tetraCDF, 2,3,7,8-

Table 2.4.3 provides a final list of chemical hazards by management option. Not included are veterinary pharmaceuticals (e.g., antibiotics and hormones), detergents, and disinfection byproducts. Few data are available by which to evaluate veterinary pharmaceuticals in leachate from carcass burial (e.g., Yuan et al. 2013), and it is unlikely that measurable amounts will be released to air as parent compound from burning carcasses. FAD control guidelines (e.g., USDA 2013b) include the use of disinfectants to decontaminate vehicles and equipment because they are necessary to reduce the spread of disease causal agents. In contrast, disinfectants are not

absolutely necessary in a natural disaster scenario because the carcasses are from healthy animals. For this reason, disinfectants are not included in the chemical agents selected for this exposure assessment. Although detergents are necessary to clean equipment during a natural disaster, detergent use is expected to be similar among the management options and so are not included in the exposure assessment.

Table 2.4.3. Chemical Hazards Possibly Associated with each Management Option

Management Type	Specific Management Option	Chemical Hazards
Combustion-based Management	On-site Open Burning (pyre) and Air-curtain Burning	Air: PAHs, dioxins, As, Cd, Cr, Cu, Fe, Mn, Ni, Pb, Zn Ash: PAHs, dioxins, As, Cd, Cr, Cu, Fe, Mn, Ni, Pb, Zn
	Off-site Fixed-facility Incineration	Regulated releases – not assessed
Land-based Management	On-site Unlined Burial	Potential plant nutrients (N, P, and S compounds), methane, As, Cd, Cr, Cu, Fe, Mn, Ni, Pb, Zn
	On-site Composting	Potential plant nutrients, As, Cd, Cr, Cu, Fe, Mn, Ni, Pb, Zn
	Off-site Lined Landfill	Regulated releases – not assessed
Material Processing	Off-site Rendering	Regulated releases – not assessed

Abbreviations: PAHs = polycyclic aromatic hydrocarbons.

2.3.6. Microbes

A wide range of microbes are potential hazards associated livestock carcass management options. These microbes, listed in Table 2.4.4, include only organisms that may be present in livestock that are not exhibiting signs or symptoms of infection or illness.

Standard thermal conditions characteristic of the on-site air-curtain burning option are likely to destroy all potential microbial hazards (NABCC 2004; Schwarz et al. 2006; Berge et al. 2009; Gwyther et al. 2011). Therefore, releases of pathogens to the environment are not anticipated and modeling was not done for on-site air-curtain burning.

Only prions are expected to survive the typical thermal conditions associated with on-site open burning. All other pathogens are expected to be destroyed during the burning process.

During the composting process, temperatures of at least 55°C (131°F) must be reached for three or more days to inactivate microbial populations (NABCC 2004). During the first phase of the composting process, the temperature at the core of the pile can reach 55–60°C (131–140°F) within 10 days and remain in that temperature range for several weeks (NABCC 2004). Several

days of those temperatures in the compost pile is adequate to inactivate bacteria, viruses, and protozoa (including their cysts/oocysts) (Franco 2002; Wilkinson et al. 2007; Berge et al. 2009; Schwarz and Bonhotal 2014; Xu et al. 2007). However, the endospores characteristic of spore-forming bacteria (e.g., *Bacillus anthracis*, *Clostridium perfringens*, and *Coxiella burnetii*) and prions would not be inactivated. Thus, spore-forming bacteria and prions remain as potential microbial hazards associated with composting.

Releases of pathogens are unlikely during the rendering, off-site lined landfilling, and off-site fixed facility incineration options because all releases from these facilities are highly regulated. These regulated facilities require the containment and treatment (e.g., chemical disinfection of wastewater) to avoid pathogen releases. Concerns associated with exposure to prions during the rendering process are well documented, and federal regulations are in place to prevent the introduction of prion-contaminated materials in rendering byproducts (Meeker 2006). The survival of prions following rendering is frequently noted as a serious drawback of this option (Taylor et al. 1995; Meeker 2006). Upon further examination, other prion exposure pathways are limited to occupational exposure to contaminated surfaces or materials (Meeker 2006). Occupational guidance precludes worker exposure to prions in areas where outbreaks of transmissible spongiform encephalopathies (TSEs) historically occurred (HSE 2007). This guidance suggests that workers in rendering facilities wear appropriate personal protective equipment (PPE), including gloves and a respirator. In the literature reviewed, there was no evidence of prion release outside of rendering facilities, and it appears that their release is unlikely. For these reasons, prions are not analyzed as a potentially hazardous biological agent associated with rendering in this scenario.

Table 2.4.4 organizes the list of microbes likely to be associated with each type of carcass management. Included in this list are six gram-positive bacteria, seven gram-negative bacteria, three protozoa, six viruses, one fungus, and one prion type. These microbes have been identified in a variety of livestock types, including swine, cattle, and poultry. Although the assumptions described in Section 3 are primarily focused on the management of cattle and not on swine and poultry, microbes associated with all livestock types are presented in Table 2.4.4. They are potential hazards associated with the management of livestock carcasses during a natural disaster.

Table 2.4.4. Microbial Hazards Possibly Associated with Each Option

Management Type	Specific Management Option	Microbes Potentially Released by Stage of Carcass Management	
		Storage, Transportation, and Handling	Carcass Management Options Including Residuals
Combustion-based Management	On-site Open Burning (pyre)	*Bacillus anthracis;* *Campylobacter* spp.; *Clostridium perfringens;* *Coxiella burnetii;* *Dermatophilus congolensis;* *Escherichia coli* O157:H7 and other shiga-toxin producing strains; *Leptospira* spp.; *Listeria monocytogenes*; *Mycobacterium avium paratuberculosis;* *M. bovis;* *Salmonella* spp.; *Shigella* spp.; *Yersinia enterocolitica*; *Cryptosporidium* spp.; *Giardia* spp.; *Toxoplasma gondii*; *Trichophyton verrucosum*; Rotavirus; Hepatitis E virus; Influenza A (avian influenza virus; Enteroviruses; Adenoviruses; Caliciviruses (e.g., norovirus); Prions (PrP^{Sc})	Prions (PrP^{Sc})[4]
	On-site Air-curtain Burning		None
	Off-site Fixed-facility Incineration		None
Land-based Management	On-site Unlined Burial	*B. anthracis;* *Campylobacter* spp.; *C. perfringens;* *Coxiella burnetii;* *Dermatophilus congolensis;* *E. coli* O157:H7 and other shiga-toxin producing strains; *Leptospira* spp.; *L. monocytogenes*; *M. avium paratuberculosis;* *M. bovis;* *Salmonella* spp.; *Shigella* spp.; *Y. enterocolitica*; *Cryptosporidium* spp.; *Giardia* spp.; *T. gondii*;	*B. anthracis;* *Campylobacter* spp.; *C. perfringens;* *Coxiella burnetii;* *Dermatophilus congolensis;* *E. coli* O157:H7 and other shiga-toxin producing strains; *Leptospira* spp.; *L. monocytogenes*; *M. avium Paratuberculosis;* *M. bovis;* *Salmonella* spp.; *Shigella* spp.; *Y. enterocolitica*; *Cryptosporidium* spp.; *Giardia* spp.; *T. gondii*;

[4] In animals, prion diseases include scrapie of sheep and goats, bovine spongiform encephalopathy (BSE) of cattle, and chronic wasting disease (CWD) of wild deer and elk. In humans, prion diseases include a group of fatal neurodegenerative and infectious disorders such as Creutzfeldt-Jacob disease (CJD), a variant form of CJD (vCJD), Gerstmann-Sträussler-Scheinker syndrome (GSS), and kuru, fatal familial insomnia (FFI) (Prusiner 1996).

Management Type	Specific Management Option	Microbes Potentially Released by Stage of Carcass Management	
		Storage, Transportation, and Handling	**Carcass Management Options Including Residuals**
		Trichophyton verrucosum; Rotavirus; Hepatitis E virus; Influenza A (avian influenza virus); Enteroviruses; Adenoviruses; Caliciviruses (e.g., norovirus); Prions (PrP^{Sc})	*Trichophyton verrucosum*; Rotavirus; Hepatitis E virus; Influenza A (avian influenza virus[6]); Enteroviruses; Adenoviruses; Caliciviruses (e.g., norovirus); Prions (PrP^{Sc})
	On-site Composting		*B. anthracis*; *C. perfringens;* *Coxiella burnetii*; Prions (PrP^{Sc})
	Off-site Lined Landfill		None
Material Processing	Off-site Rendering	*B. anthracis;* *Campylobacter* spp.; *C. perfringens;* *Coxiella burnetii;* *Dermatophilus congolensis;* *E. coli* O157:H7 and other shiga-toxin producing strains; *Leptospira* spp.; *L. monocytogenes*; *M. avium Paratuberculosis;* *M. bovis;* *Salmonella* spp.; *Shigella* spp.; *Y. enterocolitica*; *Cryptosporidium* spp.; *Giardia* spp.; *T. gondii*; *Trichophyton verrucosum*; Rotavirus; Hepatitis E virus; Influenza A (avian influenza virus[8]); Enteroviruses; Adenoviruses; Caliciviruses (e.g., norovirus); Prions (PrP^{Sc})	None

While a large number of microorganisms are classified as fungi, only one is included in Table 2.4.4. The major fungal pathogens of humans (species of *Aspergillus*, *Blastomyces*, *Candida*, *Cryptococcus*, *Paracoccidoides*, *Pneumocystis*, and various dermatophytes) are not necessarily associated with livestock carcasses, even though there might be an increased risk of infection associated with handling soil during carcass management activities (MacCallum 2014). All

microbes that can occur in healthy livestock are included as potential hazards in the on-site unlined burial option, as well as the storage, transportation, and handling stages of carcass management, because there are no initial assumptions on thermal conditions that would inactivate any of the agents. While workers handling livestock carcasses are assumed to wear PPE, the storage pile is uncovered and there are no strategies to mitigate the release of microbes to the environment from the storage pile. With respect to the on-site unlined burial option, the conditions of deep burial and associated pressures, oxygen levels, and temperatures might limit the survival of the majority of non-spore forming organisms (NABCC 2004; Gwyther et al. 2011). However, empirical studies of livestock burial sites have reported the detection of pathogenic bacteria including *Escherichia coli*, *Clostridium perfringens*, and *Salmonella* spp. in groundwater and near-by soil samples (Davies and Wray 1996; Joung et al. 2013). Although the number of samples that tested positive for the presence of these pathogens was low, pathogens were detected at sampling sites 0–50 m (0–164 ft), 51–100 m (167–328 ft), and 101–200 m (331–656 ft) from the burial site, which contained a mixture of carcasses including pigs, cattle, goats, and deer. In consideration of these data, all identified microbes are considered capable of surviving the burial process.

1.5. Expert Workshop at the 5th International Symposium on Animal Mortality Management

From September 28 through October 1, 2015, the 5th International Symposium on Animal Mortality Management[5] in Lancaster, Pennsylvania, brought together experts from academia, government, and the private sector to share information on a range of topics relating to livestock carcass management. The authors of this report held a workshop on the final day of the symposium to obtain input from experts on the proposed methods, data, and assumptions for the exposure assessment of livestock carcass management following a natural disaster. The objective of the expert workshop was to obtain real-world feedback and recommendations from livestock carcass management researchers and practitioners.

At the time of the expert workshop, a detailed conceptual model and analysis plan had been developed for the natural disaster scenario exposure assessment, but the assessment had not been

[5] The symposium program and proceedings are available for download at: http://animalmortmgmt.org/symposium/proceedings-of-the-5th-international-symposium-on-animal-mortality-management/

performed. The conceptual model and analysis plan described specific assumptions about the carcass management options and identified data sources and models that would be used to estimate exposures. Therefore, the workshop allowed for a timely review by the experts and an opportunity to refine the approach before its implementation.

Twenty-eight experts attended the three-hour workshop. It began with an introduction about the exposure assessment project, including its impetus, scope, and objectives. The remaining time was divided between two technical sessions. The first session covered the exposure assessment for the four on-site carcass management options. For each management option, the authors summarized assumptions that would affect the nature and magnitude of potential chemical and microbial exposures, including:

- The design (e.g., pyre size, construction, fuels) and implementation (e.g., burn duration, temperature) of the option
- Expected releases and exposure pathways
- Chemicals and microbes of concern

A group discussion followed the presentation for each management option.

The second technical session addressed potential sources of exposure associated with carcass handling and transportation activities. At the time of the workshop, those activities had not been included in the scope of the assessment. The authors posed a series of questions intended to build conceptual models, identify potential releases and exposure pathways, and identify useful information sources or assumptions for carcass handling and transportation.

Following the workshop, the project team met to review the meeting notes, as well as publications and other follow-up information provided by experts, to identify refinements to the exposure assessment analysis plan. Although the experts identified no major deficiencies of the analysis plan, they suggested refinements to some assumptions. The expert discussion also leads to the addition of carcass transportation and handling to the scope of the assessment. Several specific refinements and additions based on the expert workshop are listed below:

- For air-curtain burning, the fuel to carcass ratio was increased from 2:1 to 4:1. This change, which increases emissions from that management option, was based on field experience where combustion efficiency was limited by rain and use of low-quality wood fuel.
- For air-curtain burning, the burn duration was increased from 25 hour (hr) to 48 hr. The experts found the previous assumption too optimistic.
- Although carcasses should be transported in "leak-proof" containers, the experts agreed that vehicles designed to be leak-proof rarely are. Therefore, it is common practice to use a double lining of plastic and layered absorbent carbon material as added leak protection during transportation.
- The experts recommended an assumption that trucks will be loaded to no more than 60% capacity by volume because the carcasses might bloat and expand after loading.
- For carcass transportation and handling scenarios, the experts noted that abdomens typically burst within 3 or 4 days after death, with liquid releases occurring 3 to 7 days after death. These events are likely to occur during the management action in our scenario based on the assumed timing sequence of events.

3. Conceptual Models of Carcass Management Options

This section provides a conceptual model for each of the assessed management options, including carcass management processes and equipment, waste and other products (e.g., ash, finished compost) and their characteristics, releases to environmental media (i.e., air, water, soil), and exposure pathways. As discussed in Section 2, exposures are not quantified for the three off-site management options (i.e., landfilling, incineration, rendering), because all releases to the environment from those facility categories are from pollution control systems that should comply with applicable requirements. Exposure to pathogens that might survive the rendering process is assumed to be outside the scope of this assessment for natural disasters (see Section 2.4.2 for more details).

This section also describes estimated chemical release rates from the four on-site management options: open-pyre burning (Section 3.1), air-curtain burning (Section 3.2), unlined burial (Section 3.3), and composting (Section 3.4). Quantitative estimates of microbial releases to the environment could not be based on direct evidence of the concentration of microbes present in livestock at the time of management. Instead, the concentration of microbes present in cattle manure or a concentration less than the infectious dose were used as an estimate of microbes released to the environment. This is reasonable because environmental factors over time are equally likely to promote or to limit microbial growth and reproduction from the animal's time of death until the microbes' release into the environment. The qualitative potential for microbial releases and exposures from these management options are discussed in Section 6.

Sections 3.1 through 3.5 include diagrams of the conceptual models to show how chemicals and microbes are released during each option, including the management of residuals (e.g., application of finished compost, disposal of combustion ash). The diagrams also identify the exposure pathways that chemicals and microbes might follow through the abiotic and biotic media to potential receptors and chemical fate and transport processes (e.g., wet and dry deposition, erosion, bioaccumulation) in abiotic and biotic media. These diagrams are products of a conceptual modeling phase of the project that followed initial problem formulation. Presented along with the conceptual models in this section are summaries of scientific literature that support quantitative modeling of releases, fate and transport, and exposure. For example, emission factors are presented for carcass incineration as milligrams chemical emitted per

kilogram carcasses incinerated, and the models consider concentrations of chemicals in leachate measured at the bottom of experimental carcass burial pits.

Appendix C presents further details about the conceptual models for this project. In the appendix, the conceptual models are presented at two levels of detail. First, the conceptual model for each management option, including the three off-site options, is presented in a single, overview diagram. A more-detailed second set of conceptual model diagrams provides further information about the sources, transport, and fate processes. The second set is divided into a series of modules and includes one module for each management option, one module for each type of abiotic exposure medium, and several biological modules to represent food chain transfers and ultimate exposures of humans, livestock, and wildlife.

3.1. Carcass Transportation and Handling

All of the livestock carcass management options involve transportation and other handling of the carcasses. Carcass transportation and handling activities considered in the assessment occur between animal death and placement of the carcasses in the management units (e.g., burial trench, compost windrow); these activities include the following:

- Moving the carcasses from the place of death to a temporary storage location
- Storage of the carcasses temporarily until transportation and management options are ready
- Loading the carcasses onto vehicles for movement to the management location
- Transporting the carcasses in multiple truck loads
- Unloading and placing the carcasses at the management location

USDA's APHIS *National Animal Health Emergency Management System* guidelines (e.g., USDA 2013b) provide various on-site biosecurity measures to limit exposures of livestock and response personnel, particularly to FAD agents. For example, biosecurity zones should be established at the farm for decontamination of equipment and vehicles. For the exposure assessment for the natural disaster scenario in which FAD agents are not a consideration, biosecurity precautions are assumed to include only the use of PPE and implementation of the management options consistent with best practices and applicable regulations.

This section describes the nature and scope of carcass transportation and handling activities included in the assessment. In most respects, these activities are independent of the carcass

management option; that is, the potential exposures are the same for each of the management options. Table 3.1.1 summarizes the scoping assumptions for carcass transportation and handling in the exposure assessment. The assumptions are discussed further in Sections 3.5.1 through 3.5.3.

Table 3.1.1. Summary of Assumptions for Livestock Carcass Transportation and Handling

Activity	Scoping Assumptions Carcass Transportation and Handling
Carcass Handling	▪ Workers wear PPE, including coveralls, gloves, boots, and masks. ▪ Non-workers do not touch or otherwise contact carcasses, and the public would be excluded from work sites based on general safety concerns. ▪ Biosecurity zones and associated biosecurity practices required for foreign animal disease outbreaks are not used.
Temporary Carcass Storage	▪ Carcasses are moved from the mortality location to an outdoor pile on bare earth where they stay for 48 hr before on-site or off-site management. ▪ The pile has a trapezoidal cross sectional shape that is 8 ft (2.4 m) wide at the base, 3 ft (0.91 m) wide on top, and 5 ft (1.5 m) high. With a total volume of 196 yd^3 (150 m^3), the length of the pile is 132 ft (40.3 m). ▪ No disinfectants or other chemicals are applied to the pile.
Carcass Transportation	▪ Carcasses are transported in roll-off trucks with a weight capacity of 12 tons or 24,000 lb (10,886 kg) and a volume capacity of 40 yd^3 (31 m^3). ▪ Carcasses are transported in roll-off trucks with water-proof liners to minimize leakage. ▪ Tarps cover the carcasses. ▪ Eight truck trips are required to move all carcasses ▪ Twenty liters (20 L) of carcass fluids leak per trip per truck ▪ On-site transportation methods are equivalent to off-site transportation methods.

Abbreviations: PPE = personal protective equipment; hr = hr; ft = feet; lb = pound (weight); yd = yard.

1.5.1. Carcass Handling Before and after Transportation

Moving carcasses to and from the storage pile, loading and unloading vehicles, and placing the carcasses in a management unit might require workers to come in contact with the carcasses (e.g., particularly smaller livestock such as pigs or poultry). As shown in the conceptual model in Figure 3.1.1, these activities could lead to primary- and secondary-contact exposures through dermal exposure, inhalation, or hand-to-mouth transfer of particles that subsequently are ingested. The assessment assumes workers are the only humans with direct access to the carcasses. Animals that are likely to contact temporarily stored carcasses include scavenging wildlife (e.g., fox, crow, rats) and insects (e.g., flies).

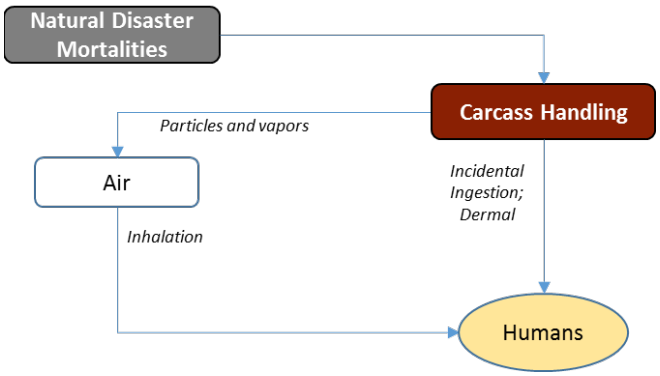


Figure 3.1.1. Conceptual model for exposure pathways from livestock carcasses handling.

Without PPE, such as gloves, boots, or respiratory protection, workers directly contacting carcasses might inhale chemicals or microbes emitted to the air from the carcasses or might accidently ingest some of the liquids released by decomposition. Assumptions about the use of PPE are based on regulations of the Occupational Safety and Health Administration (OSHA), specifically Appendix B of 29 Code of Federal Regulations [CFR] 1910.120. These regulations define required and optional equipment for four levels of protection that can be chosen based on the potential hazards expected for a job. The exposure assessment assumes use of Level-D PPE, which is the least stringent of the four levels and includes:

Required, included in the exposure assessment for the natural disaster scenario:

- Coveralls
- Boots/shoes, chemical-resistant steel toe and shank

Optional, included for the exposure assessment for the natural disaster scenario:

- Gloves
- Safety glasses or chemical splash goggles
- Dust mask or escape mask

Optional, not included in the exposure assessment for the natural disaster scenario:

- Boots, outer, chemical-resistant (disposable)
- Hard hat
- Face shield

This level of PPE is intended to preclude splashes, immersion, or the potential for unexpected inhalation of or contact with hazardous levels of any chemicals (29 CFR 1910.120 Appendix B). While dust masks would not necessarily provide protection against air-borne chemicals, the potential for acute effects level inhalation exposure is assumed to be negligible because of the passive nature of the emissions and an adequate fresh air supply for outdoor activities. For indoor activities, building ventilation systems would limit chemical exposure. Moreover, the duration of the exposure during handling would be on the order of hours. Workers and farm residents are not expected to be in close proximity to the source for an extended period. That is, their potential inhalation exposure is limited to only what they breathe in when they are in close proximity to the carcasses. Therefore, concentrations of chemicals in air would be of concern if they exceeded acute health effects levels. Accordingly, exposures from carcass handling are assumed to be adequately mitigated and are not included in the quantitative assessment.

1.5.2. Temporary Carcass Storage Before Transportation

Temporary on-site storage of carcasses is likely to be necessary while available management options are identified and evaluated, while on-site management units are constructed, and while awaiting transportation or completion of other logistical requirements (e.g., obtaining burn permits, obtaining air-curtain burning equipment from off-site). Many state regulations require carcasses to be managed within a specified timeframe, usually within 24 to 72 hours (USDA 2015). For the exposure assessment, on-site storage for 48 hours (2 days) is assumed for all management options.

The location and design of the temporary carcass storage location(s) can affect potential exposure pathways. Carcasses could be stored in a pile on the ground in open air, in a refrigerated storage unit, or in containers (USDA 2015). Carcasses on the ground could be covered with a tarp, soil, or other material, or left uncovered (USDA 2005). Carcasses might be placed on bare earth or on an impervious surface with or without leachate collection or other management features. For the natural disaster scenario, in which the livestock are neither diseased nor contaminated with elevated levels of chemicals (e.g., pesticides) or radiological agents, it can be assumed that no special precautions are necessary to contain the carcasses. Temporary storage is, therefore, assumed to occur in a pile on the ground outside without a liner

or tarp covering even though the sight of carcasses and odor of volatiles may cause distress in some individuals.

The dimensions of the storage pile are based the total amount of carcasses (i.e., 45,360 kg = 50 U.S. tons), the assumed volume of a single cattle carcass (1.5 m^3) from South Australia Environmental Protection Agency (SAEPA 2016), 100 carcasses each weighing 2,268 kg (1,000 lb). The pile is assumed to have a trapezoidal cross sectional shape that is 2.4 m (8 ft) wide at the base, 0.91 m (3 ft) wide on top, and 1.5 m (5 ft) high. With a total volume of 150 m^3 (196 yd^3), the length of the pile is 40.3 m (132 ft).

Figure 3.1.2 presents the conceptual model for the temporary carcass storage pile. Chemical releases from the storage pile include volatilization of particles and vapor to air, and leaching of liquid from the pile to the ground below. There were no sources reporting the concentrations or emission factors for chemicals released to air from uncovered, aboveground carcasses. Young et al. (2001) described the degradation process for buried carcasses in comparison to the stages of decomposing putrescible materials in a domestic landfill. The first two stages, which are most likely to occur during the two-day carcass storage, include:

1) *Initial aerobic phase*. Degradation by aerobic microbes, for which oxygen provides electron receptors with production of carbon dioxide, progresses rapidly until available oxygen is depleted internally, and further aerobic microbial activity is not possible. Changes within the body tissues within the first day or so after death prevent the growth of aerobic bacteria, except on the surface of the carcass where it is exposed to the atmosphere.
2) *Initial anaerobic phase*. Bacterial heterotrophs reduce sulfates and nitrates and begin the breakdown of long chain lipids and carbohydrates, which also releases carbon dioxide and water. Proteins are degraded through amino acids to ammonium. Hydrogen sulfide and other odor-causing chemicals also can be formed in Phase 2.

Young et al. (2001) concluded that the initial stage of intense decomposition may produce significant volumes of carbon dioxide and, possibly, malodorous gases, but the amount of methane is likely to be limited until later stages of decomposition.

Sources that discuss air quality from livestock composting generally focus on odor generation and vapors including hydrogen sulfide and ammonia. Glanville et al. (2006), for example, reported that odor levels within the first four months of composting were similar to those reported for pond water (200–300 odor detection threshold [ODT], the volumetric ratio of fresh air to sample, are at the lowest level that olfactometry panelists could detect an odor). The levels are quite low compared with manure-related facilities (4,000 ODT).Carcass management workers are those most likely to be exposed to gases from the storage pile. Their exposure to gases from the storage pile would be no longer than the duration of storage (48 hr). Workers and farm residents are not expected to continually be in close proximity to the source throughout that period. Therefore, concentrations of chemicals in air would be of concern if they exceeded acute health effects levels. Placement of a storage pile outdoors is expected to prevent its ambient concentrations of airborne chemicals from reaching harmful levels.

Any non-volatilized liquid leaching from the storage pile is assumed to percolate down through soil to the groundwater aquifer. The exposure assessment includes modeling chemical fate in the subsurface soil and in groundwater, with chemicals reaching a drinking water well 30.5 m (100 ft) downgradient. If chemical concentrations in groundwater as drawn by the well for household uses are near human welfare benchmarks of concern, livestock exposures via groundwater will be assessed. Otherwise, the latter pathway will not be assessed; the much higher minimum groundwater flow required to water 50 tons of livestock would dilute contaminants a further three to four orders of magnitude compared with the concentrations estimated for a low-flow aquifer providing sufficient water for household uses.

1.5.3. Carcass Transportation

Many equipment options are available for moving the carcasses, and assumptions about which types of equipment are used affect potential release pathways and the rates of release of chemicals and microbes. For off-site management options, where carcasses are transported over public roads, decisions about livestock carcass vehicles and equipment are guided, to some extent, by federal regulations (9 CFR 325.20 and 325.21), which require all vehicles used to transport dead, dying, disabled, and diseased livestock or parts of livestock carcasses to be leak-proof and constructed to permit thorough cleaning and sanitizing. Along with federal regulations,

local and state regulations exist that prescribe the transportation of carcasses on public roads, however, only federal regulations are considered for this assessment.

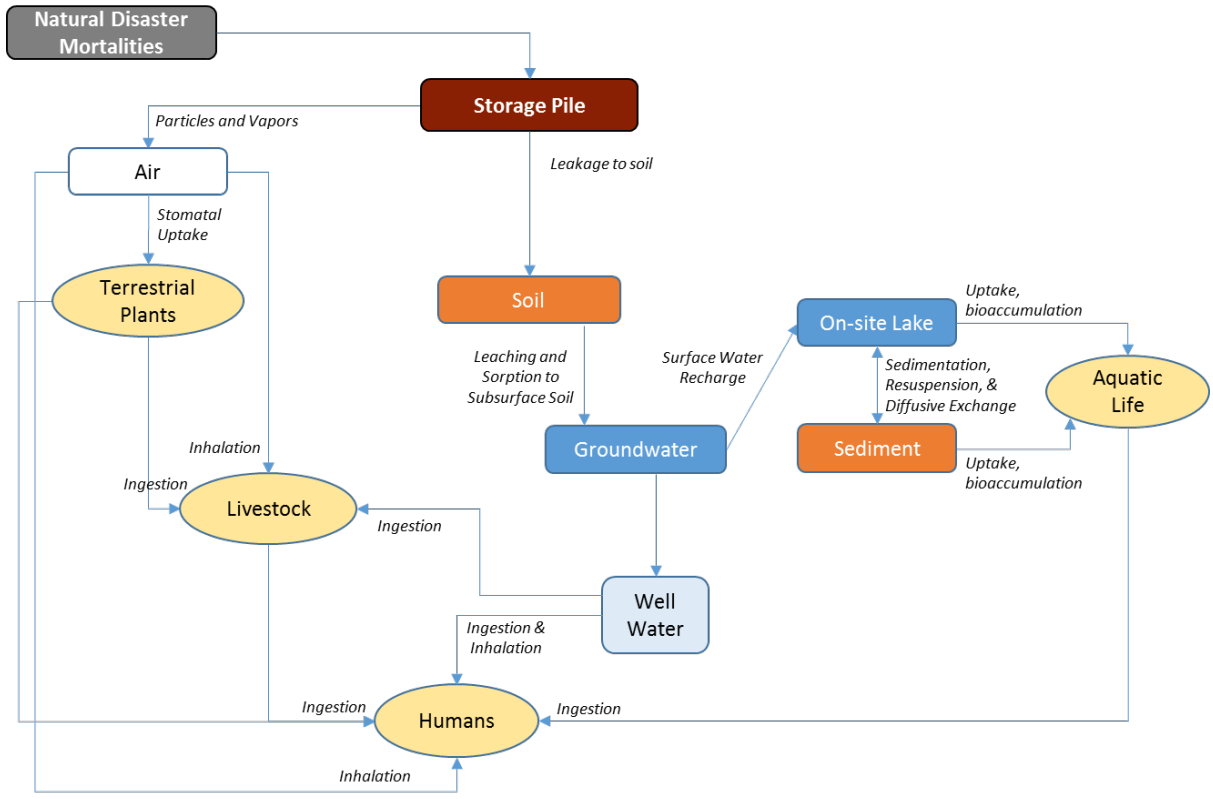


Figure 3.1.2. Conceptual model for exposure pathways from temporary carcass storage.

Figure 3.1.3 presents the conceptual model for chemical and microbial releases from carcass transportation. Potential release pathways include airborne releases from the exposed carcasses during transit, body fluid leakage from the truck bed, and spillage of carcasses and leaked body fluid in the event of an accident. The potential for these releases to occur and their estimated magnitude depend on the types of equipment (e.g., vehicle type, covers) assumed.

The University of Minnesota Center for Animal Health and Food Safety (UM-CAHFS 2014) identified three types of trucks that are commonly used to transport livestock carcasses:

- *Rendering truck* – A "rendering" truck is a semi-truck that has an attached box trailer. It has a leak-proof, sealed bed, and an open top. The length of trailer can vary, however the most common bed lengths are 28, 32, and 40 ft (8.5, 9.8, and 12.2 m). The weight capacities and lengths for a rendering truck are 40,000, 45,000, and 50,000 lb (18,144, 20,412, and 22,680

kg) for 28, 32, and 40 ft bed lengths respectively (UM-CAHFS 2014). These trucks can transport carcasses from farms to off-site facilities.

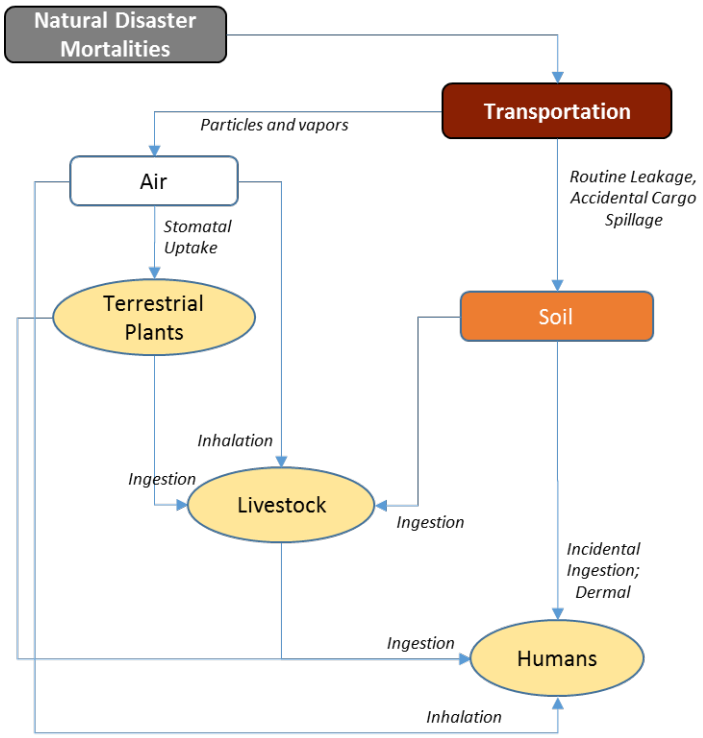


Figure 3.1.3. Conceptual model for exposure pathways from livestock carcass transportation.

- *Roll-off truck* – A roll-off truck has a removable, open-top container with wheels that allow it to be rolled off of the truck onto the ground. Roll-off containers are available in different sizes, including 10, 15, 20, 30, and 40 yd^3 (7.6, 11.5, 15.3, 22.9, and 30.6 m^3). Roll-off containers are not designed to be leak-proof, and additional measures (e.g., lining with a double layer of plastic sheeting) are often used to reduce the likelihood of leakage (UM-CAHFS 2014).
- *Dump truck* – A dump truck is an open-bed truck that has a hydraulic system to lift the front of the bed to allow the contents to dump out of the back of the truck. This truck does not necessarily come with a sealed tailgate nor is it considered leak-proof. Additional modification measures would be required to make a dump truck resist leakage. Dump trucks are available in various capacities, and include single- and tandem-axle vehicles. A tandem-axle dump truck typically has a volume capacity of approximately 15 yd^3 (11.5 m^3) and a

weight capacity of approximately 40,500 lb (18,370 kg) (UM-CAHFS 2014). The weight capacity of a dump truck can also vary by road weight limit.

The rendering truck is the only one of these truck types that is by definition considered already leak-proof. However, for the Phases 1 exposure assessment, carcasses are not diseased and timely access to available vehicles is likely to be a priority. Therefore, a lined roll-off truck with a weight capacity of 12 U.S. tons or 24,000 lb (10,886 kg) and a volume capacity of 40 yd^3 (31 m^3) is used for both on-site and off-site management options (CWS undated). Although lining of the truck is not required, a liner is assumed to comply with regulations at 9 CFR 325.20 and 325.21 as a means of meeting the leak-proof requirement.

Assuming that the volume of an adult bovine carcass is 1.5 m^3 based on SAEPA (2016), the total volume of carcasses to be transported for any of the management options is 150 m^3. The number of truck trips required to transport the carcasses may be limited by either the volume or weight capacity of the roll-off truck. As stated above, the truck is assumed to have a weight capacity of 10,886 kg and a volume capacity of 31 m^3. In addition, carcass management experts suggest (see Section 2.5) that trucks and other containers should not be filled to capacity with carcasses because the carcasses may expand after loading. Specifically, the experts stated that standard practice is not to surpass 60% of the volume capacity for each load. Thus, the effective volume capacity per load is 60% of 31 m^3, or 18.3 m^3. The volume capacity per load is reached before the weight capacity, and eight truck trips are required to transport all the carcasses.

According to information provided at the expert workshop (see Section 2.5), even leak-proof containers are “almost never leak-proof.” Therefore, a double lining of plastic and layered absorbent carbon material are often added precautions, particularly for carcasses of diseased animals. The only information available to quantify leakage is UM-CAHFS (2014). Based on consultations with rendering industry experts, the authors reported the rate of leakage from a fully loaded standard rendering truck to be around 20 L per load. No quantitative information has been found to compare this estimate to the effectivenss of liners or other practices used to make other truck types comply with the FHWA “leak-proof” requirement of 9 CFR 325.21. This rate of leakage (i.e., 20 L) is assumed for each truckload for all management options.

A tarp covering is assumed for all truck transportation in the exposure assessment. A tarp covering is routinely used during carcass transportation to restrict contents from visibility or ejection (UM-CAHFS 2014). Although not required by federal regulation, tarps may be required under a state regulation or rule. Tarps can be waterproof (e.g., waterproofed canvas, vinyl coated polyester mesh), but they are not airtight. They can be secured manually (e.g., with bungee cords) or with a mechanical tarp roller if the truck is equipped with one. The effectiveness of the cover is affected by the type and condition of tarp, the type of securing method, the form and condition of the cargo, freeboard space between the cargo and top of the truck, weather (e.g., wind temperature), and vehicle speed.

If a truck carrying carcasses gets into an accident en route to an off-site carcass management facility, hazardous agents may be released to the ground or air. The likelihood of an accident can be evaluated with accident statistics for large trucks (i.e., gross weight at least 10,000 lb [4,536 kg]) from the US Department of Transportation (USDOT) for 2013, the most recent year with data available (USDOT 2015). Large trucks traveled 275,018 million miles (442,597 million km) in the United States in 2013, and approximately 327,000 accidents involving large trucks were reported to the police. Based on this information, there were 0.74 accidents reported to the police per million km traveled (1.2 accidents per million miles traveled), or a risk of 7.4 E-07 risk of an accident per km traveled.

A truck accident involving a load of livestock carcasses would be of concern for the exposure assessment only if the cargo spills from the truck. The accident statistics discussed above are for all accidents reported to the police, not necessarily ones that included spillage. However, available statistics indicate that cargo was spilled in 12% of the accidents in 2013 involving trucks that carried hazardous waste. If it is assumed that this rate of accident spillage for trucks carrying hazardous waste is the same as the rate of spillage for all large truck accidents, then the risk of an accident with spillage per km traveled is 8.9 E-08 (= 7.4 E-07 x 12%).

The likelihood that an individual truckload is involved in an accident with spillage depends on the distance traveled to the management location. If the average distance traveled per truck trip is assumed to be 100 km, then the risk of an accident with spillage per truck load is 8.9 E-06 (= 8.9 E-08 x 100 km), and the risk for eight truck loads is 7.1 E-05. This analysis indicates a low likelihood of carcasses being released as a result of an accident during transit to an off-site

management facility. Moreover, if an accident were to occur and carcasses were released directly to the ground, response actions would be taken quickly to remove the carcasses and associated wastes. Based on the calculated low rate of accidents with spillage occurring, and the limited extent and duration of any releases, exposure pathways associated with truck accidents are not included in the quantitative assessment.

3.2. On-site Open Burning (Pyre)

An overview of the conceptual model for the on-site open burning (pyre) management option is presented in Figure 3.2.1, and further assumptions for open burning are provided in Table 3.2.1. With this option, the carcasses are burned in a single pyre resulting in release of gases and particles, including active or inactivated microbes, over the course of an assumed 48-hr burn duration (USDA 2005). Ash may be managed on site or removed to an off-site landfill. For this exposure assessment, the ash is managed on site, specifically by being buried or covered with clean soil in place (i.e., over the area of ground on which the pyre burned). The fuels used to promote burning of the carcasses also will release some chemicals in vapor and particulate-phase to air while leaving other chemicals in the residual ash. Particles released to air can include microbes and can cover a range of sizes from submicron (less than 1 micrometer [µm]) to a few millimeters (mm) in length or diameter.

There are no sources directly reporting measurement of combustion temperatures within carcass pyres. Based on information on the ignition and combustion temperatures of wood and coal reported by Bartok (2003), 550°C (1,022°F) is the temperature assumed for this assessment. There is likely to be a significant temperature gradient within a pyre, however, with portions near the center of the pyre being significantly higher than the average temperature. Other portions, particularly near the edges of the pyre or near wetter materials, are likely to be significantly lower in temperature than the average.

Section 3.2.1 discusses chemicals released to air from open burning, and Section 3.2.2 discusses possible releases from buried ash from percolation of rainwater through the ash layer.

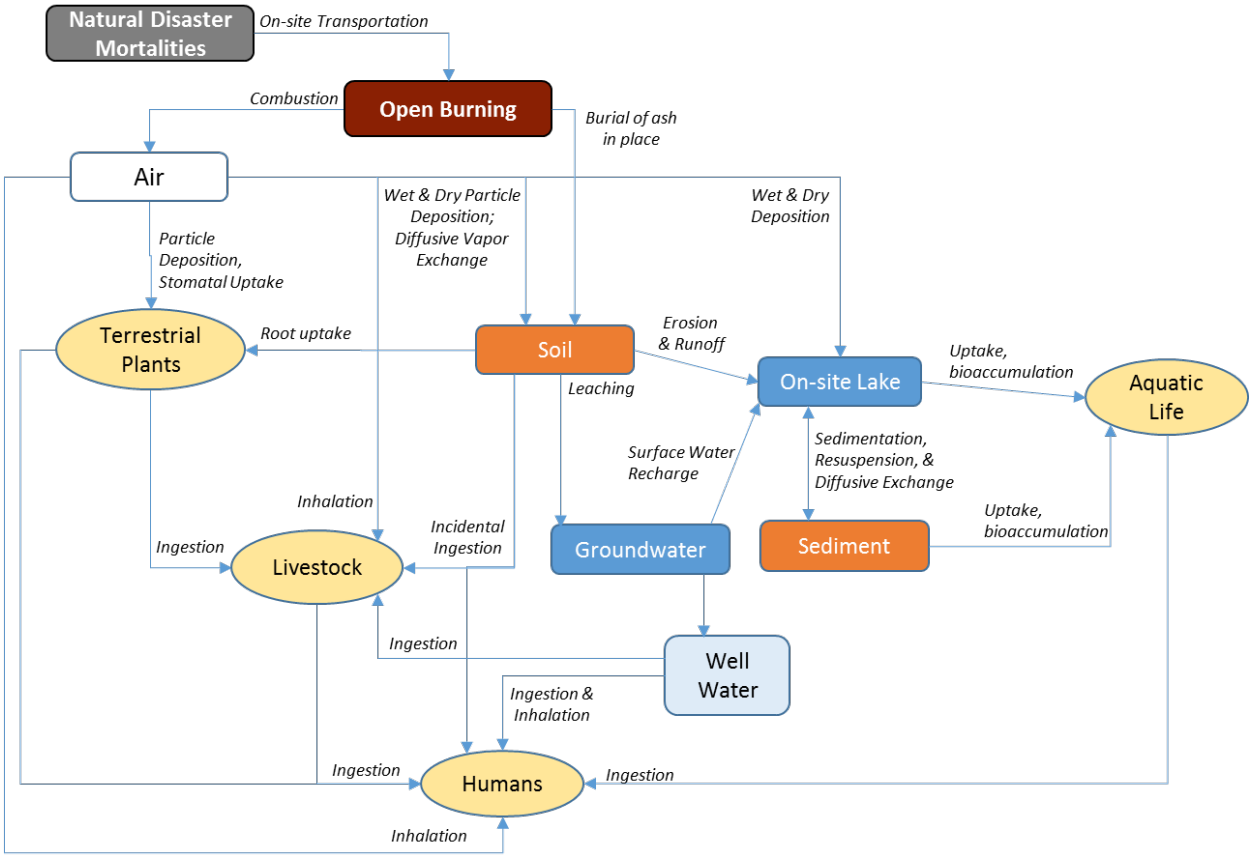


Figure 3.2.1. Conceptual model of exposure pathways from on-site open burning of livestock carcasses.

1.5.1. Releases of Combustion Products to Air

Chen et al. (2003, 2004) studied emissions of PAHs and metals from different types of incinerators, including a hog farm waste incinerator (HOWI), which burned at 255–595°C with unrefined methane gas as the auxiliary fuel, and a livestock disease control incinerator (LIWI), which burned at a higher temperature (755–891°C) fueled by diesel fuel. The temperature assumed for open-pyre burning (550°C) is most similar to the HOWI studied by Chen and colleagues.

Table 3.2.1. Source and Exposure Pathway Assumptions for On-site Open Burning Management Option

Conceptual Model Feature	Assumptions
Pyre Design and Use	▪ Based on pyre construction guidelines provided by USDA (2005), 45,359 kg (50 tons) of carcasses are burned in a single pyre that is 2.4 m (8 ft) wide by 91.4 m (300 ft) long. ▪ Fuels used in construction of the pyre include: 300 hay bales, 300 timbers (8 ft by 1 ft^2 (2.4 m by 0.30 m by 0.30 m) each, 50 lb (22.7 kg) kindling, 10,000 lb (4,536 kg) coal, and 100 gal (378.5 L) fuel oil (USDA 2005). ▪ Combustion is complete within 48 hr (USDA 2005). ▪ The combustion temperature is 550°C (1022°F). ▪ After combustion, the ash is buried in place. Cover depth is sufficient to place ash below the root zone.
Air Pathways	▪ Inhalation of particulate matter and vapor-phase gases by humans is assumed to be at point of maximum concentration. ▪ Humans also might inhale airborne microbial particles or aerosols. ▪ Downwind air concentrations of vapor-phase chemicals could be absorbed by plant leaf stomata. ▪ Downwind air deposition of particulate-phase chemicals and microbial particles to the top surfaces of leaves are unlikely to result in absorption of chemical or internalization of microbes. ▪ Reference air concentrations to protect individual humans should also be protective of mammalian livestock. Therefore, inhalation by livestock is not assessed (USEPA 2005a).
Soil Ingestion Pathways	▪ Potential ingestion pathways associated with surface soil include incidental soil ingestion by humans and livestock, erosion and runoff to the lake and uptake by aquatic animals, and plant absorption of chemicals from soils, with subsequent ingestion by humans and livestock. ▪ Chemicals deposited from air to soil near the source are primarily particulate-phase and are distributed in the top two centimeters of surface soil; leaching to deeper soils is limited and not evaluated. ▪ A fraction of chemicals deposited to surface soil will run off or erode to the on-site lake. ▪ Farming, livestock pasturing, and grazing will not be performed on the pyre site until after revegetation with grasses or cover crops that appear healthy.
Groundwater and Well Water	▪ The water table is assumed to be 1 m (~ 3 ft) below the surface. ▪ An on-site groundwater well 30.5 m (100 ft) downgradient from the pyre site is used for drinking water. Well water serves farm residents. Livestock drinking well water is assessed only if concentrations estimated for low-flow aquifers sufficient to supply one household indicate possible concern (see Section 3.1.2). ▪ Leaching to groundwater is assumed only for the ash burial; leaching following air deposition to the agricultural field is unlikely to contribute substantially to groundwater concentrations. ▪ Groundwater is not treated before use. ▪ Non-ingestion exposure to humans from well water could include inhalation of aerosolized/volatilized agents; however, exposures via that pathway would be less

Conceptual Model Feature	Assumptions
	than via direct ingestion with the possible exception of trapped methane gas or ammonia.
Surface Water, Sediment, and Aquatic Life	▪ Incidental ingestion and dermal exposure from recreational activities on or in the on-site lake are possible, although not included in the conceptual model diagram or the scope of the exposure assessment. ▪ Ingestion of recreationally caught fish occurs.
Production of Food on the Farm	▪ Residents of the farm consume farm-grown plants. ▪ Livestock also consume farm-grown plants, then humans consume livestock products (e.g., meat, milk, eggs).

Abbreviations: USDA = U.S. Department of Agriculture; ft = feet; lb = pound; gal = gallon; hr = hour; USEPA = U.S. Environmental Protection Agency.

Emission factors (EFs) for low-, medium, and high-molecular weight PAHs and for metals released from hog carcasses are shown in Tables 3.2.2 and 3.2.3, respectively. Methane combustion alone should produce minimal PAHs and no metals; hence all of the PAHs and metals reported for hog incineration with methane are assumed to have originated from the carcass combustion. Chen et al. (2003, 2004) did not analyze emissions for dioxins, mercury, or arsenic.

Table 3.2.2. Emission Factors for PAHs from HOWI Incinerator Carcass Burning (mg/kg carcass)[a]

Waste Stream	Total PAHs	LM PAHs	MM PAHs	HM PAHs
Stack Flue Gas	285.0	235. 0	34.7	15.6

Abbreviations: PAHs = polycyclic aromatic hydrocarbons; HOWI = hog farm waste incinerator; LM = low molecular weight; MM = medium molecular weight; HM = high molecular weight.
[a] Based on Chen et al. (2003), Table 5. Total PAHs are based on the sum of 21 PAH species. Low-, medium-, and high-molecular weight groups include two- and three-ringed PAHs (LW), four-ringed PAHs (MM), and five-, six-, and seven-ringed PAHs (HW), respectively.

Table 3.2.3. Emission Factors for Metals from HOWI Hog Carcass Incineration (mg/kg carcass)

Waste Stream	Fe	Cd	Cr	Cu	Mn	Ni	Pb	Zn
Stack Flue Gas (vapor-phase)[a]	11.32	0.03	0.37	0.20	0.16	0.47	0.47	0.49
Bottom Ash (particle-phase)[a]	11.7	0.31	5.46	23.1	2.34	8.07	1.33	2.32

Abbreviations: HOWI = hog farm waste incinerator.
[a] Based on Chen et al. (2004), Table 4, HOWI.

Appendix A describes how compound-specific exposure factors (EFs) were estimated for PAHs based on the data reported by Chen et al. (2003). The profile of individual PAHs released from hogs burned with methane (Chen et al. 2003) and from poultry burned with wood in an air-

curtain burner (USEPA 2013a) are similar (Appendix Table A.1), with releases of naphthalene approximating 50% of the total and 3- and 4-ringed PAHs predominating in the remaining emissions.

To estimate total emissions from open-pyre burning of livestock carcasses, emissions of materials that originated from the fuels used to burn the carcasses must be added to the emissions from carcasses alone. Table 3.2.4 lists the quantity of each type of fuel needed for open-pyre burning of large carcasses totaling 45,359 kg (50 U.S. tons) calculated from information presented by the USDA (2005).

Table 3.2.4. Fuel Mass Used for Open-Pyre Burning and Quantity of Ash Remaining

Waste Stream	Assumptions	Material Mass (kg)	Ash Percent (%)	Ash Mass (kg)
Carcasses	100 carcasses; 1,000 lb (453.6 kg) each	45,359	6	2,722
Heavy Timbers	3 timbers per carcass (8 ft^3 or 0.23 m^3 each)[a] 500 kg/m^3 per railroad tie[b]	34,000	1	340
Kindling	50 lb (22.7 kg) per carcass[a]	2,300	1	23
Straw Bales	3 bales per carcass[a] 20 kg per bale[b]	6,000	1	60
Coal	100 lb (45.4 kg) per carcass[a]	4,536	2	91
Gasoline	1 gal (3.79 L) per carcass[a]	—	0	0
Total				3,236

Abbreviations: lb = pound; ft = feet; ft^3 = cubic foot; gal = gallon.
[a] USDA (2005)
[b] Watkiss and Smith (2001).

In addition to air emission of PAHs, metals, and other chemicals per kg of carcass burned, there are emissions per kg from timbers, kindling, straw, coal, and diesel added to estimate total emissions from open-pyre burning. Watkiss and Smith (2001) reviewed EFs published for domestic combustion sources including coal, wood, and straw, and data from crematoria to estimate likely emissions from the open-pyre burning of livestock during the 2001 outbreak of foot-and-mouth disease (FMD) in the United Kingdom. Toward the end of the outbreak, Watkiss and Smith (2001) compared the chemical-specific EFs from the literature with measurements made at actual pyres and with dispersion modelling. They used their dispersion modelling to match measured values, where available. Table 3.2.5 lists the final EFs, per kg material burned, estimated by Watkiss and Smith (2001). They were unable to estimate dioxin production by type of material burned, but they estimated total dioxin release from all materials in a pyre in

collaboration with outside experts (Coleman and Foan, NAEI & EA, personal communication 2001 to Watkiss and Smith, 2001).

Table 3.2.5. Emission Factors to Air for Open-Pyre Burning by Material Burned (weight chemical/weight material burned)[a]

Fuel	Benzo(a) pyrene (mg/kg)	Dioxins (µg/kg)	PM_{10} (g/kg)	NOx (g/kg)	SO_2 (g/kg)	CO (g/kg)	HCl (g/kg)
Coal	1.5	na	49.57	1.42	20	45.0	2.35
Wood (sleepers)[b]	1.3	na	7.9	0.72	0.037	99.3	1.175
Wood (kindling)	1.3	na	7.9	0.72	0.037	99.3	1.175
Straw	7.2	na	5.0	2.32	0.037	71.3	na
Diesel oil	na	na	0.25	2.16	2.8	0.24	0.01
Carcasses	7.2	na	10	4.63	1.4	142.6	0.7
Combined material	ne	1.0	ne	ne	ne	ne	ne

Abbreviations: PM_{10} = particulate matter 10 micrometers diameter or smaller; na = not available; ne = not estimated.
[a] Based on Watkiss and Smith (2001) Table 3. Units vary by chemical.
[b] In the U.S., "sleepers," as they are called by Watkiss and Smith (2001), are usually referred to as "railroad ties."

Appendix A presents PAH congener-specific EFs to air for the quantities of each estimated to be released from carcasses, wood (and kindling), coal, and straw in Table 3.2.4. Emissions for each congener were estimated from emissions of benzo[a]pyrene reported by Watkiss and Smith (2001) assuming that the PAH emissions profile measured for each type of material burned could be indexed to benzo[a]pyrene emission rates. Table A.3 in Appendix A documents the derivation of congener-specific PAH EFs from carcasses only for open-pyre burning. Table A.5 documents the derivation of congener-specific PAH emissions from wood/kindling added to the pyre, while Table A.8 presents EFs for PAHs from the coal added to the pyre. Tables A.10 and A.11 document derivation of EFs for PAHs from the hay bales or straw added to an open pyre.

Appendix B presents estimates of dioxin emissions from open-pyre burning of 45,359 kg (50 tons) of carcasses using the quantities of fuels specified in Table 3.2.4. Although no data were found to quantify dioxins produced from the combustion of animal carcasses alone (e.g., via methane combustion), data were available linking dioxin releases to combustion of wood/kindling and for crematoria in which a variety of unspecified materials also are combusted with bodies. Table B.1 in Appendix B documents the derivation of congener-specific EFs from the wood added to an open pyre. For the coal added to an open pyre, dioxin emissions are not expected, based on data from coal-fired power plants. Czuczwa and Hites (1984) reported that

fly ash from coal-fired power plants produce some CDDs, but that no TCDDs or pentachorodibenzo-p-dioxin (PeCDDs) have been detected (ATSDR 1998). Moreover, CDDs were present in much lower concentrations in fly ash from coal-fired plants than from fly ash from municipal ash (ATSDR 1998). For the assessment, dioxin emissions from coal are set to zero. For dioxin emissions from straw added to the pyre, dioxin emissions were reported in 2,3,7,8-TCDD toxicity equivalency factors (TEFs) (Appendix B, Section B.1.4).

Appendix D summarizes the air emission factors used for open-pyre burning by type of material combusted. All emission factors originally in units of the quantity of chemical released to air per quantity of material burned were converted to emission factors in units of quantity of chemical released per unit time for air modeling.

1.5.2. Leaching from Remaining Open-Burning Ash

Following combustion of the pyre, the remaining ash on the ground might be removed to a landfill. For this assessment, however, the ash is assumed to be buried or covered in place with a layer of clean soil of sufficient depth to isolate the ash from plant roots. The area over which the ash is distributed is the area of the pyre, which is 91.4 m long by 2.4 m wide (300 ft long by 8 ft wide), or 223 m^2 (= 0.056 ac or 400 ft^2). Because the soil cover is permeable to rainwater, contaminants in the ash have the potential to leach into subsurface soil and groundwater each time it rains.

The amount of ash remaining from open burning was estimated from the quantities of carcasses (i.e., 45,359 kg or 50 U.S. tons) and fuels placed in the pyre. The weight of ash remaining after burning the carcass was assumed to be 6% of the uncombusted weight of carcasses (NRC 2000). This assumption is the approximate midpoint of a distribution of body-ash content estimated by the National Research Council (NRC 2000) for cattle with various body condition scores (based on visual assessments of animal fatness).

Quantities of fuel materials for open burning, shown in Table 3.2.4, are based on USDA (2005) recommendations for constructing a large animal carcass pyre. The ash remaining from woody and other plant-based fuels, including timbers, kindling, and straw, is assumed to weigh 1% of the original weight (Pitman 2006). Coal ash is assumed to weigh 2% of the uncombusted weight (OSU 1999). Diesel, which is used as an accelerant, is not included in the ash contaminant data

because no ash remains from its combustion. The total ash quantity estimates by fuel type are shown in Table 3.2.4 (above).

There were no available studies reporting contaminant concentrations in bottom ash (i.e., ash remaining on the ground) from open burning of livestock carcasses. Consequently, the assessment estimates chemicals in bottom ash by combining concentrations known to be in carcasses and from each of the different fuel types (Table 3.2.6).

Table 3.2.6. Estimated Concentration of Chemicals Remaining in Bottom Ash from Open Burning

Chemical	Concentration in Ash from Carcasses (µg/kg)	Concentration in Ash from Wood Fuels (µg/kg)	Concentration in Ash from Coal Fuel (µg/kg)	Total Concentration in Pyre Ash (µg/kg)
Arsenic	na	3.0E+03	1.4E+02	3.9E+02
Cadmium	3.1E+02	1.2E+03	na	4.1E+02
Chromium	5.5E+03	1.9E+05	5.2E+04	3.0E+04
Copper	2.3E+04	1.5E+05	4.8E+04	4.0E+04
Iron	1.2E+04	1.2E+07	4.9E+07	2.9E+06
Lead	1.3E+03	7.7E+03	1.7E+04	2.6E+03
Manganese	2.3E+03	1.2E+07	2.8E+05	1.6E+06
Nickel	8.1E+03	2.7E+04	4.2E+04	1.2E+04
Mercury	na	3.2E+00	na	4.2E-01
Zinc	3.2E+03	4.9E+05	5.7E+04	6.8E+04
Total PAHs	7.3E+02	1.7E+04	4.3E+03	2.9E+03
Total Dioxin/furan	na	7.8E-02	na	1.2E-02

Abbreviations: na = not analyzed (in original citation); PAH = polycyclic aromatic hydrocarbon.

Concentrations in ash from the carcasses alone were estimated using data reported by Chen et al. (2003, 2004) for bottom ash from the HOWI livestock incinerator fueled by unrefined methane (from which no ash residues are expected). As described above, the combustion characteristics for the HOWI livestock incinerator are not necessarily representative of those for open-burning. However, its relatively low burn temperature is comparable to ignition and combustion temperatures of wood and coal reported by Bartok (2003).

Total PAHs were present in bottom ash at a concentration of 737 ng/g (Chen et al. 2003). The concentrations of the individual PAHs evaluated for bottom ash were estimated from the histograms presented by Chen et al. (2003) for the HOWI incinerator (top panel of Figure 4,

Incinerator A). Leaching from ash was modeled separately for individual PAHs based on those data.

For metals in livestock carcass ash, the concentration of each metal in the buried ash are based on EFs (in units of mg[metal]/kg[carcasses]) reported by Chen et al. (2004, Table 4) for bottom ash in the HOWI incinerator (Incinerator A). Data were not available to estimate concentrations of dioxins/furans in ash from burning of livestock carcasses.

Concentrations of all types of PAHs in the ashes of woody fuels from open burning were estimated with data from Bundt et al. (2001); however, they did not identify concentrations of individual PAHs in wood ash. Bundt et al. (2001) reported a total concentration for 20 PAHs of 16.8 mg/kg in ash collected from two medium-sized wood-chip furnaces operated at temperatures between 550°C and 650°C. Because different PAHs exhibit different mobilities in soils, that total concentration is apportioned to individual PAHs based on the PAH distribution profile in bottom ash from the HOWI incinerated carcasses reported by Chen et al. (2003, Figure 4a).

The concentrations of metals in the ash residues of woody fuels used in open burning are based on an analysis of bottom ash from wood burned at temperatures between 600°C and 1,000°C (Narodoslawsky and Obennberger 1996). Concentrations of dioxins/furans in the ash of woody fuels are from Wunderli et al. (2000, Figure 1), who reported concentrations of 17 individual dioxin/furan congeners in bottom ash from wood combustion. Table 3.2.6 lists the estimated total concentrations of total PAHs, individual metals, and total dioxin/furans in ash from the open-burning option.

Chemicals in coal ash include PAHs and metals. Concentrations of metals and PAHs in coal ashes are estimated using data from Tiwari et al. (2014) and Ruwei et al. (2013), respectively. Concentrations of individual metals and total PAHs are shown in Table 3.2.6. Data were not available to estimate concentrations of dioxins/furans in coal ash. Czuczwa and Hites (1984) reported that TCDDs and PeCDDs (the homologue groups containing the most toxic congeners) were not detected in ash from coal-fired power plants.

The total concentrations of chemicals in the bottom ash remaining from open burning (last column in Table 3.2.6) are calculated from the mass-weighted contributions of each source of

ash (i.e., carcasses and fuel types). For each source of ash, the concentration presented in Table 3.2.6 was multiplied by the ash weight (see Table 3.2.4) to determine the mass of chemical from the source in the total ash. For these calculations, "wood fuels" represent the total of ash from timbers, kindling, and straw bales. The mass from the other three sources was then added for each chemical, and the total was divided by the total weight of the ash to calculate the total concentration of the chemical in the ash.

3.3. On-site Air-curtain Burning

The conceptual model for on-site air-curtain burning is presented in Figure 3.3.1. Note that the compartments in this conceptual model are identical to those in the on-site open burning conceptual model (Figure 3.2.1). The two management options differ with respect to air emissions profiles and residual ash composition. With air-curtain burning, carcasses are burned in a partially enclosed (partially open on top) refractory fire box. A forced air flow, driven by a diesel-powered blower, creates an air "lid" over the burn area that recirculates much of the smoke and soot within the fire box and provides additional mixing of air within the burning mass. Hazardous chemicals can be released to the environment when combustion products escape to air and when the ash is buried on-site under a layer of clean fill. Further assumptions for the air-curtain burning management option are stated in Table 3.3.1.

The characteristics of air emissions and ash remaining after air-curtain burning depend on several factors, including combustion temperature, effectiveness of the "air curtain" in retaining ash particles, carcass type, and the nature and amounts of fuels used. Although Engstrom (2015) reported coal-fired air-curtain burning during the 2015 outbreak of highly pathogenic avian influenza (HPAI) in the United States, published sources (e.g., NABCC 2004; SKM 2005) generally describe air-curtain burning as being fueled primarily with scrap wood, with smaller amounts of diesel, or other liquid fuels used as accelerants to initiate combustion.

The National Agricultural Biosecurity Center Consortium (NABCC) (2004) reported that the wood-to-carcass ratios for air-curtain burning vary between 1:1 and 2:1. As reported by SKM (2005) the average wood-to-carcass ratio for four in-ground carcass air-curtain burning trials in in New Zealand was 2.29. Ratios for the individual trials ranged from 1.84 to 3.01. At the expert workshop discussed in Section 2.5, attendees familiar with air-curtain burning equipment used during previous HPAI outbreaks observed that a wood-to-carcass ratio as high as 4:1 could be

needed. For the 2002 HPAI outbreak in Virginia, Peer et al. (2006) reported that approximately 4.4 U.S. tons of wood were needed per U.S. ton of poultry carcasses burned. Reasons for needing more wood than "expected" include heavy rains on the initially stockpiled wood and use of low-quality wood (e.g., rotted, saturated, or scrap wood including pieces of metal) by contractors after the initial wood stockpile was burned. As a conservative approach, the 4:1 wood to carcass ratio is assumed for the air-curtain burning option.

The rate at which carcasses and fuels burn depends on the nature of those materials and the design and operation of the burner. Ford (2003), as cited in NABCC (2004), communicated a rate of 6 tons (5,443 kg) per hour, presumably for carcasses and fuel combined. Earlier, Ford (1994) reported 91,060 lb (41,300 kg) of hog carcasses burned during three 7-hr periods in an air-curtain burner, which equals approximately 2.2 U.S. tons (2,000 kg) of carcasses per hour. The quantity of wood burned over the same time period (21 hr) equaled 33 cords (120 m^3). Assuming a wood density of approximately 500 kg/m^3 (e.g., for pinewood), the weight of 33 cords would be approximately 60,000 kg, for a wood-to-carcass ratio of approximately 1.5:1 and a total throughput of 5.5 tons (5,000 kg) of carcasses plus wood per hour. Another source, McClaskey (2014, p 180), reported combustion of animal carcasses at a rate of 2 tons (1,814 kg) per hour (the quantity of wood required was not specified). Investigators who conducted an air-curtain burning trial in New Zealand reported a lower rate of carcass and fuel burning (SKM 2005). They reported average throughputs of 0.65 tonnes (650 kg) of carcasses per hour and 1.8 tonnes (1,800 kg) wood per hour for a total of 2.45 tonnes (2,450 kg) or 2.7 U.S. tons of fuel plus carcasses. Specifications available for a commercially available air-curtain burner similar to the design assumed for this analysis indicate higher possible throughputs (e.g., 6–10 U.S. tons [5,443–9,072 kg] per hour; Air Burners, Inc. 2012); however, specifications note that the actual burn rate will depend on many factors, including materials burned. Air-curtain burners are often used to dispose of woody debris only, which is likely to burn faster than carcasses.

Participants in the expert workshop discussed in Section 2.5 recommended a burn duration of 48 hr for the exposure assessment scenario. With 50 U.S. tons (45.4 tonnes) of carcasses and 200 U.S. tons (181 tonnes) of wood fuel (i.e., four times the weight of the carcasses), the throughput over 48-hr burn would equal 5.2 U.S. tons (4,720 kg or 4.7 tonnes) per hour (i.e., 50 U.S. tons of carcasses + 200 U.S. tons of fuel) / 48 hr = 5.2 U.S. tons/hr.)

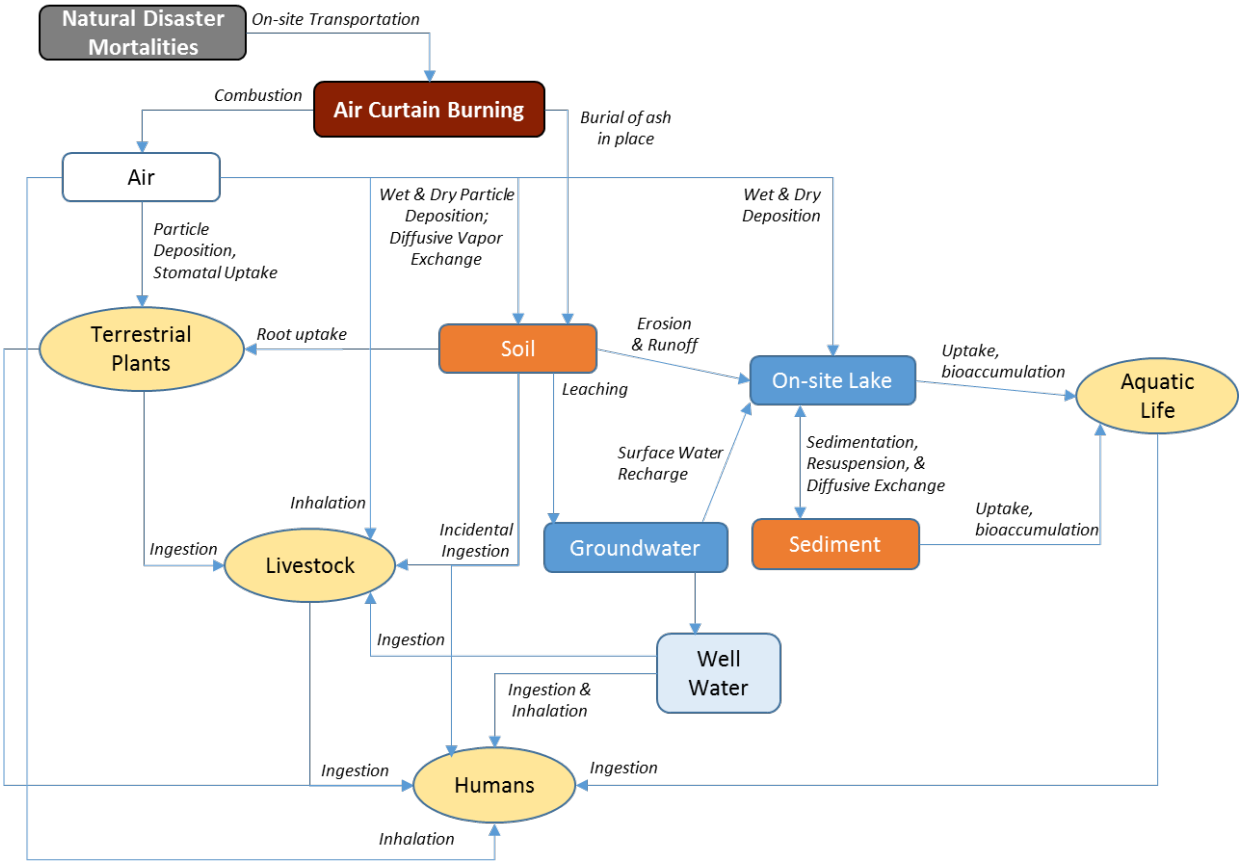


Figure 3.3.1. Conceptual model for exposure pathways from on-site air-curtain burning of livestock carcasses.

Table 3.3.1. Assumptions for On-site Air-curtain Burning of Livestock Carcasses

Conceptual Model Feature	Assumptions
Burner Design and Use	▪ Carcasses are burned in an above-ground refractory box with a forced-air "curtain" on top. The fire box measures 8.3 m long, by 2.6 m wide, and 2.5 m height, and the overall dimensions of the air-curtain burner unit are 11.4 m long, by 3.6 m long, and 2.9 m high.[6] ▪ Combustion fuels include scrap wood, previously stockpiled logs, and diesel fuel. Wood fuel is supplied at a 4:1 ratio by weight to carcasses (see text). ▪ The combustion temperature in the carcass mass is 850°C (1,600°F). ▪ The air-curtain burner is operated continuously for 48 hr to burn 226,796 kg (250 U.S. tons) of carcasses and associated fuels. (For safe continuous operation, three worker shifts work 8 hr each.) ▪ Combustion ash is placed in an excavated 21.6 m^2 pit with a length and width equal to the dimensions of the fire box (8.3 m long by 2.6 m wide). ▪ The burial trench for the ash is unlined and covered with clean fill.
Air Pathways	▪ Human inhalation of particulate matter and vapor-phase gases is assumed to occur only near the air-curtain burner, and be at the maximum concentration emitted from the unit. ▪ Reference air concentrations to protect individual humans should also be protective of mammalian livestock. Therefore, inhalation by nearby livestock over a two-day exposure is not assessed (USEPA 2005a). ▪ Downwind air concentrations of gas-phase chemicals could be absorbed by plant leaves. The short combustion duration (48 hr) relative to the time required by crop plants to mature to harvest suggests that foliar absorption from the air and incorporation into plant tissues would be negligible.
Soil Pathways	▪ Incidental soil ingestion by humans and livestock is considered for agents deposited from air to soil. Deposition from air occurs over a short period of approximately two days. ▪ Farming, livestock pasturing, and grazing do not occur on the ash disposal site. If the cover fill is disturbed by these activities, plants might suffer root burn, while animals might be exposed to specific metals from negligible to toxic concentrations. This is not further considered in the assessment because of the high levels of uncertainty associated with this type of exposure. ▪ Buried ash does not contribute to surface soil concentrations.
Groundwater and Well Water	▪ Leaching to groundwater is assumed only for the ash burial trench; leaching following air deposition to the agricultural field is assumed to not contribute significantly to groundwater concentrations. ▪ The water table will be assumed to be 1 m below the bottom of the ash pit. ▪ An on-site groundwater well is used for drinking water. Well water serves farm residents. Livestock drinking well water is assessed only if concentrations estimated for low-flow aquifers sufficient to supply one household indicate possible concern (see Section 3.1.2). ▪ Groundwater is not treated or filtered before use.
Surface Water, Sediment, and Aquatic Life	▪ Incidental ingestion from recreational surface water use is not included in the conceptual model. ▪ Ingestion of aquatic life includes recreationally caught fish.
Production of Food on the Farm	▪ The production of food on the farm includes terrestrial plants consumed by humans and livestock, with possible transfers to dairy products and eggs.

[6] Assumptions about the refractory box design are based on the specifications of Air Burners Inc., Model S-372, available at: http://www.airburners.com/DATA-FILES_Print/ab-s327_Specs_PRNT.pdf.

Abbreviations: hr = hour.

Section 3.3.1 discusses chemicals released to air from air-curtain burning, and Section 3.3.2 discusses possible releases from buried ash to groundwater from percolation of rainwater through the ash layer.

1.5.1. Releases of Combustion Products to Air

The same inorganic and organic chemicals are released to air from air-curtain burning as from open-pyre burning, but at different rates because of the different fuels used, improved effectiveness of combustion, and different burn temperatures. Emission factors for PAHs and metals from air-curtain burning were derived from stack flue measurements published by Chen et al. (2003, 2004) for a livestock disease control incinerator (identified as LIWI by the authors). The burn temperatures (i.e., 755–891°C) reported by Chen et al. (2003, 2004) for the LIWI incinerator are comparable to temperatures typically achieved during air-curtain burning of livestock carcasses. Ford (2003) and McPherson Systems, Inc. (2003), both cited by NABCC (2004), reported air-curtain burning temperatures as high as 1,600°F (~871°C). The United Kingdom Department for Environment, Food, and Rural Affairs (DEFRA 2002, cited in NABCC 2004) reported burn temperatures in the range of 600–1,000°C. Those temperatures are comparable to the temperatures reported by Chen et al. (2003, 2004) for the LIWI incinerator. However, other investigators have reported substantially higher air-curtain burning temperatures. Ford (1994) reported 1,800–2,800°F (980–1,540°C) for an evaluation of air-curtain burning of hog carcasses (high fat content), and the technology overview currently provided by McPherson Systems, Inc. (2015) reports burning temperatures from 1,800–2,500°F (980–1,370°C) In New Zealand, temperatures measured above the flames in a trench with an air-curtain burner along the long side ranged from 270 to 855°C in the same trench measured at roughly the same time, depending on the sampling location in the trench (SKM 2005). Higher temperatures were reached, but could not be measured because radiant heat prevented the workmen from approaching sufficiently close to suspend the thermistor over the trench. As listed in Table 3.3.1, this assessment assumes 850°C in the mass of carcasses for air-curtain burning. This means the LIWI incinerator data for PAH and metal emissions from Chen et al. (2003, 2004) are considered representative for releases from carcasses for that burn temperature.

Table 3.3.2 lists the air EFs reported by Chen et al. (2003) for PAHs from the LIWI in three molecular weight categories. Appendix A presents congener-specific EFs for PAHs released to air. Table A.4 in Appendix A documents the derivation of congener-specific PAH EFs from carcasses in the air-curtain burner, while Table A.7 documents the derivation of congener-specific PAH emissions from wood added to the air-curtain burner.

Table 3.3.2. Emission Factors for PAHs from LIWI Incinerator Carcass Burning (mg/kg waste)[a]

Waste Stream	Total PAHs	LM PAHs	MM PAHs	HM PAHs
Stack Flue Gas	2.867	2.435	0.234	0.198

Abbreviations: PAHs = polycyclic aromatic hydrocarbons; LIWI = livestock disease control incinerator; LM = low molecular weight; MM = medium molecular weight; HM = high molecular weight.
[a] Based on Chen et al. (2003), Table 5, LIWI. Total PAHs are based on the sum of 21 PAH species. Low, medium, and high molecular weight groups include species containing two- and three-ringed PAHs (LW), four-ringed PAHs (MM), and five-, six-, and seven-ringed PAHs.

The derivation of EFs for dioxins from air-curtain burning using woody fuels is described in Appendix B, Section B.1.2. Chen et al. (2003, 2004) did not sample for dioxins. For dioxins released from burning 200 tons of wood, data from industrial wood-burning facilities (i.e., USEPA 2012) represent the higher burn temperatures for air-curtain burning than for open-pyre burning (Table B.2).

Emission factors for metals released from air-curtain burning are based on the sum of metals released into the air from carcass burning (Table 3.3.3) and metals released from the wood added to the air-curtain burner. Though coal can be used to supplement or replace wood fuel to burn carcasses in an air curtain burner, it seems not to be a common practice. Review of the carcass management literature found no reports of coal addition to air-curtain burners used in carcass incineration. There are several sources that discuss wood alone as a fuel source.

Table 3.3.3. Emission Factors for Metals from LIWI Animal Carcass Incineration (mg/kg waste)

Waste Stream [a]	Fe	Cd	Cr	Cu	Mn	Ni	Pb	Zn
Stack Flue Gas (vapor-phase)	1.10	0.01	0.07	0.02	0.02	0.06	0.18	0.19
Bottom Ash (particle-phase)	412	0.03	3.74	11.9	8.61	7.22	35.7	89.2

[a] Based on Chen et al. (2004), Table 4, LIWI.

Appendix D summarizes the air emission factors used for air-curtain burning by type of material combusted (i.e., carcasses and wood). All emission factors originally in units of the quantity of

chemical released to air per quantity of material burned were converted to emission factors in units of quantity of chemical released per unit time (i.e., g/s) for air modeling assuming 226,796 kg (250 U.S. tons) of carcasses and wood fuel over 48 hr.

1.5.2. Leaching from Combustion Ash

Table 3.3.4 provides the assumptions used to estimate the amount of ash remaining from the air-curtain burning option. The quantity of ash from burning carcasses (i.e., 2,722 kg or 6% of the original carcass mass) is the same estimate used for the open burning option, which was described in Section 3.3.4. Although less ash is expected from air-curtain burning of the carcasses than from open burning because of the higher combustion temperature, there were no data identified that would allow preparation of separate estimates for the ash generated from carcasses under the two combustion options.

Table 3.3.4. Quantity of Ash from Air-curtain Burning

Material	Assumptions	Fuel Mass (kg)	Ash Percent (%)	Ash Mass (kg)
Carcasses	100 carcasses, 1,000 lb (453.6 kg) each	45,359	6	2,722
Wood	4,000 lb per carcass [a, b]	181,437	0.3	498
Total				3,220

Abbreviations: lb = pound.
[a] NABCC (2004).
[b] The assumed amount of wood represents a 4:1 fuel-to-carcass ratio, see text.

For wood fuels, however, a higher combustion efficiency is assumed for air-curtain burning (0.3% remaining ash) than for open burning (1%). This assumption for air-curtain burning is based on Narodoslawsky and Obennberger (1996), who reported a wood dry weight of 88% (i.e., 12% moisture), a percent ash (dry weight basis) of 0.4%, and 78% bottom ash (as opposed to fly ash). Multiplying those percentages results in the final bottom ash estimate of 0.3% of the original weight of the fresh wood, or 498 kg of wood ash remaining (Table 3.3.4).

Table 3.3.5 presents the estimated concentrations of chemicals remaining in bottom ash from the air-curtain burning option. The estimated concentrations of metals and PAHs from carcass combustion are based on bottom ash data reported by Chen et al. (2003, 2004) for the LIWI incinerator, which as described above, achieved combustion temperatures comparable to air-curtain burning.

Concentrations of metals, PAHs, and dioxins/furans in the bottom ash remaining from the wood fuels used in air-curtain burning are based on the same data sources used for the woody fuels of open burning (see Section 3.1). The available data could not differentiate the concentrations of metals and dioxin/furans in the wood ash from the two options. Therefore, the assessment uses the same concentrations for those chemicals in wood ash as in Tables 3.2.6 and 3.3.5.

Table 3.3.5. Estimated Concentration of Chemicals in Ash from Air-curtain Burning

Chemical	Concentration in Ash from Carcasses (µg/kg)	Concentration in Ash from Wood Fuels (µg/kg)	Total Concentration in Air curtain Burning Ash (µg/kg)
Arsenic	na	3.0E+03	4.6E+02
Cadmium	3.0E+01	1.2E+03	2.1E+02
Chromium	3.7E+03	1.9E+05	3.2E+04
Copper	1.2E+04	1.5E+05	3.3E+04
Iron	4.1E+05	1.2E+07	2.2E+06
Lead	3.6E+04	7.7E+03	3.1E+04
Manganese	8.6E+03	1.2E+07	1.9E+06
Nickel	7.2E+03	2.7E+04	1.0E+04
Mercury	na	3.2E+00	5.0E-01
Zinc	8.9E+04	4.9E+05	1.5E+05
Total PAHs	4.7E+02	1.1E+04	2.1+03
Total Dioxin/furan	na	7.8E-02	1.2E-02

Abbreviations: na = not analyzed (in original citation); PAHs = polycyclic aromatic hydrocarbons.

The PAH concentrations in wood ash from air-curtain burning were estimated separately from PAH concentrations in wood ash remaining after an open pyre. Bundt et al. (2001) reported a total PAH concentration of 16.8 µg/kg in wood ash produced by medium-sized wood-chip furnaces burning at 550–650°C, which are temperatures consistent with the assumed open burning temperature (i.e., 550°C) scenario, and less than the temperature assumed for air-curtain burning (i.e., 850°C). While the total PAH concentration of 16.8 µg/kg could be used as the total PAH concentration in wood ash from pyre burning, it does not necessarily appear appropriate for air-curtain burning.

PAH concentrations were not identified for wood burning at temperatures consistent with the air-curtain burning option, but they are expected to be lower than in bottom ash from an open pyre due to the higher air-curtain burn temperatures. PAH concentrations for wood burning were estimated using data available from Chen et al. (2003) on PAHs in ash from high- and low-

temperature carcass burning. Specifically, Chen et al. (2003) reported total PAH concentrations in bottom ash from carcass burning with the HOWI (low temperature, comparable to open burning) and LIWI (higher temperature, comparable to air-curtain burning) incinerators. The ratio of total PAHs in as from the LIWI to HOWI incinerators is 0.65:1 (i.e., 474 µg/kg:732 µg/kg). That ratio, applied to the total wood ash PAH concentration of 16.8 µg/kg reported by Bundt et al. (2001), suggests the total PAH concentration in bottom ash from wood burning in an air-curtain burner could be 10.9 µg/kg. The relative abundance of individual PAH compounds reported by Chen et al. (2003, Figure 4b in original report) for the LIWI incinerator was used to apportion the total estimated PAH concentration to the individual compounds.

The last column in Table 3.3.5 shows the total concentrations of chemicals in the ash remaining from air-curtain burning. The concentrations of each chemical in carcass ash and in wood ash is based on the relative weight of ash from those materials, which are shown in Table 3.3.4. In other words, the concentration of each chemical in wood ash was multiplied by 4 (weighted by a factor of 4) to reflect the 4:1 ratio of wood:carcasses to estimate the concentration in total ash.

3.4. On-site Burial

Figure 3.4.1 provides an overview of the conceptual model for the on-site livestock carcass burial option. In this option, livestock carcasses are placed in an unlined, excavated pit or trench in a suitable location on site.[7] The carcasses are covered with clean fill creating a mound over the site that will flatten over time as the carcasses lose fluids and other mass during decomposition. Although access to the site is not restricted, it will not be used in the relatively near future for crop farming or raising livestock; it will be seeded over for soil stabilization.

As the carcasses decompose rapidly at first (over months) with the remainder decomposing more slowly (over years), vapor-phase chemicals can diffuse upward though the soil cover to aboveground air. Soluble chemicals can leach with carcass fluids and with rainwater permeating through subsurface soils to groundwater. In addition, colloids and small particulates (e.g., on order of microns) with sorbed chemicals and microbes can percolate through any larger interstitial spaces or pores (e.g., along plant roots) through subsurface soils. Where they contact

[7] Mass livestock burial trenches might be created off-site following some natural disasters. It is assumed that in those cases, state and federal representatives would participate in selection of location(s) with appropriate conditions (e.g., high over groundwater, far from any groundwater wells).

the solid-phase pore walls, adsorption (and to a lesser extent desorption) is likely to occur (Ginn et al. 2002; Kim and Kim 2012; Li et al. 1996). Some fraction of the particles might reach groundwater, with the remainder effectively fixed to stationary soil particles (i.e., filtered out). Equilibrium desorption might continue for years, but would yield negligible concentrations in groundwater. Many of the microbes described in Section 2.4.2 are considered facultative anaerobes and can survive in environments with or without the presence of oxygen. However, *Coxiella burnetii* is considered to be aerobic and can only survive in the presence of oxygen; it would be inactivated if it reached the saturated zone.

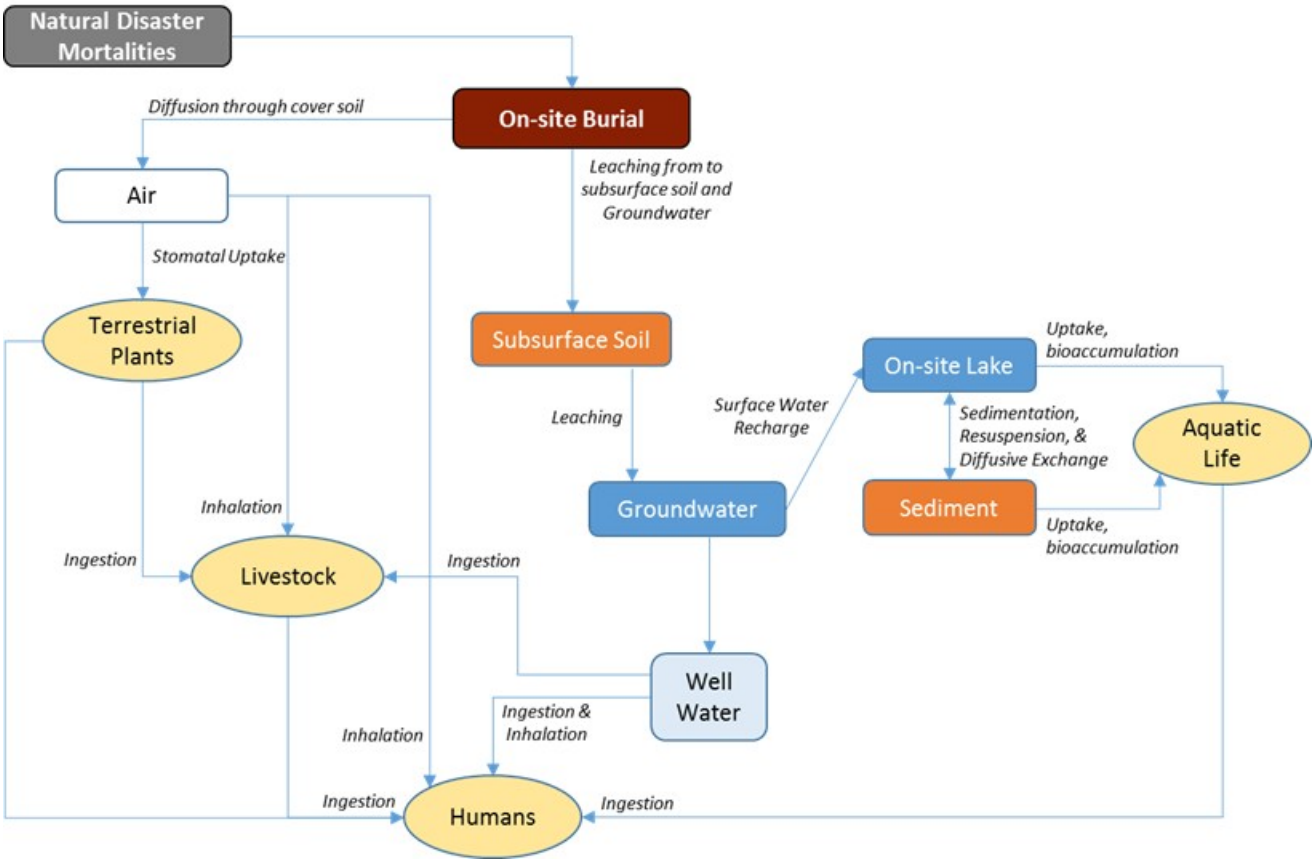


Figure 3.4.1. Conceptual model for exposure pathways from on-site burial of livestock carcasses.

Gases formed during decomposition initially cause carcasses to bloat. If the carcass abdominal cavities are not opened before burial, if the top of the burial trench is not adequately covered with dirt, or if there is insufficient venting of the carcass pit to air, bloated carcasses or fluids might emerge from the surface (USDA 2005). This assessment, however, assumes the carcasses are properly prepared, placed, and covered within the pit so there is slow release of vapor-phase

gases to air over the months required for biodegradation. When gases reach the surface, they are readily diluted in ambient air. For this reason, the inhalation pathways pictured in Figure 3.4.1 do not affect the assessment Leaching of chemicals and microbes toward groundwater is the focus of the exposure pathway assessment for burial as discussed in Section 3.4.1. Table 3.4.1 identifies further assumptions for the on-site burial conceptual model and exposure scenario.

Table 3.4.1. Assumptions for the On-site Burial of Livestock Carcasses

Conceptual Model Feature	Assumptions
Burial Trench Design and Use	▪ 45,359 kg (50 U.S. tons) of livestock carcasses are placed in a single trench that is 9 ft deep, 7 ft wide, and 300 ft long (2.7 by 2.1 by 91.4 m) based on guidelines provided by USDA (2005). ▪ The carcasses are covered with 6 ft (1.8 m) of soil, including 3 ft (0.9 m) mounded over the site starting at ground level (USDA 2005). ▪ An unsaturated zone of 1 m (3.3 ft) extends below the bottom of the burial trench.
Air Pathways	▪ Gases generated by carcass decomposition can slowly seep upward through cover soil to air. ▪ Microbes and non-volatile chemicals are not released to air.
Soil Pathways	▪ Volatile gases emitted to air from on-site burial will remain in air and not be deposited to the surface soil (i.e., sporadic wet deposition would be effectively cancelled by vaporization). ▪ Soil erosion and runoff from the burial site to surface water are not included in the conceptual model, because there is soil capping the burial site. ▪ Methane from the anaerobic phase of carcass decomposition can permeate through subsurface soils. While accumulation of methane in a closed building could pose an explosion risk, this assessment assumes there will be no accumulation of methane after release.
Groundwater and Well Water	▪ Chemicals and pathogens can leach to groundwater from carcasses and subsurface soil beneath the burial trench. ▪ The water table remains at least 1 m below the burial trench throughout the year. ▪ An on-site groundwater well is used for drinking water, other household water uses (e.g., showering) (see Table 3.2.1). ▪ Groundwater is not treated before use. ▪ Humans can inhale aerosolized/volatilized agents from well water during showering and other home water uses.
Surface Water, Sediment, and Aquatic Life	▪ Chemicals and microbes from buried carcasses can reach the on-site lake only via groundwater (assuming appropriate hydrology). ▪ Humans on the farm ingest fish caught from the on-site lake.
Production of Food on the Farm	▪ Potential exposures via food produced on the farm are not assessed for this option (see Table 3.4.2).

Abbreviations: ft = feet; USDA = U.S. Department of Agriculture.

Not shown in Figure 3.4.1, is methane gas produced by anaerobic decomposition of the livestock carcasses that might travel horizontally through soils in the unsaturated zone soils, potentially posing an explosive threat if it accumulates inside a closed structure. The process would be

similar to landfill gas intrusion, which has occurred when methane produced within a landfill migrates horizontally through the ground, seeps into a building foundation, and accumulates in the enclosed airspace to an explosive concentration (USEPA 2005a). Leaching from buried carcasses to groundwater is discussed in Section 3.4.1, and seepage of methane gas from a burial trench is discussed in Section 3.4.2.

1.5.1. Leaching from Buried Carcasses

Table 3.4.2 summarizes the basis of assumptions for estimating releases from carcass burial. Unlike combustion of carcasses, which is completed over a few days, decomposition of buried carcasses and leaching of materials from carcasses occurs over much longer time frames. Young et al. (2001) estimated likely annual chemical releases from buried carcasses over a 60-year period (Table 3.4.3). They estimated that 60% of a buried mammalian corpse is readily degraded (half-life of 1 year), 15% degrades at a moderate rate (half-life of 5 years), 20% degrades slowly (half-life 10 years), while 5% is inert (the amount left over after high-temperature incineration, primarily mineral salts). The release of bodily fluids for buried livestock carcasses is rapid at first, with steadily declining release rates after the first few months or year (Young et al., 2001). Young and colleagues estimated that approximately 33% of the carcass mass is released as fluids during the first 2 months after burial, of which half is released within the first week. If the leachate has the density of water (i.e., 1 kg/L), for 45,359 kg (50 U.S. tons) of carcasses, approximately 15,000 L of fluid would be released in the first 2 months, with 7,500 L released during the first week. Approximately 60% of the carcass mass is released as fluid by the end of the first year (Young et al., 2001), meaning that approximately 27,000 L can be expected to be released from the carcasses in the first year.

During the first few months of fluid release from the carcasses, water entering the pit from precipitation will dilute the liquid. When the fluid release declines after the first few months of degradation, however, leachate concentrations can depend on local precipitation as well as conditions in the burial trench. The contribution of precipitation was not included in the leachate modeling approach for the on-site burial option because depending on when precipitation occurred, it might or might not dilute concentrations during the most active period of leachate releases.

Table 3.4.2. On-site Burial Release Characterization

Release Type	Approach, Assumptions, and Information Sources
Leaching to subsurface soils and to groundwater	▪ Total leachate from 45,359 kg of carcasses is likely to be 15,000 L over the first 2 months following burial. ▪ Chemical releases are estimated in three time steps: first 1–2 weeks, first 8–10 weeks, and the first year. Releases after the first year would decrease over time. ▪ Young et al. (2001) estimated release rates for total organic carbon (TOC), ammonium (NH_4^+), potassium (K^+), and chloride ions (Cl^-) for the time steps (Table 5.3 in Young et al. 2001). Field measurements of chemical concentrations in leachate at specific times after burial (e.g., Pratt and Fonstad 2009; Yuan et al. 2013) extend the chemicals covered from those estimated by Young et al. (2001; i.e., TOC, NH_4^+, Cl^-, and K^+) to include the remaining chemical constituents of the carcasses (Section 2.4.1 above).
Diffusion of gases through cover soil	▪ Concentrations of hydrogen sulfide (H_2S) and ammonia (NH_3) reported by Glanville et al. (2006) indicate that odor thresholds might, on occasion, be exceeded close to a burial trench. In general, however, the passive rate of release, distributed over the length and width of the burial trench, and high dilution by the atmospheric air under most meteorological conditions preclude the releases from reaching concentrations that might be hazardous to humans and other animals.

Table 3.4.3. Potential Annual Releases (kg) of Chemicals from 1,000 kg Buried Livestock[a]

Year	TOC	NH_4	Cl	K
1	24	2.9	0.12	0.28
2	10.1	1.2	0.05	0.12
3	4.8	0.6	0.03	0.07
4	2.7	0.3	0.015	0.035
5	1.8	0.2	0.008	0.018
6	1.3	0.2	0.006	0.014
7	1.1	0.1	0.006	0.014
8	1.0	0.1	0.004	0.009
9	0.8	0.1	0.004	0.009
10	0.8	0.08	0.004	0.009
20 (average/yr)	0.3	0.05	<0.002	<0.005
30 (average/yr)	0.1	0.02	<0.002	<0.005
40 (average/yr)	0.03	<0.008	<0.002	<0.005
50 (average/yr)	0.02	<0.008	<0.002	<0.005
60 (average/yr)	0.003	<0.008	<0.002	<0.005

Abbreviations: TOC = total organic carbon; yr = year.
[a] From Table 5.3 of Young et al. (2001).

Estimates of the chemical concentrations in leachate percolating from an unlined burial trench over time are based on measured concentrations in leachate accumulating in experimental livestock carcass burial pits in Saskatoon, Canada, as reported by Pratt and Fonstad (2009). Each

of five pits was 7 by 9 m^2 and 2.5 m deep. All five pits were completely lined with impermeable 40-mil polyethylene with a leachate sampling tube at the bottom center of each. Three pits, one each for cattle, swine, and poultry, were covered with a 40 mil liner and capped with 0.9 to 2 m of soil. Two ventilation pipes placed through the top liner allowed for the escape of gases formed during carcass decomposition.

Pratt and Fonstad (2009) sampled the leachate accumulating above the bottom liner of the pit at periodic intervals after burial over a 2-year period. The concentration profiles of different chemicals in the accumulated leachate over a two-year period were similar across livestock categories, as shown in Table 3.4.4.

Table 3.4.4. Average Two-year Leachate Concentrations (mg[chemical]/L[leachate]) by Livestock Category (Pratt and Fonstad 2009)

Chemical Species	Poultry	Swine	Cattle
Bicarbonate	39,133	48,467	50,733
Chloride	2,570	2,380	2,813
Nitrogen (ammonium)	10,400	13,300	14,100
Nitrogen (nitrate and nitrite)	2.3	3.1	3.8
Calcium	81	48	36
Magnesium	79	17	18
Phosphorus	1,927	1,513	1,150
Potassium	2,400	2,400	2,000
Sulfate	3,970	3,900	2,900
Zinc	2.2	1.8	1.7

The concentration of elements in leachate from cattle burial pits as reported by Pratt and Fonstad (2009) are used to assess possible human exposures via groundwater. Those data are presented in Table 3.4.5.

For this exposure assessment, a groundwater well is assumed to be located 30.5 m (100 ft) downgradient of an unlined burial trench containing 45,359 kg of cattle carcasses. Data used to represent the three time-frames of interest—first week, first 8–10 weeks, and first year—are included as the first three data columns in Table 3.4.5.

As described by Pratt and Fonstad (2009), many of the chemical species concentrations (e.g., aluminum, calcium, magnesium, manganese, molybdenum, nickel) were highest during the first weeks of burial, and were lower in samples taken after a few months and years (in Table 3.4.5,

see chemicals with the time of maximum concentration occurring at 0.5 months). Those chemical species might have complexed with other chemicals and precipitated out of solution or become strongly sorbed to organic particulate matter. Sulfate concentrations might have declined (Pratt and Fonstad 2009) as hydrogen sulfide escaped to air via the two vent pipes. The concentrations of other chemicals, notably organic and inorganic carbon, boron, chloride, and ammonium nitrogen increased over time in the contained leachate as carcass degradation continued after the major releases of fluids in the first two months (Table 3.4.5, chemicals with time of maximum concentration at 12 months).

1.5.2. Methane Seepage from Buried Carcasses

Landfill gas intrusion into structures is a well-understood phenomenon that caused at least 30 incidents of property damage or of death or injury to residents or workers in nearby buildings (USEPA 2005a). There are no methane explosion damage cases associated with livestock carcass burials. However, a 45,359 kg carcass burial would produce significant quantities of methane, which makes the risk of damage worthy of discussion.

Yuan et al. (2013) studied gas production over 650 days from cattle carcasses "buried" in laboratory-scale anaerobic decomposition reactors loaded with measured amounts of cattle carcass material. They found the average rate of methane production to be 0.58 L/kg-d (dry weight basis) for homogenized carcass materials. Non-homogenized carcass materials produced methane at one fifth of that rate (i.e., approximately 0.12 L/kg-d dry weight) and the equipment clogged; those results therefore are not considered further. Gas production was approximately 65% methane and 20% carbon dioxide. Other gases produced included oxygen (O_2) and nitrogen (N_2) at approximately 5% and 15%, respectively. Methane production did not start until the carcass materials reached a favorable pH around day 50 of the experiment, and it varied substantially from day to day after that, with its production ceasing between 340 and 650 days depending on the reactor vessel.

The total yield of methane from homogenized carcass materials was 0.33 m^3/kg. Extrapolating the bench-scale results to cattle carcasses of 500 kg (1,100 lb) each, Yuan et al. (2013) estimated that 50 m^3 (36 kg) of methane would be produced per carcass. That means production of 4,540 m^3 (3,266 kg) methane per 45,359 kg of carcasses over the decomposition interval.

Table 3.4.5. Estimated Concentration of Elements in Accumulating Leachate from Cattle (pit no. 4)

Chemical Species	Conc. 1 Week After Burial (mg/L) (08/17/05)	Average Concentration Over 1st 3 Sampling Events (mg/L)	Average Concentration 0 12 Months (mg/L)	Maximum Concentration (mg/L)	Time of Maximum (months after burial)
Aluminum	1.7	1.45	0.62	1.70	0.5
Ammonium[a]	5,200	7,703	10,975	13,900	3
Barium	0.3	0.47	0.18	0.60	1
Beryllium	nd	nd	nd	nd	na
Bicarbonate	35,100	39,633	47,245	53,400	9
Boron	nd	0.80	0.67	0.96	12
Cadmium	nd	nd	nd	nd	na
Calcium	60	37	38	60	0.5
Chloride	2,605	2,590	2,482	3,266	12
Chromium	nd	nd	nd	nd	na
Cobalt	0.1	nd	nd	0.10	0.5
Copper	0.6	1	0.78	1.10	1
Inorganic Carbon	6,900	7,797	9,250	10,400	9
Organic Carbon	43,000	45,000	55,810	64,800	12
Iron	110	66	32.6	110.0	0.5
Lead	nd	nd	nd	nd	na
Magnesium	30	23	18.8	30.00	0.5
Manganese	0.5	0.4	0.27	0.50	0.5
Molybdenum	1.8	0.7	0.18	1.80	0.5
Nickel	0.4	0.25	0.07	0.40	0.5
Nitrate[a]	23	13	5.9	23.0	0.5
Nitrite[a]					
Total Nitrogen	18,300	15,100	18,300	20,100	9
Phosphorus	920	1,173	1,174	1300	1
Potassium	1,900	2,033	2,068	2,200	9
Silicon[b]	29	27	24	29.00	0.5
Silver	nd	nd	nd	nd	na
Sodium	1,600	2,100	2,016	2,700	2
Strontium	0.7	0.43	0.29	0.70	0.5
Sulfate	3,700	4,833	5,026	6,800	3
Sulphur	1,200	1,600	1,670	2,300	3
Titanium	0.2	nd	0.01	0.20	0.5
Vanadium	nd	nd	nd	nd	na
Zinc	3.5	4	2.6	4.20	1
Zirconium	0.2	nd	0.01	0.20	0.5

Source: Pratt and Fonstad (2009).
Abbreviations: nd = not detected; na = not applicable.
[a] As nitrogen (N).
[b] Soluble silicon.

For methane intrusion from a burial trench initially containing 45,359 kg of cattle carcasses into a closed building, a number of conditions must be met. First, methane generation and release into adjacent soils depends on the type and age of the waste, its moisture content, the type of cover material, ambient temperature, and other factors. For example, permeable cover materials, such

as gravel and sand, allow for the gas to ascend vertically more rapidly than silts and clays (ATSDR 2001), thereby reducing the horizontal transport of methane gas.

Second, the subsequent movement toward structures depends on the position of the structures relative to the source, the distance from the source, as well as conducive geological and soil conditions. The direction, flow rate, and travel distance of gas migration is controlled by a number of environmental variables and is primarily driven by a variation in concentration (diffusion) and/or pressure differences (convection) (NHBC-RSK 2007). Heavy rains post-burial can seep into void spaces occupied by gas, pushing the gas to lower pressure areas. Methane gas will also migrate via the path of least of resistance, meaning that natural rock fissures and man-made pipes provide easy paths for the gas to travel to potentially dangerous areas. Foundation cracks in buildings near a burial site provide a path for methane to migrate through and accumulate in the building, significantly increasing the risk of explosion (ATSDR 2001).

Finally, the concentration of methane seeping into a building must be within a relatively narrow explosive range. A highly flammable gas, methane becomes explosive in mixtures with oxygen between a lower explosive limit (LEL) of 5% volume of methane/volume of air (v/v) and an upper explosive limit (UEL) of 15% v/v. Methane concentrations above the UEL (> 15%/v) are too rich (O_2 levels are too low) to support combustion (USEPA 2005a).

In the 1990s, USEPA regulations under both Resource Conservation and Recovery Act (RCRA) and the Clean Air Act (CAA) reduced the likelihood of landfill gas intrusion by requiring landfill gas collection and management. Those regulations, however, do not apply to livestock carcass burial.

There are no technical or regulatory barriers to prevent methane explosion damage from occurring at or near a livestock carcass burial location. Inserting vertical narrow (e.g., half-inch) pipes into the buried carcass mass in several locations, however, could assist in vertical venting of methane. Given all of these considerations, the possibility of a methane explosion as part of the on-site burial management option is considered unlikely and is not evaluated as part of the assessment.

3.5. Composting

The conceptual model for the composting option is shown in Figure 3.5.1. According to Looper (2001), composting of dairy cow carcasses generally takes six to eight months, with 90% of the flesh decomposed after eight weeks. Carcasses are difficult to find in the pile after four months, with only a few bones present.

In this management option, the carcasses are placed in outdoor composting windrows that are constructed according to specifications provided by USDA (2005). Carcasses are placed on a base layer and covered with a 2 ft (0.6 m) thick layer of bulking material (e.g., woodchips) on the top and all sides. For large animals, Glanville et al. (2006) recommends placing one U.S. ton (907 kg) of carcass, in a single layer, per 8 ft (2.4 m) of windrow. Using this recommendation, the total length of windrow for 45, 359 kg (50 U.S. tons) of large animal carcasses is 122 m (400 ft). The exposure assessment assumes two 16 ft (4.9 m) wide by 60 m (200 ft) long windrows.

Based on minimum siting recommendations in NABCC (2004) and USDA (2015), the assessment assumed windrow construction occurs in a well-drained area that is at least 3 ft (90 cm) above the high water table level or bedrock and at least 200 ft (61 m) horizontally from a water body.

The windrow is assumed to be placed on bare earth where any liquid not retained by a two-foot base layer of woodchips could leach to soil and groundwater. Gases liberated by decomposition diffuse upward through the bulking material to the atmosphere. The elevated temperatures (e.g., at least 55°C (131°F) for three or more days) associated with thermophilic microbial digestion of carcass materials produced in the compost pile can deactivate many kinds of pathogenic microbes (see Section 2.4.2 for more information) (Schwartz and Bonhotal 2014). The assessment assumes most pathogens are inactivated by the time the compost is processed as a product that can be applied in an on-site agricultural field in accordance with a nutrient management plan. Transport of chemicals and any surviving microbes from the compost application site can occur by runoff/erosion to the lake, leaching to groundwater (reaching the well) and, subsequently, to the lake and aquatic food web. Other specific assumptions used to model the composting option are shown Table 3.5.1.

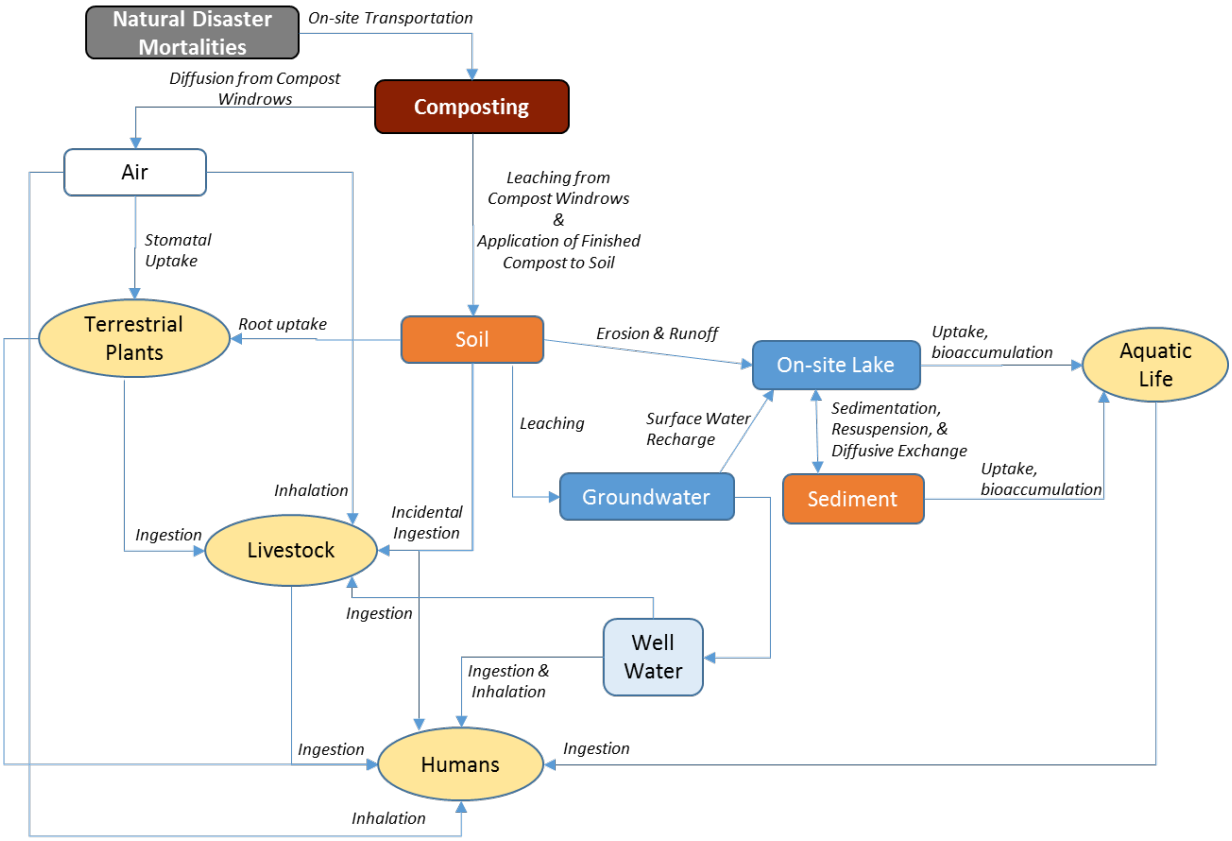


Figure 3.5.1. Conceptual model of exposure pathways from livestock carcass composting.

Table 3.5.1. Assumptions for the Composting Management Option

Conceptual Model Feature	Assumptions
Compost Windrow Design	▪ Composting is performed on bare earth at a site with 2–4% grade (USDA 2005, 2015). ▪ Carcasses are composted in two windrows that are 4.9 m (16 ft) wide by 61 m (200 ft) long. ▪ An initial layer of bulking material (e.g., woodchips) 2 ft deep are placed across the entire base of the eventual windrow (USDA 2005). ▪ An additional two feet of bulking material are placed on the sides and top of the windrow (USDA 2005). ▪ Runoff from the windrows will be contained with hay bales. ▪ Most pathogens are inactivated by temperatures of at least 131°F (55°C) for at least three days of composting (USDA 2015). Spore-forming pathogens and prions might not be inactivated under these standard composting conditions. ▪ Releases to air from windrow turning are not evaluated. Windrows for cattle composting are not turned; windrows for poultry might be turned one time after pathogens are likely to be inactivated.
Air Pathways	▪ Gases generated by carcass decomposition diffuse upward through the top cover of woodchips to air, where they quickly disperse to non-hazardous levels. Biological agents and non-volatile chemicals will be contained by the bulking material (e.g., woodchips). ▪ Inhalation by livestock will not be included in the exposure assessment (see Table 3.1.1).
Soil Pathways	▪ The base layer of bulking material beneath the windrows limits contamination of groundwater. Woodchips used as carbon bulking material absorb all but 5% of the liquid released from the carcasses inside the windrow (Glanville et al. 2006). This leakage can seep through soil to groundwater.
Surface Water, Sediment, and Aquatic Life	▪ Agents from composted carcasses can reach the lake only via runoff/erosion from the compost application site (not from the windrow itself).
Production of Food on the Farm	▪ For this assessment, compost is applied to a field according to a federal- or state-approved nutrient management plan and crops human consumption are grown in that field.

1.5.1. Leaching to Groundwater

As described in Section 3.4.1, a large amount of fluid (approximately 33% of the carcass mass in the first 2 months) is released from decomposing carcasses. While carcass burial methods typically do not include a means to contain leachate, properly constructed compost piles include sufficient bulking materials to trap and absorb leachate (Payne et al. 2015). The bulking material effectively acts as a sorbent, allowing water to evaporate while the bulk of the minerals and non-volatile organic and inorganic compounds remain in the bulking material, which later is mixed into the finished compost. Leachate from the fluids in carcasses alone (approximately 65% of the fresh carcass mass) should be captured in the bulking material for the most part. Using corn

stalks as the sorbent bulking material, researchers including Glanville et al. (2006) and Donaldson et al. (2012) found the volume of leachate from experimental compost windrows to be no more than 5% of precipitation falling (500–600 mm) on the windrows (i.e., the bulking material facilitated evaporation of water back into the air for 95% of the rainfall). The cattle windrows contained the equivalent of 90 mm rainfall if spread evenly over the area directly beneath the carcasses. That is in addition to the 530 and 590 mm of precipitation measured during two trials. However, the total depth of leachate captured beneath the test units ranged from 7 to 29 mm. Across the trials, leachate depths never exceeded 1–5% of the accumulated precipitation (Glanville et al. 2006; Payne et al. 2015). Contaminants were detected in soils below the windrows, but increases in total carbon and nitrogen (Table 3.5.2), limited to the top 15 cm of soil under the compost pile, were estimated to be less than 8% of the total carbon in the top 15 cm of soil. Based on those studies, it is assumed that at least 95% of the contaminant mass associated with the composting carcasses was present in the finished compost.

In soils beneath compost piles constructed with various carbon-based bulking materials (e.g., corn silage, ground cornstalks), Glanville et al. (2006) detected leached chloride at all depths measured (up to 120 cm). Chloride is not considered a serious water pollutant, but is an indicator of leachate movement because it does not absorb to soil and is very mobile in the environment (Glanville et al. 2006).

Table 3.5.2. Change in Chemical Concentrations Pre- and Post-Composting Cattle Carcasses using Corn Stalks (Glanville et al. 2006)

Depth Interval Beneath Compost Pile (cm)	Chemical Concentrations in Top 120 cm of Soil Prior to Composting (mg/kg dw)			Change in Chemical Concentration (post composting minus pre composting concentration) (mg/kg dw)		
	Ammonia N	Nitrate N	Chloride	Ammonia N	Nitrate N	Chloride
0–15	5.2±5.1	12.5±9.4	55.0±33.0	302±368*	2.8±28.7	79.2±71.3*
15–30	3.2±2.6	8.4±6.7	56.2±30.5	41.5±60.2	6.2±29.1	47.4±41.7*
30–45	2.9±1.8	6.4±6.7	58.5±38.0	4.8±11.2	7.6±25.6	18.7±28.3
45–60	2.5±1.5	6.0±6.4	50.9±48.2	4.0±13.5	7.2±23.8	31.8±74.1*
60–90	1.8±1.4	6.5±7.1	25.6±20.3	0.7±6.2	3.7±22.6	25.9±49.6*
90–120	1.6±1.3	7.1±6.7	21.8±15.2	2.5±14.1	1.1±14.8	16.5±39.7*

Abbreviations: dw = dry weight.
* Indicates that increase is significantly different from zero.

Other leachate chemicals monitored by Glanville et al. (2006) appear to have been sorbed/exchanged by soil, with moderate increases in ammonia nitrogen (Table 3.5.2) and total

carbon in the top 15 cm of the soil. Based on these findings, the soil beneath the windrow is assumed to further attenuate the potential for contamination of groundwater.

1.5.2. Releases to Air from the Windrow

The layer of bulking material placed over and around composting carcasses allows for vapors to diffuse out of the windrow while containing particles, including microbes. Sources that discuss air quality from livestock composting generally focus on odor generation and vapors including hydrogen sulfide and ammonia. Glanville et al. (2006), for example, reported odor levels within the first four months of composting were similar to those reported for pond water (200–300 ODT). This volumetric ratio of fresh air to sample was at the lowest level that olfactometry panelists could detect an odor. These levels are quite low compared with manure-related facilities (4,000 ODT). Glanville and colleagues concluded that properly managed emergency mortality composting would not present odor nuisance problems.

1.5.3. Application of Compost to Soil

As described above and shown in Figure 3.5.1, the finished compost was assumed to be applied to soil on site. The rate of finished compost application to soil (i.e., tons of compost per acre) and the total area of soil receiving compost assume the nitrogen (N) content of the compost is at an agronomic rate, ostensibly following the farm's nutrient management plan. An agronomic rate of application occurs when the nutrient content added to the soil does not exceed the uptake capabilities of crops to be planted at the site, nor does it result in fertilizer burn (NABCC 2004). Agronomic fertilization rates also help to protect air, soil, and water quality. For example, nutrients supplied in excess of the agronomic rate may run off or leach to surface water, causing eutrophication, or to groundwater degrading its quality.

Agronomic rate calculations require information about the nutrient content of the fertilizer or soil amendment and the nutrient requirements of intended crops, if any. Tables 3.5.3 and 3.5.4 provide nutrient content values reported for finished cattle and hog compost, respectively. The agronomic rate of application is based on the lower ranges of nitrogen content for cattle compost in Table 3.5.3, specifically 5 kg of potentially available nitrogen per U.S. ton of compost. The lower end of the reported range was used because it results in a higher rate of compost application per acre, and higher chemical loadings, than the higher end of the reported range.

Because the hypothetical farm is modeled with meteorological data from Iowa (see Section 2.3.1), the scenario also uses assumptions about the nutrient requirements of soils and crops in Iowa. The Iowa Water Environment Association (IAWEA) recommends nitrogen requirements for both consumer (i.e., corn, wheat, oats) and non-consumer crops (i.e., various forage grasses) (IAWEA 2011). The ranges of IAWEA-recommended values for various forage grasses are presented in Table 3.5.5. As a conservative assumption, the upper bound from the grass with the highest nitrogen requirement was selected as the value for use in the analysis (cool season tall grass, requiring 120 lb N/ac or 135 kg N/ha). This approach does not assume additional nitrogen credits to the soil (i.e., commercial fertilizers, previous legume crop growth), and consequently, the entire nitrogen requirement is met through the application of compost.

Table 3.5.3. Nutrient Content of the Cattle Carcass Compost (Kube 2002 as cited in NABCC 2004)

Nutrient	kg of Nutrients/U.S. ton (2,000 lb) of Compost (kg/tonne)
Total Kjeldahl Nitrogen (TKN-N)	10–25 (11–27.6)
Potentially Available Nitrogen (N)	5–15 (5.5–16.5)
Phosphorus (P)	2–20 (2.2–22)
Potassium (K)	4–20 (4.4–22)

Abbreviations: lb = pound; tonne = metric ton.

Table 3.5.4. Nutrient Content of Hog Carcass Compost (McGahan 2002 as cited in NABCC 2004)

Nutrient	Percent (%)	kg/tonne
Total Kjeldahl Nitrogen (TKN-N)	1.28	13.0
Ammonia Nitrogen (NH_3-N)	0.22	2.00
Phosphorus (P)	0.27	2.84
Potassium (K)	0.28	2.90

Abbreviations: tonne = metric ton.

Table 3.5.5. Nitrogen Requirements for Forage Grasses in Iowa (IAWEA 2011)

Forage Type	lb N/ac (kg N/ha)
Cool season tall grass	100–120 (112–135)
Blue grass	60–80 (67–90)
Sorghum-sudan	80 (90)
Legume grass	40 (45)
Warm season grass	90 (101)

Abbreviations: lb = pound; ac = acre; ha = hectare.

In addition to the agronomic rate, an estimate of the final quantity of compost is needed to calculate the total area to which the compost could be applied. The final volume of compost is estimated based on the initial volume and the volume reduction at the completion of composting. Langston et al. (2002 as cited in NABCC 2004) and Kube (2002 as cited in NABCC 2004) found that after three months of composting, the final volume of swine and cattle carcasses was 20% and 25% less, respectively, than the original volumes. As described earlier, the initial volume of the windrows is estimated to be 357 m^3. Assuming that the final volume of compost is 25% less than the initial volume, the estimated final volume is 268 m^3. As advised by NABCC (2004), the ratio of bulking material to carcasses should result in a final compost mixture with a bulk density that does not exceed 600 kg/m^3 (37.5 lb/ft^3). Applying this upper limit density to the final volume of compost, the estimated final mass of compost applied to a field is 160,650 kg (161 tonnes or 177 U.S. tons). For the agronomic rate calculations, the weight of the compost must be expressed in dry weight. According to Chen et al. (2012), the moisture content of finished compost is typically 40%. With this assumption, the dry weight of the compost is 96.4 tonnes (106 U.S. tons).

Using the above assumptions, the total area of compost application is calculated with the following equation:

$$Total\ Area = *\ dry\ metric\ tons\ compost \qquad \textbf{Eqn. 3.1}$$

where:

kg available N = 5.5 kg N/dry tonne of compost
kg N required = 135 kg N/ha
dry tonnes of compost = 96.4 tonnes

With this approach, the estimated area over which the finished compost can be applied is about 4 ha (~40,000 m^2 or 10 ac). This amounts to an application rate of about 24 dry tonnes of compost per hectare.

A final consideration in evaluating the compost application area is the amount of phosphorus added to the soil as the result of agronomic nitrogen management. Based on the application rate estimated above and the reported range of phosphorus in finished compost (Table 3.5.3), the

addition of phosphorus would range from 52.8 to 528 kg/ha. Although nutrient requirements are site-specific, the USEPA Part 503 Biosolids Rule, part 24 requires compost application to be discontinued if the phosphorus content of the soil reaches 300 lb/ac (336 kg/ha). This indicates that phosphorus additions, instead of nitrogen additions, might limit the compost application rate in some cases. In those cases, the application rate would be lower than estimated above based on the nitrogen content.

Reported concentrations of chemicals in finished livestock compost are available for nutrients (see Tables 3.5.3 and 3.5.4) and veterinary drugs. According to a literature summary by Schwarz and Bonhotal (2014), non-steroidal anti-inflammatory drugs (NSAID) appear to not persist during livestock composting. However, there is evidence that sodium pentobarbital, a commonly used euthanasia drug, is persistent throughout composting (Payne et al. 2015). Euthanasia drugs are assumed to not be present in livestock killed by a natural disaster.

Because limited data were identified on the concentrations of metals in finished compost, emission factors for carcass incineration reported by Chen et al. (2004) are used as surrogate data to estimate metals added to soil in the application of finished compost. As described in Sections 3.3 and 3.4, Chen et al. (2004) reported metal emission factors (i.e., mg element per kg of carcass incinerated) for bottom and fly ash from the HOWI and LIWI incinerators. Assuming that all of the metal content in the incinerated carcasses is retained in either the bottom or fly ash, and that all of the metal content in composted carcasses either remains in the finished compost or leaches to the ground below, the data from Chen et al. (2004) can be used to estimate the metal content of the finished compost.

Table 3.5.6 shows the total amount of metals estimated in the bottom and fly ash from incineration of 50 tons of carcasses. Because the assumption that all of the metal content in the incinerated carcasses is retained in ash is likely an overestimation, the greater metal abundance estimate for the HOWI or LIWI incinerators (see the “Max” column in Table 3.5.6) form the basis for the compost metal estimates. The total amount of the metals, converted from mg to g, were then divided by the total area of compost application (estimated above) to calculate the estimated loading of the metals to soil in g/m^2.

Table 3.5.6. Estimated Loading of Metals to Soil with Compost Application

Element	mg in Bottom and Fly Ash (surrogate for total element in carcasses)			Loading Rate to Soil (g/m^2)
	HOWI	LIWI	Max	
Cadmium	1.5E+04	1.8E+03	1.5E+04	3.9E-04
Chromium	2.6E+05	1.7E+05	2.6E+05	6.7E-03
Copper	1.1E+06	5.4E+05	1.1E+06	2.7E-02
Iron	1.0E+06	1.9E+07	1.9E+07	4.7E-01
Lead	8.2E+04	1.6E+06	1.6E+06	4.1E-02
Manganese	1.1E+05	3.9E+05	3.9E+05	9.9E-03
Nickel	3.9E+05	3.3E+05	3.9E+05	9.8E-03
Zinc	1.7E+05	4.1E+06	4.1E+06	1.0E-01

Abbreviations: HOWI = hog farm waste incinerator; LIWI = livestock disease control incinerator; max = maximum.

This section reviews pertinent aspects of all the carcass management options and specifically identifies assumptions used to estimate chemical and microbial releases to air, soil, and water. The conceptual models identify all potential pathways regardless of whether or not they are part of the quantitative exposure modeling. The next section describes data and methods used to model the fate of chemicals in the identified exposure pathways. Exposure estimation for chemicals and microbes is presented in Sections 5 and 6.

4. Chemical Fate and Transport

This section describes approaches used to evaluate the fate and transport of chemicals in abiotic and biotic environmental media following their release from livestock carcass management options, as described in Section 3. The modeling approaches use existing, peer-reviewed modeling tools and frameworks for most potential exposure pathways. This includes those involving air dispersion and deposition, soil erosion and runoff to surface water, bioaccumulation in the aquatic food web, and uptake by terrestrial plants, crops, and livestock from air and soils. Modeling approaches estimate leaching to groundwater used as drinking water and groundwater recharge to surface water. Separate approaches assess exposure to chemicals and microbes because most chemical fate and transport models do not evaluate the environmental fate and transport of microbes or microbe-sized abiotic particles.

Air concentrations and wet, dry, and total deposition resulting from chemical releases to air from open-pyre burning and air-curtain burning of carcasses are modeled with American Meteorological Society/USEPA Regulatory Model air dispersion model AERMOD (version 14134). Chemical fate and transport in surface soil, surface water, and as food is produced and consumed on the farm are modeled with algorithms, default environmental assumptions, and chemical data from USEPA's (2005a) *Human Health Risk Assessment Protocol (HHRAP) for Hazardous Waste Combustion Facilities*. HHRAP is a peer-reviewed environmental modeling framework developed, refined, and used by USEPA's Office of Land and Emergency Management (OLEM) (formerly Office of Solid Waste and Emergency Response) to estimate, for chemicals released initially to air, their further transport and fate in soils, surface water, terrestrial plants and animals, and to estimate human ingestion of chemicals in food and soils. Concentrations of chemicals in fish are estimated by modeling uptake from surface water and sediment followed by accumulation through an aquatic food web. Separate aquatic food web modeling approaches were required for organic and inorganic chemicals. Bioaccumulation of nonionic organic chemicals was modeled with AQUAWEB, a steady-state solution model of aquatic bioaccumulation created by Arnot and Gobas (2004). AQUAWEB was not designed to model the behavior of inorganic chemicals, including metals, in aquatic food webs. For metals included in the assessment, bioaccumulation to game and pan fish is estimated using previously-published bioaccumulation factors (BAFs).

HHRAP and the other modeling frameworks described above do not include equations to simulate chemical fate and transport in subsurface soil and groundwater, or to estimate chemical loading to surface water from groundwater. Modeling in these environmental compartments is needed to evaluate leaching from buried carcasses, compost windrows, temporary carcass storage piles, and combustion ash buried on-site. Leaching from combustion ash to groundwater is modeled using a health-protective, screening-level approach in which Kd values (i.e., chemical-specific soil-water partitioning coefficients) estimate the leaching of chemicals from the ash to infiltrating precipitation and sorption of chemicals from leachate to subsurface soil. A similar approach is used to model groundwater contamination from carcass burial and leaching from compost windrows and carcass storage piles.

Sections 4.1 through 4.6 describe the modeling methods and results for specific media compartments.

4.1. Air

As described in Section 3, the release of particle-bound chemicals to air is identified in the conceptual models for the combustion-based management options. In addition, vapor emissions to air are identified in the conceptual models for burial and composting, as well as the temporary carcass storage pile that is included in all management options. These gas emissions are primarily carbon dioxide, hydrogen sulfide, ammonia, methane, and malodorous gases. The passive release of these vapors occurs over a broad area (e.g., diffused over the 2.1 m by 91.4 m burial trench) with dilution in outdoor air. In this situation, it is reasonable to assume these chemicals are unlikely to reach the acute effects concentrations that pose health risks to humans or livestock. For this reason, the assessment does not model the chemical fate and transport of these vapor emissions to air.

This assessment uses AERMOD (version 14134)[8] to model air concentrations and wet, dry, and total deposition resulting from chemical releases to the air from the use of open-pyre burning and air-curtain burning. As shown in Table 4.1.1, the open pyre is represented as a line of five point sources spaced at 20 m intervals, which covers most of the 91 m length of the pyre. The air-curtain burner is represented as a single point source The relatively small length of the air-curtain

[8] Complete documentation of AERMOD and related tools, including AERMOD, AERMET, and AERSURFACE, is available at http://www3.epa.gov/scram001/dispersion_prefrec.htm.

firebox (i.e., 8.3 m) does not necessitate adding additional point sources. The assessment assumes emissions originate at the height of the combustion units and from areas with diameters equal to the width of the combustion units. For the air-curtain burner, the assessment uses the dimensions of the fire box[9]. Release heights and diameters are shown in Table 4.1.1 (exit-gas temperatures and velocities are discussed later in this section).

Table 4.1.1. Parameterization of Combustion Units in AERMOD

Combustion Unit	Source Type	Height (m)	"Stack" Diameter (m)	Exit gas Temperature (°C)	Exit gas Velocity (m/s)
Open pyre	Point (5 at 20 m spacing)	1.8	2.44	550	3.9
Air-curtain burner	Point (1)	2.5	2.6	550	7.8

Abbreviations: s = second.

AERMET is the meteorological pre-processor for the air dispersion model used within the exposure assessment, AERMOD. Both AERMET and AERMOD require values for three parameters not typically available from meteorological stations: site albedo, surface roughness, and Bowen ratio.[10] This assessment uses USEPA's AERSURFACE pre-processor to estimate values for these three parameters. It samples land cover around a site and, along with inputs regarding climatological conditions, uses look-up tables to estimate albedo, surface roughness, and Bowen ratio for the site. This assessment assumes land cover near the hypothetical farm is representative of agricultural areas surrounding Iowa City, Iowa, and is not specific to an actual location. Using this assumed land cover (shown in Table 4.1.2), and information on a local climate in Iowa (e.g., not arid; not near an airport; season assignments as shown in Table 4.1.3), the AERSURFACE lookup tables (version 1/6/2013) estimate albedo, surface roughness, and Bowen ratio for the hypothetical farm site. Those estimates include wetness data for 2014, when January and March received considerably less precipitation than normal, and April, June, and September received considerably more precipitation than normal. Table 4.1.4 summarizes the precipitation information. Approximately 97 cm of rain or snow fell in 2014 during 168

[9] See the overall air-curtain-burner dimensions at http://www.airburners.com/DATA-FILES_Print/ab-s327_Specs_PRNT.pdf.

[10] In meteorology, albedo is a measure of the reflectivity of the earth's surface. In air dispersion modeling, albedo can be used to model the thermodynamic interaction between the land or water surface and the atmosphere. Thermodynamics in an air dispersion model also may use the Bowen ratio, which is an indicator of heat transfer between air and water. An indicator of the land cover, surface roughness length, affects the movement of air above the land or water surface.

individual precipitation events lasting a total of 435 hours. That is equivalent to 968 L/m^2 for the year.

Table 4.1.2. Land Cover Surrounding Hypothetical Farm, with Percent Area Covered

Land cover Category	Percent of Area Around Site (%)
Open Water	1
Developed, Open Space	3
Developed, Low Intensity	2
Deciduous Forest	5
Grassland/Herbaceous	10
Pasture/Hay	30
Cultivated Crops	45
Woody Wetlands	3
Emergent Herbaceous Wetlands	1

Table 4.1.3. Seasons at the Hypothetical Farm

Month	Season
January	Winter with continuous snow cover
February	Winter with continuous snow cover
March	Winter with no snow
April	Transitional spring with partial green coverage
May	Transitional spring with partial green coverage
June	Summer with lush vegetation
July	Summer with lush vegetation
August	Summer with lush vegetation
September	Autumn before frost and harvest
October	Late autumn after frost or harvest
November	Late autumn after frost or harvest
December	Winter with continuous snow cover

Wind conditions at Iowa City in 2014 are summarized in the wind rose diagram shown as Figure 4.1.1. Winds blew from the south approximately 14% of the time, from the west approximately 15% of the time, from the southeast 20% of the time, and from the northwest 20% of the time. Inhalation receptors are located in the predominant downwind direction (southeast) during the two days of carcass burning. In addition, the lake is assumed to be southeast of the pyre or air-curtain burner location.

Table 4.1.4. Summary of Precipitation Data for Iowa City Used in This Assessment

Parameter	Value (units)
Total annual precipitation	96.84 (cm/yr)
Number of rain events	168 (events/yr)
Total duration precipitation	435 (hr/yr)
Precipitation per event	0.5764 (cm/event)
Precipitation per hour of rain	0.2226 (cm/per hour of rain)
Average hours per event	2.6 (hr/event)
Water volume per event	5764 (centimeters $[cm]^3/m^2$)
Water volume per year	968.4 (L/m^2)

Abbreviations: yr = year; hr = hour.

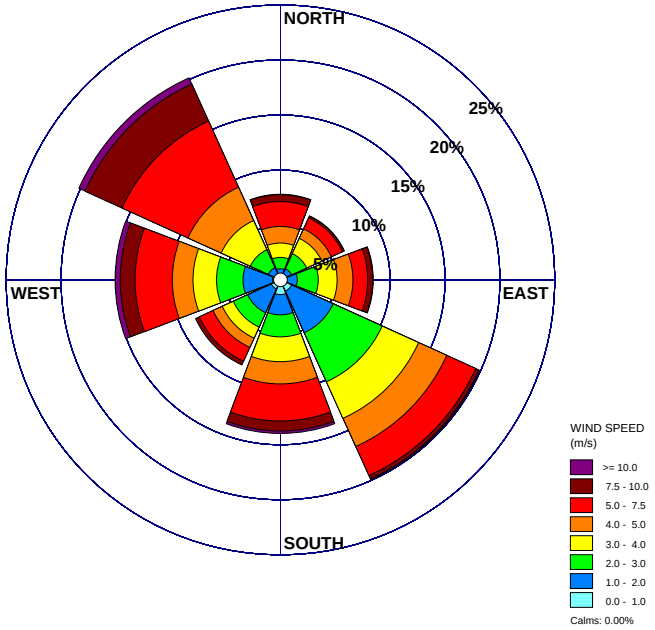


Figure 4.1.1. Wind rose for Iowa City in 2014.

Combustion was modeled as being from point sources because they are the only source type in AERMOD that explicitly uses data on exit-gas temperature and exit-gas velocity to calculate the plume rise of buoyant and/or high-velocity emissions. In this assessment, the emissions will exhibit significant buoyancy that is driven by the high temperature of the combustion events. The air-curtain burner emissions escape at 7.8 m/s, based on measurements from a sampling flue constructed over an air-curtain-incinerator pit burning cattle carcasses (see Table 14 of SKM, 2005). In contrast, open pyres lack the artificial wind current created by an air-curtain burner. The assessment assumes one-half of that velocity (i.e., 3.9 m/s) for open-pyre emissions.

Information from the literature suggests that temperatures of open pyres might be within the range of 300 to 400°C (Chen et al. 2004), with temperatures from 421 to 524°C needed to ignite coal and from 260 to 593°C needed to fully burn wood (Bartok 2003). With coal and wood used as fuels, the open pyres in this assessment were modeled with an exit-gas temperature of 550°C. For a trench air-curtain burner trial in New Zealand, temperatures measured above the flames in ranged from 140 to 850°C (SKM 2005). Given that large range of potential near exit-gas temperatures, the air-curtain burners in this assessment were modeled with the same exit-gas temperature as open pyres (i.e., 550°C) deemed adequate to fully burn the wood fuel used in the burners.

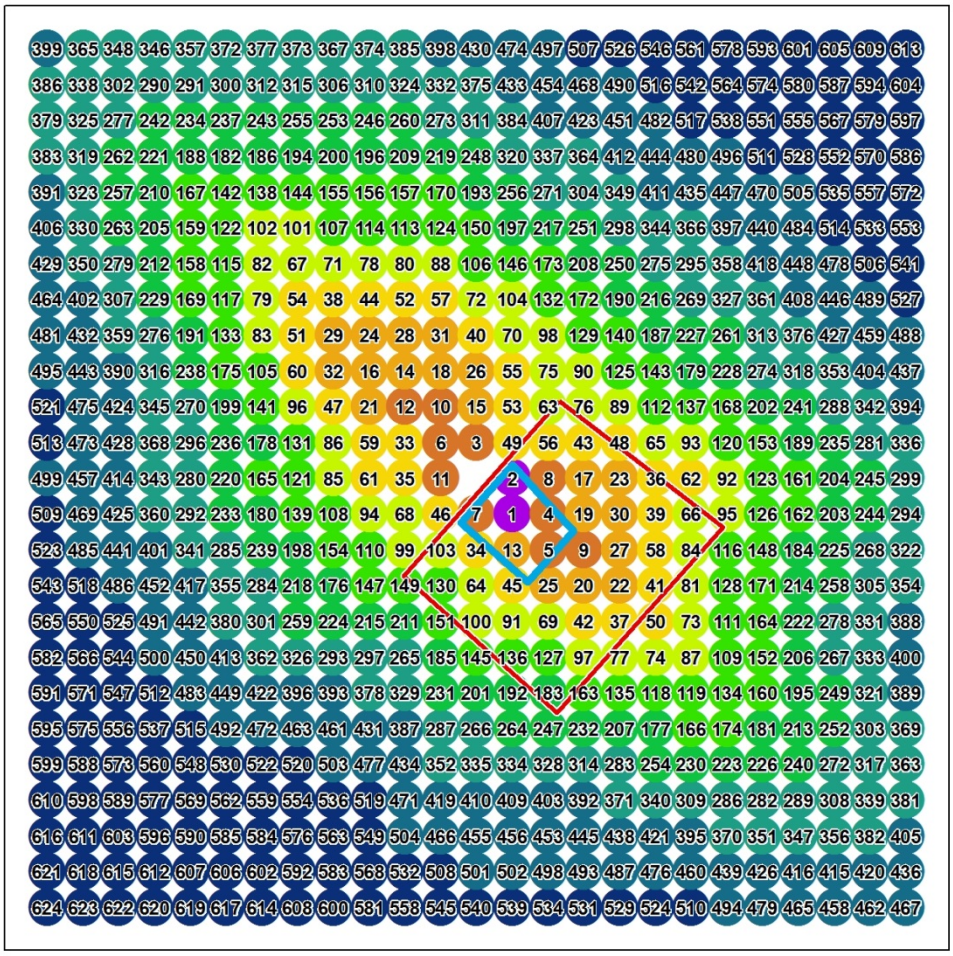
For the on-site combustion options, data on vapor-phase and particle-phase emissions of metals are from Chen et al. (2004). Although the data source included vapor-phase measurements (Chen et al. 2004), the measurements were taken inside the flue where temperatures were relatively high. The assessment assumes that metal vapors coagulate when cooled in ambient air to form aerosol particles that subsequently sorb to larger air-borne ash particles (based on Linak and Wendt 1993). The modeling initially sums the vapor-phase and particulate-phase emission estimates, and continues the modeling process entirely as particulate-phase. This allows use of the simpler of AERMOD's two- particle-deposition schemes, where the mass-mean particulate diameter and the fraction of particulate mass that is $PM_{2.5}$ are specified for each chemical from each combusted material. This simpler method is recommended when the particle-size distribution is not well known, and when less than about 10% of particles by mass are believed to be larger than PM_{10}. This is the case for all chemicals from all combusted materials, except for metals emitted from coal. For coal, the estimates of mass fractions and densities of several classes of particulate diameter ranging from 0.1 µm to 25 µm are available (Bond et al. 2002, see Appendix D, Table D.1, for the particle-size settings used in AERMOD).

For deposition of chemicals released during on-site combustion activities that remain in vapor-phase at ambient temperatures, the assessment uses estimates of chemical diffusivity in air, diffusivity in water, Henry's Law Constant (HLC), and cuticular resistance to uptake by lipids for individual leaves, as shown in Appendix D, Table D.2. The primary land cover is defined as "agricultural land."

The modeled emission rates of particle-phase and vapor-phase chemicals, and of particle-phase metals from on-site combustion activities, are in Appendix D, Table D.3. These emission rates correspond to the emission factors (see Sections 3.1 and 3.2) multiplied by the mass of combusted material and divided by a 48 hr combustion period.

The modeling receptors are characterized by a Cartesian grid of points at ground level, spaced 250 m apart, on a 6 km by 6 km square centered on the middle of the open pyre or air-curtain burner sources. Concentrations of particles in air are modeled at an approximate breathing height of 1.8 m, and deposition fluxes are modeled at ground level (i.e., 0 m height). Figure 4.1.2 depicts the annual-total modeled deposition of the total chemical emissions from open-pyre and air-curtain-burning sources that are operating continuously and based on actual, hourly meteorology. The receptor labeling indicates the ranking of relative deposition amounts, with 1 indicating the location receiving the highest deposition. The shading corresponds to relative deposition intensity, from higher amounts in purples and oranges to much lower amounts in blues. The 36 km^2 modeling domain is located where the deposition rates are highest over the course of the year. The maxima from depositions and the modeled concentrations of emissions in air are highly unlikely to occur outside of this domain. The 250 m spacing gives 16 different spatial estimates of air concentrations and deposition fluxes for each square kilometer. This spatial resolution allows deposition to the hypothetical lake (at 6 locations), and the hypothetical watershed (at approximately 32 locations).

According to the annual deposition totals plotted in Figure 4.1.2, wind conditions will tend to concentrate deposition of chemicals from the air along an axis from northwest of the combustion source to southeast (as expected based on the wind rose shown in Figure 4.1.1). According to the modeling and the local meteorology data, the locations with the highest deposited mass, most often will be within 600 m of the center of the combustion unit and generally to the southeast. The hypothetical lake (approximately 40.5 ha) was set directly southeast of the source (see blue polygon in Figure 4.1.2), and its hypothetical watershed (approximately 202 ha) surrounds the lake on three sides (see red polygon in Figure 4.1.2). This placement is most likely to receive the maximum amount of modeled chemical deposition for an open-pyre or air-curtain burner combustion event at any time during the year. Concentrations of emitted chemicals and deposition amounts are not estimated at the location of the combustion unit.



Notes: Shading corresponds to relative deposition amount (from higher amounts in purple and orange to much lower amounts in blues). Shading scale uses unequal intervals to provide higher resolution in areas of large gradients. Receptor labeling also corresponds relative to deposition amount (1=highest amount). White area at center is the location of the source. Blue polygon corresponds to the location of the hypothetical lake. Red polygon corresponds to the location of the watershed of the hypothetical lake.

Figure 4.1.2 Modeled, annual-total deposited mass of chemicals emitted from open-pyre and air-curtain burner units, using hourly meteorology.

The AERMOD modeling assume the combustion units operated continuously every hour of the year at a rate that would manage 46,359 kg (100 U.S. tons) of cattle every 48 hr (the length of a combustion "event"). This approach allows only the meteorological conditions to change from one hour or day to the next. This approach also enables calculation of the average concentration of the chemicals, and total deposition, for any 48 hr period of the year (i.e., for a combustion event that could begin at any hour of the year). For example, the event-average concentration of the chemicals in the air and event-total deposition amounts are calculated for a combustion event beginning at midnight on February 1st by averaging and totaling the hourly modeling results for

February 1st at 12 AM to February 3rd at 12 AM. This post-processing estimates event-average concentrations of chemicals in the air, and event-total deposition amounts for 8,760 unique combustion events, each beginning on a different hour of the year (365 d x 24 hr = 8,760 hr).

In practice, people try to avoid conducting open-pyre burning activities on windy days, and it is not possible to keep pyres lit during heavy precipitation. Consequently, the modeling assumes that burns do not occur during particularly windy or heavy precipitation periods. Such periods are defined as having at least 10% of the combustion hours (i.e., at least 5 hr of a 48 hr combustion event) with wind speeds of at least 8.94 m/s (20 mi/hr) and/or precipitation amounts of at least 2.5 mm/hr (0.1 in/hr); i.e., at least 12.7 mm (0.5 in) for a 48 hr period. Using those criteria, there were 1,428 total 48 hr periods when on-site combustion would not occur. These periods are excluded from the results presented in this assessment. The modeling results identified the location of the highest total deposition of emitted chemicals during any suitable 48 hr period. The results also identify the period leading to the greatest deposition to the lake and its watershed. With further modeling, the assessment evaluates the corresponding impact of emitted chemicals in terrestrial and aquatic media.

4.2. Surface Soil

The assessment estimates chemical concentrations reaching the surface soil from the combustion-based management options and the composting management option. With the on-site combustion of carcasses from a natural disaster, chemicals deposit from air to soil via diffusion (vapor-phase) or by gravity (particle-phase). During the composting management option, metals and other persistent chemicals present in the finished compost are applied to soil with the compost. Fate and transport processes (e.g., mixing, runoff, erosion, plant root uptake) affecting chemicals in the soil are modeled with USEPA's (2005a) *HHRAP for Hazardous Waste Combustion Facilities*.[11] HHRAP is a peer-reviewed environmental modeling framework developed, refined, and used by USEPA's Office of Resource Conservation and Recovery (formerly the Office of Solid Waste) to estimate chemical transport of chemicals released to air from a point source and their subsequent fate and transport in soil, surface water, and terrestrial plants and animals. HHRAP also estimates human exposure to chemicals ingested with food

[11] Further information on HHRAP is available at: http://www3.epa.gov/epawaste/hazard/tsd/td/combust/riskvol.htm and http://www3.epa.gov/epawaste/hazard/tsd/td/combust/risk.htm.

grown in or soils picked up within the modeled area of contamination. See Appendices D and G for further information about the HHRAP methods applied in this project.

HHRAP is a method for performing multi-pathway, site-specific risk assessments for facilities burning hazardous waste. However, the algorithms in HHRAP can be applied for sources other than combustors. HHRAP is not a computerized model, but rather a collection of recommended algorithms, default assumptions, and chemical data. This project uses applicable components of HHRAP to create an HHRAP Soil and Surface Water Excel model, referred to hereafter as the HHRAP SSW Model (or just SSW). This model includes HHRAP algorithms for the soil, surface water, and sediment compartments, specifically those that evaluate loading and loss processes via deposition, diffusion, erosion, runoff, leaching, volatilization, and sediment burial. Appendix E provides details about the HHRAP algorithms included in the HHRAP SSW Model, and Appendix F provides values of input parameters. The HHRAP modeling approach assumes steady-state conditions within each biotic and abiotic media compartment (e.g., soil, surface water, terrestrial plants), and chemical partitioning within a compartment (e.g., between soil particles and soil pore water, between suspended sediment particles and the water column) is calculated assuming equilibrium conditions. The HHRAP approach does not maintain a chemical mass balance, and chemical feedback mechanisms are not included. For example, the volatilization of a chemical from a water body does not affect the concentration of that chemical in the air.

The HHRAP SSW Model calculates chemical concentrations in soil after an area receives deposition of the chemical from the air or after compost is applied as a soil amendment. Inputs required for these estimates include the depth of mixing in the soil, soil moisture content, and the densities of the compost and receiving soils. All input value assumptions are listed in Appendix F. Where appropriate, the SSW Model uses HHRAP default assumptions. For example, HHRAP provides default assumptions for soil moisture at 0.2 milliliters (mL) water/cm^3 soil and bulk-soil density at 1,500 kg/m^3 (93.6 lb/ft^3) (surface soil, unsaturated).

Tables 4.2.1 and 4.2.2 present the chemical loading rates and resulting soil concentration estimates for the combustion-based and composting management options, respectively. Soil concentrations represent the concentration of chemicals after mixing the chemical loadings into the surface soil and after a year of loss processes included in the HHRAP soil compartment

algorithms. The two combustion-based options assume no tillage, and the chemicals penetrate no more than 2 cm (0.79 in) where they remain vulnerable to runoff and to erosion with soil particles. The composting option uses the HHRAP default mixing depth for tilled soil of 20 cm (7.9 in). In Table 4.2.1, concentrations of individual PAH compounds and dioxin/furan congeners are totaled.

Table 4.2.1 Estimated Chemical Deposition from Air to Soil and Final Soil Concentrations for Combustion-based Management Options

Chemical	Total Deposition: Wet and Dry Particle Phase + Wet and Dry Vapor Phase (g/m^2 yr)		Soil Chemical Concentration from Total Deposition (mg/kg)	
	Open Burning	Air curtain Burning	Open Burning	Air curtain Burning
Arsenic	2.8E-08	5.4E-09	1.3E-12	3.2E-13
Cadmium	4.4E-08	3.6E-08	1.4E-10	1.4E-10
Chromium	4.9E-07	1.7E-07	3.0E-10	1.3E-10
Copper	3.7E-07	1.9E-07	6.9E-10	4.2E-10
Iron	1.4E-04	1.0E-05	4.0E-04	3.3E-05
Lead	4.3E-07	1.7E-07	2.0E-08	9.6E-09
Manganese	1.3E-06	1.3E-05	3.8E-06	4.2E-05
Nickel	3.8E-07	7.8E-08	1.3E-09	3.2E-10
Zinc	2.8E-06	3.1E-06	8.8E-09	1.2E-08
Total Dioxins	4.2E-14	1.4E-12	1.2E-13	5.4E-12
Total PAHs	2.2E-06	5.7E-09	5.4E-06	1.7E-08

Abbreviations: yr = year; PAHs = polycyclic aromatic hydrocarbons.

Table 4.2.2 Estimated Chemical Loading and Final Soil Concentrations for the Composting Management Option

Chemical	Loading to Soil (g/m^2)	Soil Chemical Concentration (mg/kg)
Cadmium	3.9E-04	6.9E-05
Chromium	6.7E-03	2.4E-04
Copper	2.7E-02	2.8E-03
Iron	4.7E-01	7.8E-01
Lead	4.1E-02	4.8E-02
Manganese	9.9E-03	1.6E-02
Nickel	9.8E-03	1.9E-03
Zinc	1.0E-01	1.9E-02

4.3. Groundwater

Estimates of concentrations or amounts of chemicals in groundwater are needed to estimate human exposure from use of well water in the home (e.g., drinking, cooking, and washing). Groundwater concentrations or amounts of chemicals also allow estimation of the contribution of groundwater transport of chemicals to the lake via recharge. The assessment estimates chemical fate and transport in groundwater from the following sources:

- Buried carcasses releasing liquids (leachate) that seeps into soil beneath the burial trench
- Buried combustion ash that leaches chemicals to infiltrating precipitation
- Compost windrows leaking leachate from the carcasses that is not absorbed by the bulking material
- The carcass storage pile releasing leachate to the ground below the pile as early stage decomposition progresses

1.5.1. Leaching from Buried Carcasses

Cell lysis and degradation of tissues starts soon after death. As lysis progresses, free fluids and gases begin to bloat the carcass. Fluids and gases escape via natural orifices and later via the skin once its integrity is lost. The quantity of leachate is highest during the first week or two after burial, depending on the ambient temperature and activity of the native microflora degrading the carcass. Lower quantities of carcass body fluids continue to be released over the first two months (Young et al. 2001).

As stated in Section 3.4.1, for 45,359 kg (50 U.S. tons) of carcasses, approximately 7,500 L of fluid would be released in the first week, another approximately 7,500 L would be released over the next 2 months, and the remaining fluids would leach more slowly, with some influence of ambient precipitation infiltrating the burial trench and contributing to continued leaching. This assessment assumes 60% of the weight of the carcasses, or approximately 27,000 kg, will be leached as fluids during the first year after burial (Young et al. 2001). Assuming the leachate has the same density as water (i.e., 1 kg/L), approximately 27,000 L is expected to be released from the carcasses during the first year after burial.

Many states recommend or mandate minimum depths of unsaturated soil beneath carcass burial pits to protect groundwater quality. These distances are as little as 1 ft (~0.3 m), but are more

typically 3 ft (~1 m) or more (NABCC 2004). Subsurface soils should sorb some of the contaminants. To include "filtering" of chemicals by soil between the burial trench and the groundwater aquifer, and to minimize the need for uncertain site-specific assumptions and highly complex groundwater modeling, a health-protective, screening-level approach is adopted by this project. Specifically, sorption of contaminants from the leachate to the soil is estimated with K_d values, which are chemical-specific soil-water partitioning coefficients. The chemical-specific K_d values are listed in Appendix G, along with further details about estimating leachate from the burial trench to groundwater. No other attenuation or dilution processes are included in the groundwater modeling. Once the leachate plume reaches groundwater, it is assumed to travel horizontally in a constrained aquifer (i.e., a relatively impermeable layer of silt or clay essentially prevents further downward movement of water).

To simulate the filtering of chemicals from the leachate to subsurface soil, it is necessary to calculate the volume and dry weight of soil that would be saturated by the leachate amounts for each time period. These estimates assume soil porosity of 20% and dry soil particle density of 2.7 g/cm^3 (0.098 lb/ft^3), both of which are default assumptions from HHRAP (USEPA 2005a).

Chemical partitioning between soil and leachate was estimated using the K_d equation:

$$K_d = \frac{mg\ [solid\ phase\ contaminant]/kg\ [soil]}{mg\ [aqueous\ phase\ contaminatn/L\ [water]} \qquad \textbf{Eqn. 4.1}$$

For brevity, the equation can be rewritten as:

$$K_d = (mg_s/kg_s)/(mg_a/L_a) \qquad \textbf{Eqn. 4.2}$$

where:

mg_s = mg [solid-phase contaminant]
mg_a = mg [aqueous phase contaminant]
kg_s = kg [soil dry weight]
L_a = L [volume of leachate]

Chemical-specific K_d values, are listed in Appendix G.

After passing through soil, mg_a equals the initial, pre-partitioning mass of chemical available (mg_{init}) minus the amount sorbed to the solid phase (mg_s). For this approach, instant and homogenous equilibrium is assumed between the solid and aqueous phases.

With the assumptions above, the equation above can be rewritten as follows:

$$K_d = (mg_s/kg_s)/((mg_{init} - mg_s)/L_a) \quad \textbf{Eqn. 4.3}$$

The equation above is then solved for mg_s, using the constant assumptions listed above, to estimate the mass of chemical sorbed to soil.

$$mg_s = (K_d * kg_s * mg_{init})/(L_a + K_d * kg_s) \quad \textbf{Eqn. 4.4}$$

The mass of chemical remaining in the leachate after filtering by the soil is then mg_{int} - mg_s. This is the chemical mass that enters the groundwater aquifer upgradient of the drinking water well and on-site lake. Further information on this approach is presented in Appendix G.

1.5.2. Leaching from Buried Combustion Bottom-Ash

Figure 4.3.1 shows the site setting and conceptual approach used to estimate the leaching of chemicals from buried bottom ash to groundwater. Chemical fate and transport in groundwater is modeled using an approach similar to that described above for leaching from buried carcasses. In the ash leaching approach, K_d values estimate the leaching of chemicals from the ash to infiltrating precipitation with each rain event for a one-year period. As the leachate from each rain event moves through the unsaturated zone of subsurface soil beneath the ash, a portion of the chemicals in the leachate are filtered by the soil (i.e., sorb to soil particles) as estimated with K_d values. The leaching calculations are shown in Appendix H.

Leaching from the ash is estimated for a series of rainfalls during the first year after ash burial. At the hypothetical site, there were 168 “precipitation events” in 2014, with at total amount of 38.1 in (96.8 cm) (see Table 4.1.4). The average precipitation for the 168 events is 0.23 in (0.58 cm), and the average precipitation per ground area is 0.14 gal/ft^2 (5.8 L/m^2). This amount is used

to estimate leaching of chemicals from the bottom ash to the water that infiltrates it during each precipitation event.

Leaching calculations also require estimates of the weight of ash per area (i.e., ft^2 or m^2) based on the fuel amounts, combustion efficiencies, and ash placement areas for each combustion-based option. For the open-pyre burning option, the weight of the ash per area is calculated as 3.07 lb/ft^2 (15 kg/m^2). Ash from air-curtain burning occupies a smaller area than that used by the pyre, with a resulting weight per area of 16 lb/ft^2 (78 kg/m^2). See Appendix H for further information about these values.

With each precipitation event, the K_d is applied to the contaminant mass in the ash to estimate the fraction that partitions to the aqueous phase as rainfall percolates through subsurface soils toward groundwater (i.e., "leachate"). The mass that does not partition to the aqueous phase remains in the ash as the contaminant mass available to be carried down via percolation during the next precipitation event.

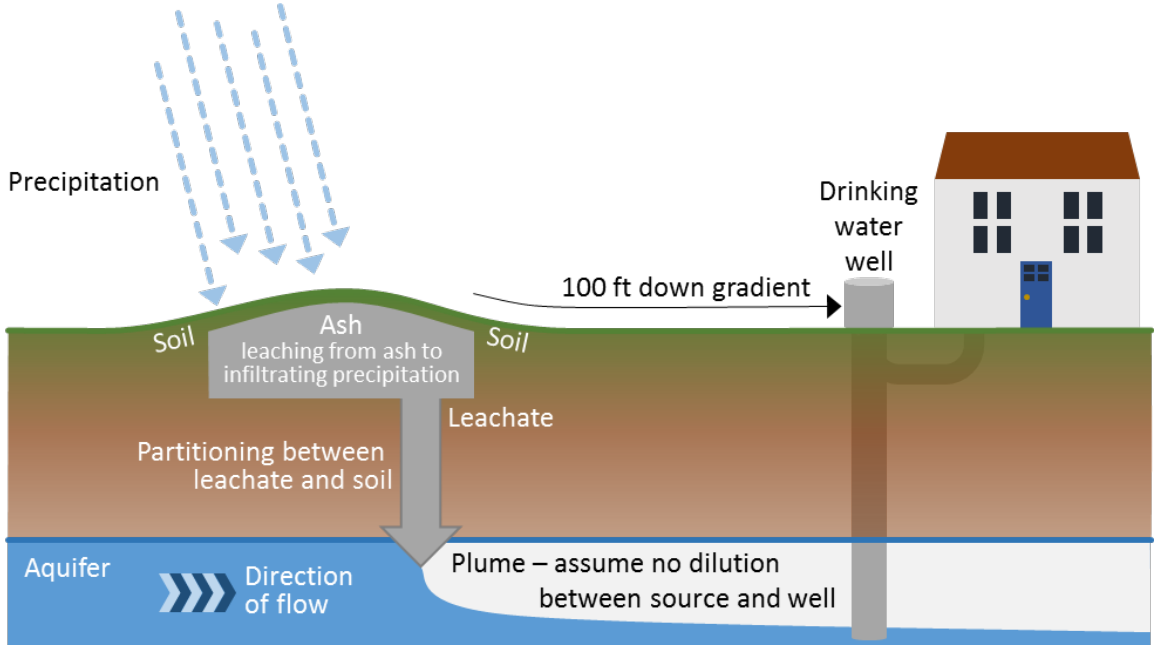


Figure 4.3.1 Modeling scenario for chemical movement from buried combustion ash to groundwater with percolation of water.

Similar to the partitioning approach used for the carcass burial scenario, chemicals carried toward groundwater by rainfall percolating through the ash layer was estimated using Equation 4.2. In this use of the equation, the solid-phase material is ash (i.e., 15 kg of ash for open

burning, 78 kg of ash for air-curtain burning), and the aqueous volume is 5.8 L as discussed above. The assessment assumes that after any loss of chemical in water percolating through the ash, mg_s equals the initial, pre-leaching mass of chemical available (mg_{init}) minus the amount leached to the aqueous phase (mg_a). Equilibrium between the solid and aqueous phases is assumed to occur instantly and homogenously throughout the ash layer.

With the assumptions above, the Equation 4.2 can be rewritten as follows:

$$K_d = (mg_{init} - mg_a \div kg_s)/(mg_a \div L_a) \quad \textbf{Eqn. 4.5}$$

Equation 4.5 is then solved for mg_a, using the assumed constants, to estimate the mass of chemicals carried with water percolating through the ash per rain event.

$$mg_a = (L_a * mg_{init})/(kg_s * K_d + L_a) \quad \textbf{Eqn. 4.6}$$

In addition, Equation 4.4 is used to estimate the amount of chemical adsorbed from the percolating water to soil particles in the unsaturated zone after a precipitation event. For this step, kg_s is the dry weight of soil saturated by the 5.8 L of leachate per m^2. The kg_s value is estimated as 62 kg, using default soil assumptions from HHRAP (USEPA 2005a), specifically a soil porosity of 20% and a dry soil particle density of 2.7 g/cm^3.

Subtracting the amount filtered by soil from the amount carried downward in rainwater percolating through the buried ash yields the amount of chemical that reaches groundwater per precipitation event. For each combustion-based option, this amount is calculated per m^2 of ash area. These amounts are multiplied by the whole ash areas to determine the total amount of chemical leached to groundwater per rain event.

At the end of the first rain event, the amount of chemical reaching the groundwater divided by the initial amount of chemical in the ash is the fraction of chemical "leached" (f_{leach}). The cumulative amount of chemical that reaches the groundwater after all rain events in the first year is calculated with Equation 4.7:

$$mg_{total} = [mg_{init} * (1 - f_{leach})^{RainEvents}] \quad \textbf{Eqn. 4.7}$$

A limitation that causes over-estimation by this approach is the adsorption capacity in subsurface soil layers not being diminished by adsorption during earlier precipitation events. However, because chemicals with a high affinity for binding with solids, including most PAHs and dioxin/furans, move only short distances from buried bottom ash, this limitation is unlikely to be significant for those chemicals. See Appendix H for further details about the approach for estimating chemical leaching from buried bottom ash to groundwater.

1.5.3. Leaching from the Compost Windrow

Livestock compost windrows are constructed with a thick layer of carbon-based bulking material (e.g., wood chips) that absorbs liquids released by the decomposing carcasses. Excess liquid can be released if the bulking material layer is too thin or if the material does not have a sufficient absorptive capacity (e.g., corn husks). The bottom layer of bulking material can absorb precipitation only up to the point of saturation. As discussed in Section 3.5.1, Glanville et al. (2006) and Donaldson et al. (2012) both reported volumes of leachate from experimental compost windrows to not exceed 5% of the precipitation that falls on the windrows. Based on that information, the assessment assumes that only 5% of the volume of fluids released by decomposition will seep into the ground beneath the windrow. Specifically, the volume of leachate released from buried carcasses during the first year (27,000 L) was multiplied by 5% to estimate the approximate volume of fluid released to ground from the windrow (1,350 L).

Average chemical concentrations in leachate from carcass burial during the first year (Table 3.4.5 in Section 3.4.1) are used as the concentrations in the windrow leachate. Sorption of leachate chemicals to soil in the unsaturated zone is estimated with the same K_d partitioning approach used for carcass burial and leaching from buried bottom ash. See Appendix G for further details.

1.5.4. Leaching from the Storage Pile

As a component of all carcass management options, the storage pile releases leachate to the ground beneath it as decomposing carcasses release bodily fluids. The amount of fluid released from the storage pile depends on the time after death. As discussed in Section 3.4.1, Young et al. (2001) provided a basis for estimating the rate of liquid released during the early stages of decomposition. In particular, approximately 7,500 L is expected to leak from the carcasses

during the first week averaging about 1,070 L of liquid leachate per day. In actuality, most of the releases during the first week occur after the abdomen of an animal bursts from gas buildup. According to the workshop experts (Section 2.5), the abdomen in a livestock carcass typically bursts 3 to 4 days after death, with leachate releases occurring 3 to 7 days after death. Before the abdomen bursts, liquid matter unrelated to decomposition (e.g., feces, urine, blood, ingesta, serum, saliva) can be released (UM-CAHFS 2014). Because liquids could be released at varying but unknown rates throughout the first post-mortem week, the total amount released during the first week is averaged to calculate a daily rate.

The methods used to estimate leaching to groundwater from the storage pile are based on the methods described above to estimate leaching from the burial trench. Chemical concentrations in the storage pile leachate are assumed to be the same as the concentrations in leachate from buried carcasses over the first week (Table 3.4.5 in Section 3.4.1), and the K_d partitioning approach estimates the amount of leachate chemicals "filtered" by soil in the unsaturated zone. The leachate chemicals not sorbed to soil particles enter the aquifer undiluted by water from precipitation. The next section describes how the assessment uses this information to evaluate potential chemical concentrations in drinking water. See Appendix G for further details.

1.5.5. Interception of Groundwater By Well

This section describes how leaching from the buried carcasses, buried combustion ash, the compost windrow, and the carcass storage pile have the potential to contribute to concentrations of chemicals in drinking water. The above sections (4.3.1 through 4.3.4) describe how the assessment estimates chemical mass leached from these sources to the aquifer. To then estimate how much of the chemical mass reaches a down-gradient drinking water well, the assessment considers the proportion of the contaminated plume intercepted by the well. To do this, the amount reaching the aquifer is multiplied by the percent of the contaminated plume intercepted by the well, to calculate an interception fraction. The well's interception fractions are calculated by dividing the well diameter by the horizontal width of the contaminant plume in the aquifer, which, in turn, is equal to the width of the leachate source. This approach assumes the long side of each source is perpendicular to the direction of groundwater flow, and that the plume does not disperse horizontally over the relatively short distance between the source and the well (assumed as 30.5 m or 100 ft). Figure 4.3.2 shows the conceptual configuration of this approach for

estimating the quantity of chemicals in leachate that reach the well downgradient from the burial trench.

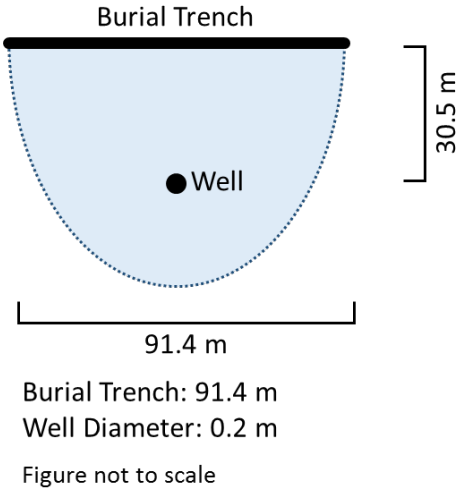


Figure 4.3.2. Well interception of leachate plume from burial trench.

The assumed plume widths are:

- **Burial** – The burial trench is 2.4 m wide by 91.4 m long, and is sited with the long dimension perpendicular to the direction of groundwater flow. The width of the plume equals the length of the trench, 91.4 m.
- **Open burning** – The length of the disposal area equals the length of the pyre, or 91.4 m because ash is buried in place. The width of the groundwater plume also equals this distance.
- **Air-curtain burning** – Ash is buried in a pit measuring 3.6 m by 11.4 m. Using the long edge of the disposal area as the width of the plume, the width of the plume is 11.4 m.
- **Composting** – The width of the groundwater plume equals the length of the compost windrow, 61 m. The composting scenario includes two windrows of the same length. These are assumed to be parallel and perpendicular to the direction of groundwater flow, with both windrows contributing equally to the groundwater leaching. For the purpose of fate and transport modeling, the two windrows are treated as a single source.
- **Storage pile** – The storage pile measures 2.4 m wide by 40.3 m long. The long edge is used as the assumed width of the groundwater plume (40.3 m).

Well interception fractions are calculated using a "typical" standard well size identified from recommendations by the Indiana State Department of Health.12 Indiana recommends that all wells should be encased (and water tight) for at least 25 ft (7.62 m) below the ground surface. The inner pipe diameter can range from 5–10 in (12.7–24.5 cm). Based on this information, the well is assumed to have an 8 in (0.20 m) well pipe diameter. The vertical distance over which the well screening/packed gravel intercepts groundwater or an aquifer depends on desired flow rates; this project assumes the entire depth of the confined groundwater or aquifer can intercept water to be pumped to the surface. Table 4.3.1 shows the calculated well interception fractions.

Table 4.3.1. Summary of Calculations for Groundwater Well Intercept Fraction

Source	Well Diameter (m)	Plume Width (m)	Groundwater Well Intercept Fraction
Burial Trench	0.2	91.4	0.0022
Burial of Ash from Open Burning	0.2	91.4	0.0022
Burial of Ash from Air curtain Burning	0.2	11.4	0.0180
Composting Windrow	0.2	61	0.0033
Carcass Storage Pile	0.2	40.3	0.0050

To estimate the potential for flowing groundwater to dilute chemicals that are intercepted by the well, the assessment assumes water from the well provides the farm the average quantity of water used per household in the United States. An average U.S. household uses more than 300 gal (1,136 L) per day.[13] Chemical concentrations in drinking water are estimated by first multiplying the chemical mass leached per time period (i.e., 1 day, 1 week, 60 days, 1 year), discussed above, by the intercept factions, and then dividing the mass of chemical intercepted by the amount of water withdrawn over the same time periods.

For the burial option, the assessment estimates average concentrations of chemicals in drinking water for the first week, the first two months, and the first year following burial (Table 4.3.2).

[12] http://www.in.gov/isdh/23258.htm#C1
[13] https://www3.epa.gov/watersense/our_water/water_use_today.html

Table 4.3.2. Estimated Concentrations of Chemicals Leaching from Buried Carcasses That Might Reach On-siteDrinking Water Well

Chemical Species	Concentration in Drinking Water(mg/L), 0.20 m Diameter Well Drawing 1,136 L/d		
	1st week	1st 60 days	1st year
Aluminum	6.0E-08	2.4E-08	5.5E-09
Ammonium[a]	1.6E+00	9.8E-01	6.1E-01
Barium	3.9E-07	2.8E-07	5.6E-08
Beryllium	nd	nd	nd
Bicarbonate	5.2E+01	1.6E+01	6.1E+00
Boron	nd	1.0E-04	3.7E-05
Cadmium	nd	nd	nd
Calcium	1.9E-02	4.7E-03	2.1E-03
Chloride	8.2E-01	3.3E-01	1.4E-01
Chromium	nd	nd	nd
Cobalt	1.2E-07	nd	1.2E-09
Copper	7.4E-08	5.2E-08	2.4E-08
Inorganic Carbon	1.4E+01	3.8E+00	1.3E+00
Organic Carbon	8.9E+01	2.2E+01	8.0E+00
Iron	9.0E-05	2.5E-05	6.6E-06
Lead	nd	nd	nd
Magnesium	9.4E-03	3.0E-03	1.1E-03
Manganese	4.1E-07	1.5E-07	5.5E-08
Molybdenum	5.7E-04	8.5E-05	1.0E-05
Nickel	3.3E-07	9.5E-08	1.3E-08
Nitrate/nitrite[a]	7.2E-03	1.7E-03	3.3E-04
Total Nitrogen	3.8E+01	7.3E+00	2.6E+00
Phosphorus	2.9E-01	1.5E-01	6.6E-02
Potassium	6.0E-01	2.6E-01	1.2E-01
Silicon[b]	9.1E-03	3.4E-03	1.3E-03
Sodium	5.0E-01	2.7E-01	1.1E-01
Strontium	2.2E-04	5.5E-05	1.6E-05
Sulfate	2.3E+00	1.1E+00	4.3E-01
Sulphur	3.8E-01	2.0E-01	9.4E-02
Titanium	6.3E-05	nd	4.7E-07
Zinc	3.0E-06	1.5E-06	5.6E-07
Zirconium	6.3E-05	nd	4.7E-07

Abbreviations: nd = not detected; d = day.
[a] As nitrogen (N). [b] Soluble silicon.

This corresponds to the time intervals of Pratt and Fonstad (2009). Estimates of drinking water exposures are based only on the first year (i.e., leaching in the first year following carcass management).The total chemical mass intercepted by the well on a daily basis from this release is divided by the total annual water use and the number of days per year (i.e., 1,136 L/d x 365 d). For chemical releases from buried ash and the compost windrows, the total mass of chemical

intercepted by the well is divided by the total water withdrawn per year for average annual concentrations (Tables 4.3.3 and 4.3.4). For the storage pile, the amounts of chemicals leached to groundwater are calculated as two days' worth of release at concentrations reported by Pratt and Fonstad (2009) for the first week. The chemical amounts intercepted by the well are then divided by the total annual water use (Table 4.3.4). See Appendix G and Appendix H for further details about these calculations.

Table 4.3.3. Estimated Concentrations of Chemicals Leaching from Buried Ash That Might Reach On-site Drinking Water Well

Chemical Species	Concentrations in Drinking Water (mg/L) Typical Well (0.20 m Diameter and Drawing 1,136 L/d)	
	Open Burning	Air curtain Burning
Arsenic	4.8E-08	8.5E-08
Cadmium	7.7E-09	5.7E-09
Chromium	8.6E-06	1.4E-05
Copper	2.3E-08	2.8E-08
Iron	7.3E-05	8.0E-05
Lead	3.4E-10	6.0E-09
Manganese	4.0E-05	7.0E-05
Nickel	2.9E-07	3.8E-07
Zinc	1.8E-06	6.1E-06
Total Dioxins	3.1E-21	5.5E-21
Total PAHs	8.5E-12	2.2E-11

Abbreviations: d = day; PAHs = polycyclic aromatic hydrocarbon.

Table 4.3.4. Estimated Concentrations of Chemicals in Leachate fom a Carcass Storage Pile or a Composting Windrow that Might Reach On-site Drinking Water Well from Compost and Storage Pile

Chemical Species	Concentrations in Drinking Water (mg/L) Typical Well (0.20 m Diameter and Drawing 1,136 L/d)	
	Compost Windrow	Carcass Storage Pile
Aluminum	4.1E-10	2.7E-09
Ammonium[a]	4.6E-02	5.2E-02
Barium	4.2E-09	1.7E-08
Bicarbonate	4.6E-01	8.1E-01
Boron	2.8E-06	nd
Calcium	1.6E-04	6.0E-04
Chloride	1.0E-02	2.6E-02
Cobalt	9.1E-11	5.3E-09
Copper	1.8E-09	3.3E-09
Inorganic Carbon	9.9E-02	1.8E-01
Organic Carbon	6.0E-01	1.1E+00
Iron	4.9E-07	4.0E-06
Magnesium	7.9E-05	3.0E-04
Manganese	4.1E-09	1.8E-08
Molybdenum	7.6E-07	1.8E-05
Nickel	9.9E-10	1.5E-08
Nitrate/nitrite[a]	2.5E-05	2.3E-04
Total Nitrogen	2.0E-01	4.7E-01
Phosphorus	4.9E-03	9.3E-03
Potassium	8.7E-03	1.9E-02
Silicon[b]	1.0E-04	2.9E-04
Sodium	8.5E-03	1.6E-02
Strontium	1.2E-06	7.0E-06
Sulfate	3.2E-02	5.7E-02
Sulphur	7.0E-03	1.2E-02
Titanium	3.5E-08	2.0E-06
Zinc	4.2E-08	1.3E-07
Zirconium	3.5E-08	2.0E-06

Abbreviations: nd = not detected; d = day.

Note: Pratt and Fonstad (2009) also analyzed leachate for beryllium, cadmium, chromium, and lead, but those elements could not be detected. They did not sample the leachate for arsenic; iron is likely to remain chelated, and so would not be free to leach from the windrow or pile.

[a] As nitrogen (N).

[b] Soluble silicon.

4.4. Surface Waters and Sediment

As described in Section 2.3.3, the hypothetical site for the assessment includes an on-site lake. None of the on-site management options directly release chemicals to the lake, but chemicals could be transported to the lake by one or more processes:

- Wet and dry deposition of particles with sorbed chemicals from air (following combustion)
- Diffusive exchange of vapor-phase chemicals between the air and surface water
- Runoff and erosion of chemicals from surface soils into the surface water
- Groundwater flow into the lake from the sediment bed

The first three of these processes are modeled using HHRAP equations and default assumptions for chemicals associated with each of the carcass management options (see Section 5 and Equation 5-35 in USEPA, 2005a). The HHRAP approach to estimating concentrations of chemicals in surface water includes three abiotic loss processes: volatilization, hydraulic turnover or flushing, and sediment burial. Appendix E and USEPA (2005a) summarize the methods and assumptions for the modeling the surface water and sediment compartments. There is no net diffusion of vapor-phase chemicals expected from air to surface water. The assessment assumes vapor-phase chemicals deposited to the lake in precipitation are revolatilized to air. Chemicals deposited to the soil from air-borne contaminants after combustion-based options may runoff and erode to surface waters.

The HHRAP SSW models runoff and erosion processes, in addition to the fate of chemicals in the water column and sediment bed. Appendix E documents the HHRAP SSW Model, and Appendix F documents the selected parameter values and their sources. HHRAP does not include equations to simulate recharge from groundwater to surface water. Options to include this process include: (1) select a groundwater model capable of simulating flux from groundwater to surface water; (2) develop a simplified estimation method to “bound” the possible maximum loadings; and (3) exclude this pathway from the quantitative assessment. The assessment chose the second option to estimate groundwater loading to surface water, with the chemicals and nutrients carried in the groundwater.

The simplified method to estimate groundwater recharge to surface is applied for the burial option, leaching from combustion ash, and leaching from the compost windrow and the carcass

storage pile. As described in Section 4.3, the groundwater modeling methods include a step that estimates the total amount (i.e., in milligrams in the first year following carcass management) of each chemical that reaches the groundwater aquifer. Recharge to the lake is estimated by assuming the total chemical quantities that reach groundwater, minus the mass drawn by the drinking water well, eventually reaches the lake. Because it will take time for groundwater to travel from the source to the lake, the chemicals in groundwater do not necessarily enter the lake in the first year after carcass management. However, the analysis assumes that all chemicals discharge from groundwater to the lake occurs within a 12-month period. The amounts reaching the lake are divided by the volume of the lake to estimate concentrations of each chemical in the lake water. This approach is conservative (i.e., overestimates chemical concentrations in the lake) because it assumes the entire plume in a confined groundwater aquifer reaches the lake, that it all reaches the lake within one a one-year period (might be a year following the start of leaching), and that all of the chemical flowing into the lake in the year remains in the water column (i.e., there is no outflow from the lake and chemicals that made it to groundwater do not precipitate out or sorb to suspended sediments and settle to the bottom). The calculations for this approach are provided in Appendix I.

The volume of the 40.5 ha (100 ac) lake is calculated by multiplying the surface area (40.5 ha = 404,686 m^2) by the average depth (4.38 m, see Section 2.3.3). The resulting volume is 1.8E+06 m^3, which equals 1.8E+09 L. As discussed in Section 2.3.3, a smaller (i.e., 4.05 ha or 10 ac) lake is also included in the assessment to evaluate the effect of the assumed lake size. With its average depth of 3.02 m, the volume of the smaller lake is 1.2E+05 m^3 or 1.2E+08 L.

When combined, the chemical loadings to the 40.5 ha lake from all of the processes listed at the top of this section are summed to estimate the concentrations in surface water (i.e., in the on-site lake) shown in Table 4.4.1. No estimate is shown when data are unavailable or no pathways exist for the chemical of interest. For example, PAHs and dioxins, which are products of combustion, are not included in the surface water concentration estimates for the composting and burial options.

In Table 4.4.1, the surface water concentrations for the composting option are presented separately for leaching from the compost windrow and runoff/erosion following application of the finished compost to soil. These contributions are presented separately because the sources

represent distinct activities and occur at different locations and times on-site. Therefore, decisions about the management of each compost activity can be made independent of the other activity.

To evaluate the effect of the assumed lake size on the chemical concentrations in surface water, Table 4.4.2 compares chemical concentrations in the large and small lakes (40.5 and 4.05 ha, respectively) for the burial management option. The concentrations in the small lake are approximately 14.5 times greater than in the large lake. Both lake sizes are large enough to intersect the entire plume area (i.e., the widest extent of the plume is narrower than the square root of the lake area).

Table 4.4.1 Estimated Total Concentrations of Chemicals in Surface Water

Chemical Species	Concentrations in Surface Water (µg/L), Large Lake (40.5 ha)					
	Storage Pile	Open Burning	Air curtain Burning	Burial	Composting Windrow	Compost Application
Total Toxic Dioxins/furans	na	9.3E-13	3.2E-11	na	na	na
Total PAHs	na	2.0E-04	4.7E-07	na	na	na
Arsenic	na	2.3E-04	4.3E-05	na	na	na
Cadmium	na	1.4E-04	1.1E-04	na	na	1.9E-03
Chromium	na	6.1E-03	2.1E-03	na	na	6.3E-02
Copper	1.6E-10	2.6E-03	1.3E-03	2.5E-09	1.3E-10	2.6E-01
Iron	1.9E-07	1.4E+00	1.0E-01	7.1E-07	3.5E-08	1.3E+02
Lead	na	1.2E-04	4.5E-05	na	na	5.9E-02
Manganese	8.6E-10	5.0E-03	4.9E-02	5.8E-09	2.9E-10	5.6E-01
Nickel	6.9E-10	1.4E-03	2.8E-04	1.4E-09	7.1E-11	6.3E-02
Zinc	6.3E-09	1.1E-02	1.2E-02	6.0E-08	3.0E-09	6.8E-01
Ammonium	2.5E-03	na	na	6.6E-02	3.3E-03	na
Chloride	1.2E-03	na	na	1.5E-02	7.4E-04	na
Phosphorus	4.4E-04	na	na	7.0E-03	3.5E-04	na
Potassium	9.0E-04	na	na	1.2E-02	6.2E-04	na
Sodium	7.6E-04	na	na	1.2E-02	6.0E-04	na
Sulfate	2.7E-03	na	na	4.6E-02	2.3E-03	na
Sulphur	5.7E-04	na	na	1.0E-02	5.0E-04	na
Total Nitrogen	2.2E-02	na	na	2.8E-01	1.4E-02	na

Abbreviations: ha = hectares; na = not assessed; PAHs = polycyclic aromatic hydrocarbons.

Table 4.4.2. Effect of Lake Size on Estimated Concentrations of Chemicals in Surface Water – Burial Option

Chemical Species	Concentrations in Surface Water (µg/L)			
	Burial Option	Large Lake (40.5 ha)	Burial Option	Small Lake (4.05 ha)
Total Dioxins/furans[a]	na		na	
Total PAHs[a]	na		na	
Copper	2.5E-09		3.7E-08	
Iron	7.1E-07		1.0E-05	
Manganese	5.9E-09		8.5E-08	
Nickel	1.4E-09		2.1E-08	
Zinc	6.0E-08		8.7E-07	
Ammonium	6.6E-02		9.5E-01	
Chloride	1.5E-02		2.2E-01	
Phosphorus	7.0E-03		1.0E-01	
Potassium	1.2E-02		1.8E-01	
Sodium	1.2E-02		1.8E-01	
Sulfate	4.6E-02		6.7E-01	
Sulphur	1.0E-02		1.5E-01	
Total Nitrogen	2.8E-01		4.0E+00	

Abbreviations: ha = hectares; na = not assessed; PAHs = polycyclic aromatic hydrocarbons.
a Dioxins, furans, and PAHs are not in carcasses buried or composted; these are produced by pyrolysis in combustion-based carcass management options. Therefore, they are not assessed for the burial option.

4.5. Bioaccumulation in Fish

Concentrations of chemicals in aquatic animals in the on-site lake allow estimation of human exposures from consuming fish caught from the lake. Although fish ingestion exposures are included in the conceptual models for all four on-site carcass management options, the sources of chemicals to the aquatic food web differ. For the combustion-based options, chemicals reach the lake through deposition from air, runoff and erosion from soil, and possibly recharge to the lake from groundwater. For the burial option, chemicals can only reach the lake through groundwater recharge to the lake. Composting could add chemicals to the lake from (a) surface runoff and erosion, and (b) the 5% of rainwater that percolates through the windrow to the soil beneath that is not absorbed by woodchips surrounding the carcasses. All management options include the on-site storage pile, where liquids can leach downward into the soil toward groundwater, which might recharge into the lake.

Estimating concentrations of chemicals in the aquatic food web begins with the estimated concentrations in surface water and sediment (see in Section 4.4). Partitioning of chemicals

between the surface water and sediment compartments is modeled with HHRAP (USEPA 2005a) methods built into the HHRAP SSW Excel model (Appendix E). Two phases are included in each of two compartments: (1a) chemicals dissolved in the water column, (1b) chemicals sorbed to suspended sediment particles; (2a) chemicals dissolved in the sediment bed pore water, and (2b) chemicals sorbed to sediment particles.

Concentrations of chemicals in fish are estimated by modeling direct uptake through the gills from surface water and by ingestion of contaminated prey or foods in sediments and in the water column. Separate aquatic food web modeling approaches are required for organic and inorganic chemicals. Bioaccumulation of nonionic organic chemicals is modeled with AQUAWEB, a steady-state solution model of aquatic bioaccumulation created by Arnot and Gobas (2004) and available for downloading from Arnot Research & Consulting.[14] The biokinetic approach in AQUAWEB includes rate constants to model chemical uptake through gills and by consumption in food, possible metabolism (e.g., fish metabolize PAHs), and elimination by organisms in the food web. In addition to the water and sediment concentrations described above, the model requires environmental setting inputs including:

- average annual water temperature
- dissolved organic carbon content
- particulate organic carbon content
- total suspended solids
- sediment organic carbon content

AQUAWEB requires assumptions about the species composition of the aquatic community and, for each species and size or age class of animal included in a food web, default values for the diet, body size, fraction lipid, and fraction of pore water ventilated. This assessment uses values developed to represent small lakes in Minnesota (e.g., 40.5 ha, see Appendix J).

AQUAWEB is not designed to model the behavior of inorganic chemicals, including metals, in aquatic food webs. For metals included in the assessment (see Section 2.4.1), bioaccumulation to fish is estimated using previously-published empirical bioaccumulation factors (BAFs) (see Appendix J). The BAF approach does not include explicit accumulation through algae,

[14] Further information and model download are available at: http://www.arnotresearch.com/index.html#!/page_AQUAWEB.

zooplankton, and planktivorous fish. Those intermediate transfers through the food web are implicit in field- or microcosm-measured bioaccumulation (i.e., measured fish tissue concentrations divided by dissolved concentrations in water). This assessment assumes livestock carcasses and combustion fuels contain natural concentrations of metals (e.g., iron, copper) that are either in organic compounds or as oxides or metallic ions depending on the carcass management option.

Table 4.5.1 shows the fish tissue concentrations estimated with the methods described above. These concentrations lead to estimates of chemical exposure from fishing by the farm residents.

1.1. Terrestrial Plants and Livestock

The concentration of chemicals in plants and livestock grown at the hypothetical farm are modeled to estimate human exposure for those consuming home-grown food products. Concentrations of chemicals in farm-grown plants and livestock are estimated with an existing Excel-based computer model called the Multimedia Ingestion Risk Calculator (MIRC), which uses equations and default assumptions from HHRAP (USEPA 2005a). For documentation of MIRC, including input parameter values, see Appendix K. Detailed documentation of the relevant HHRAP methods and default assumptions is available in USEPA (2005a).

MIRC was developed for USEPA's Office of Air Quality Planning and Standards (OAQPS) to provide screening-level estimates of multimedia chemical exposures and risks associated with subsistence and recreational farmers in the vicinity of a source of chemical emissions to air and those associated with subsistence or sport anglers fishing from a contaminated lake. MIRC complies with USEPA guidelines for exposure and risk assessment, including the *Human Health Risk Assessment Protocol* (USEPA 2005a), the Agency's 2005 *Guidelines for Carcinogen Risk Assessment* (Cancer Guidelines, USEPA 2005b), *Guidance on Selecting Age Groups for Monitoring and Assessing Childhood Exposures to Environmental Contaminants* (USEPA 2005c), *Supplemental Guidance for Assessing Susceptibility from Early-Life Exposure to Carcinogens* (Supplemental Guidance, USEPA 2005d), along with implementation memoranda (USEPA 2005e, 2006), and the Agency's *Child-Specific Exposure Factors Handbook* (USEPA 2008). In addition, MIRC itself is a component of USEPA's overall approach to assessing residual (i.e., post-regulatory) risk for sources of hazardous air pollutants (HAPs) regulated under the CAA, an approach that has been reviewed by USEPA's Science Advisory Board.

Table 4.5.1. Estimated Chemical Concentrations in Fish from the On-site Lake

Chemical Species	Estimated Concentration in Trophic Level 3 and 4 Fish (mg/kg)[a]											
	Storage Pile		Open Burning		Air curtain Burning		Burial		Compost Windrow		Compost Application	
	T3	T4	T3	T4	T3	T4	T3	T4	T3	T4	T3	T4
Total Dioxins/furans	na	na	6.3E-12	4.1E-12	1.0E-09	5.7E-10	na	na	na	na	na	na
Total PAHs	na	na	6.2E-05	8.3E-05	1.3E-07	1.8E-07	na	na	na	na	na	na
Arsenic	na	na	3.9E-06	3.9E-06	7.3E-07	7.3E-07	na	na	na	na	na	na
Cadmium	na	na	5.8E-06	5.8E-06	4.6E-06	4.6E-06	na	na	na	na	7.5E-05	7.5E-05
Chromium	na	na	1.4E-03	1.4E-03	4.7E-04	4.7E-04	na	na	na	na	1.4E-02	1.4E-02
Copper	2.3E-11	2.3E-11	3.9E-04	3.9E-04	1.9E-04	1.9E-04	3.8E-10	3.8E-10	1.9E-11	1.9E-11	3.9E-02	3.9E-02
Iron	2.3E-08	2.3E-08	1.7E-01	1.7E-01	1.2E-02	1.2E-02	8.5E-08	8.5E-08	4.2E-09	4.2E-09	1.5E+01	1.5E+01
Lead	na	na	2.4E-06	2.4E-06	9.0E-07	9.0E-07	na	na	na	na	1.2E-03	1.2E-03
Manganese	2.6E-11	2.6E-11	1.5E-04	1.5E-04	1.5E-03	1.5E-03	1.8E-10	1.8E-10	8.8E-12	8.8E-12	1.7E-02	1.7E-02
Nickel	1.4E-11	1.4E-11	2.9E-05	2.9E-05	5.7E-06	5.7E-06	2.8E-11	2.8E-11	1.4E-12	1.4E-12	1.3E-03	1.3E-03
Zinc	1.5E-09	1.5E-09	2.5E-03	2.5E-03	2.7E-03	2.7E-03	1.4E-08	1.4E-08	6.9E-10	6.9E-10	1.6E-01	1.6E-01

Abbreviations: na = not assessed; PAHs = polycyclic aromatic hydrocarbons.

[a] Trophic level 4 (T4): top predatory fish in water column (e.g., walleye, northern pike); Trophic level 3 (T3): “pan” fish (e.g., bluegill, yellow perch).

MIRC assesses human exposure via ingestion pathways, including drinking water consumption, incidental soil ingestion, fish ingestion, and ingestion of ten types of agricultural products: exposed fruits, protected fruits, exposed vegetables, protected vegetables, root vegetables, beef, total dairy, pork, poultry, and eggs. For fruits and vegetables, the terms "exposed" and "protected" refer to whether the edible portion of the plant is exposed to the atmosphere.

The inputs to MIRC include chemical concentration and deposition rates:

- Total concentration of the chemical in the air
- Fraction of the chemical in the air in the vapor-phase
- Wet and dry deposition rates for particle-phase chemical
- Concentration of the chemical in drinking water
- Concentration of the chemical in soil
- Concentration of the chemical in upper trophic-level fish

Methods for estimating each of these inputs are described in previous sections.

Inputs to MIRC also include assumptions about the potentially exposed adults and children, the exposure scenario (e.g., which foods are eaten and at what rate), and chemical-specific parameters values. Built into MIRC are exposure factors for six age groups to allow use of age-group-specific body weights, ingestion rates, food preferences, and susceptibility to toxic effects. For most exposure factors and age-groups, MIRC can use mean or 50^{th}, 90^{th}, 95^{th}, and 99^{th} percentile values (only one value per factor or parameter). Mean exposure factor values are used in this assessment, because means are additive and multiplicative and higher percentiles are much less certain that mean values. Moreover, this assessment estimates relative risks among carcass management options, not absolute risks for most exposed individuals. Most default exposure factor values in MIRC are from USEPA's *Exposure Factors Handbook* (EFH; USEPA 2011) and its *Child-Specific Exposure Factors Handbook* (CSEFH; USEPA 2008). For the specific exposure factor values in this assessment see Appendix K.

MIRC requires chemical-specific parameter values as inputs including empirical partitioning and biotransfer factors (e.g., soil-water partition coefficients, soil-to-plant biotransfer factors). Values for most of the parameters in MIRC are from a chemical database developed by USEPA for use with HHRAP. For parameter values in this assessment and their sources, see Appendix K.

1.1.1. Terrestrial Plants

With the HHRAP methods built into MIRC, produce (vegetables and fruits) can be contaminated directly by deposition of airborne chemicals to foliage and fruits or indirectly by uptake of chemicals in soil. Given those two pathways, produce is divided into two main groups: aboveground and belowground. Aboveground produce is divided into fruits and vegetables. As described above, those groups are further subdivided into "exposed" and "protected" depending on whether the edible portion of the plant is exposed to the atmosphere or is protected by a husk, hull, or other outer covering. These pathways are summarized in Table 4.6.1.

The methods used to estimate exposure concentrations in produce for human consumption are also used to estimate concentrations in forage, silage, and grain grown on-site for livestock feed. Concentration estimates provided by HHRAP include wet-weight (ww) concentrations (mg/kg) of each chemical in exposed vegetables, protected vegetables, exposed fruits, protected fruits, and roots. Dry-weight (dw) concentration estimates are provided as well for above-ground produce.

Table 4.6.1. Chemical Transfer Pathways for Produce

Farm Food Media		Chemical Transfer Pathways
Aboveground Produce	▪ Exposed fruits and vegetables	▪ Direct deposition from air of particle-bound chemical (generally washed off) ▪ Air-to-plant transfer of vapor phase chemical ▪ Root uptake from soil
	▪ Protected fruits and vegetables (e.g., grains, peas)	▪ Root uptake from soil
Belowground Produce	▪ Root vegetables (e.g., onions, potatoes)	▪ Root uptake from soil

MIRC provides concentration estimates for each chemical and each food source. These results lead to estimates of the combined ingestion exposure from eating produce (see Section 5.3.2).

1.1.2. Livestock

Concentrations of chemicals are estimated in livestock products, including beef and dairy products, pork, and poultry and eggs. Note that the HHRAP methods used to model livestock did not include inhalation of vapor-phase and particulate contaminants by livestock or use of well water for watering livestock.

Chemical concentrations in animal products are estimated based on the amount of chemical consumed by each animal group through each type of feed and incidental ingestion of soil for ground-foraging animals. Table 4.6.2 summarizes the pathways by which chemicals are transferred to the farm-raised animal food products. Beef and dairy cattle consume three plant feeds (i.e., forage, silage, and grain), while pigs consume only silage and grain, and chickens consume only grain. These feed products are grown on-site and might contain chemicals.

Incidental ingestion of chemicals in soils by livestock during grazing or consumption of feed placed on the ground is estimated for the combustion-based management options using empirical soil ingestion rates and a soil bioavailability factor for livestock. The default value for that factor, which is used for the exposure assessment, for all chemicals is 1.0 (i.e., the chemical in soil is assumed to be 100% bioavailable to the animal).

HHRAP calculates chemical ingestion by livestock so that chemical concentrations in human food products can be estimated, not to estimate risks to the livestock animals. The relevant estimates provided by HHRAP are mg chemical per kg fresh or ww product. Concentrations are estimated separately for beef, total dairy, pork, poultry, and eggs. These results, for each management option and chemical, are used to estimate ingestion exposure from food. Those estimates are presented in Section 5.

Table 4.6.2. Chemical Transfer Pathways for Livestock

Farm Food Media		Chemical Transfer Pathways
Animal Products	▪ Beef and total dairy (including milk)	▪ Ingestion of forage, silage, and grain[a] ▪ Incidental soil ingestion
	▪ Pork	▪ Ingestion of silage and grain[a] ▪ Incidental soil ingestion
	▪ Poultry and eggs	▪ Ingestion of grain[a] ▪ Incidental soil ingestion

[a] Chemical concentrations in forage, silage, and grain are estimated via intermediate calculations analogous to those used for aboveground produce.

5. Exposure Estimation for Chemicals

This section describes how chemical concentrations in the environment and in food are used to estimate exposures of adults and children at the farm. In Section 7, these estimates are compared to toxicity benchmarks to normalize the exposures to the inherent toxicity of the chemicals to allow comparison of the livestock carcass management options. This section also uses chemical concentrations in the environment to discuss exposures to livestock and wildlife.

For humans, adults and children can be exposed via inhalation and ingestion. Inhalation exposure is included only in the combustion-based management options and only for the duration of the burn. Exposure concentrations (i.e., mg chemical/m^3 air) are estimated as event-average concentrations for the 48-hr combustion events. Ingestion exposure is evaluated for a one-year period starting with the beginning of the carcass management. Sources of ingestion exposure include drinking water; fish caught in the on-site lake; and home-grown fruits, vegetables, and livestock products. For both inhalation and ingestion, exposure factors (e.g., body weight, ingestion rates) used in the assessment were mean values obtained from the most recent version of USEPA's *Exposure Factors Handbook* (USEPA 2011), its *Child-specific Exposure Factors Handbook* (USEPA 2008), and its *Child-Specific Exposure Scenarios Examples* (USEPA 2014b).

Section 5.1 summarizes the exposure pathways included in the chemical exposure assessment. Section 5.2 describes the approach to characterizing the human receptors for the purpose of ranking management options by potential exposures. Section 5.3 presents the chemical exposure estimates for each of the management options included in the quantitative human exposure assessment. Section 5.4 summarizes the livestock and environmental exposure estimates expressed as environmental concentrations.

5.1. Summary of Chemical Exposure Pathways for Humans

Table 5.1.1 summarizes pathways of human exposure to chemicals included in the exposure assessment. Pathways within the scope of the assessment were first defined in Section 3 of this report. Exposures are estimated for some, but not all of those pathways. Pathways with estimated exposures are indicated with bold type and footnote "a" in Table 5.1.1.

Pathways for which exposures are not estimated are indicated by footnotes "b" and "c" in Table 5.1.1. Footnote "b" denotes exposure pathways assumed to be negligible reasons discussed below.

Footnote "c" denotes exposures that are not estimated because of applicable environmental and worker safety regulations and guidelines. For example, the assumed use of PPE, including gloves, by workers would limit incidental ingestion and direct dermal contact with carcasses, carcass fluids, and media contaminated by spills, or other contact with carcass materials. In addition, exposure pathways for the off-site management options are not estimated because releases to the environment from those options are limited by pollution control systems that are assumed to operate within permitted levels (see Section 2.1).

Exposure pathways indicated by footnote "b" in Table 5.1.1 include the pathways not quantified for reasons described below. The reasons and specific pathways are listed for each exposure source row in the Table 5.1.1:

- **Inhalation** – As discussed in Sections 3.4 and 3.5.2, gases such as ammonia and hydrogen sulfide diffuse passively from windrows and closed burial trenches. The odors often stimulate people to rapidly leave areas where these gases are diffusing, creating a behaviorally-induced reduction in exposure. The relatively slow rate of release, high dilution by the atmosphere, and limited exposure periods (i.e., minutes to hours) preclude these gases from reaching concentrations that might be hazardous to humans. Trucks that haul carcasses from the temporary storage location to the carcass management site also release chemicals into the air. Inhalation exposures from transportation of carcasses are negligible because of atmospheric dilution and very short periods for passing vehicles. These reasons for not evaluating inhalation exposures apply to five pathways in Table 5.1.1:
  - Carcass handling, exposure pathway number 1
  - Temporary carcass storage, exposure pathway number 1
  - Carcass transportation, exposure pathway number 1
  - Burial, exposure pathway number 1
  - Composting, exposure pathway number 1

Pathways with inhalation of aerosolized well water by humans (e.g., while showering) are not quantified because those pathways are assumed to be insignificant compared with ingestion of drinking water. Four pathways listed in Table 5.1.1 are not assessed for inhalation of aerosolized well water:

- Temporary carcass storage, exposure pathway number 2
- Open burning and air-curtain burning, exposure pathway number 2
- Burial, exposure pathway number 2
- Composting, exposure pathway number 2

- **Incidental ingestion** – Hand-to-mouth contact followed by ingestion could occur whenever workers and farm residents touch carcasses, leachate, or contaminated soil, and subsequently touch their mouths. For workers, this risk is avoided by the assumed appropriate use (and cleaning and storage) of gloves and other PPE. Farm residents are unlikely to be near the combustion site, and are likely to appropriately wash hands and bathe, which effectively limits their risk of ingestion exposure. Children engaging in geophagy are unlikely to access the work site, and are unlikely to directly consume contaminated soil. In all cases, the frequency and duration of exposure is likely to be very short. Consequently, accidental ingestion of chemicals associated with carcass management options is considered an incidental exposure posing negligible risk for workers and all types of farm residents. A separate consideration is that the soil exposure analysis assumes chemicals deposited from the air are instantaneously mixed and diluted with surface soil to a depth of 2 cm. For those reasons, three chemical exposure pathways in Table 5.1.1 are not quantified:

  - Carcass handling, exposure pathway number 2
  - Carcass transportation, exposure pathway number 3
  - Open burning and air-curtain burning, exposure pathway 3

Table 5.1.1. Human Exposure Pathways for Livestock Carcass Management – Chemicals

Exposure Source	Carcass Transportation and Handling			Carcass Management Options		
	Carcass Handling	Temporary Carcass Storage	Carcass Transportation	Open Burning and Air curtain Burning	Burial	Composting
Inhalation	1) Air[b]	1) Air[b] 2) Leachate → GW → In-home Aerosol[c]	1) Air[b]	**1) Air[a]** 2) Ash → GW → In-home Aerosol[b]	1) Air[b] 2) Leachate → GW → In-home Aerosol[b]	1) Air[b] 2) Compost → GW → In-home Aerosol[b]
Incidental Ingestion	2) Hand-to-mouth ingestion [b,c]	—	2) Accident → soil[b,c]	3) Air → soil[b]	—	—
Dermal	3) Direct dermal contact[c]	—	3) Accident → soil[c]	—	—	—
Fish Ingestion	—	**3) Leachate → GW → SW → Fish[a]**	—	**4) Air → SW → Fish[a]** **5) Air → soil → SW → Fish[a]** **6) Ash → GW → SW → Fish[a]**	**3) Leachate → GW → SW → Fish[a]**	**3) Compost → soil → SW → Fish[a]** **4) Compost → GW → SW → Fish[a]**
Ground-water Ingestion	—	**4) Leachate → GW[a]**	—	**7) Ash → GW[a]**	**4) Leachate → GW[a]**	**5) Compost → GW[a]**
Food Produced on the Farm -- Ingestion	—	5) Air → Plants/livestock[b] 6) Leachate → GW → Livestock[b]	—	**8) Air → Plants/livestock[a]** **9) Air → Soil → Plants/ Livestock[a]** 10) Ash → GW → Livestock[b]	5) Air → Plants/ Livestock[b] 6) Leachate → GW → Livestock[b]	**6) Compost → Soil → Plants/ Livestock[a]** 7) Air → Plants/ Livestock[b] 8) Compost → soil → GW → Livestock[b]

Abbreviations: "—" = no exposure pathways; SW = surface water; GW = groundwater.

Exposure pathways shown in bold were included in the quantitative exposure assessment. Pathways were not quantitatively assessed for the following reasons:

[a] Quantitative methods were available for exposure assessment; Results are presented in Section 6.3.

[b] Potential exposures were assumed to be negligible based on source conditions or chemical properties.

[c] Environmental releases or exposures were assumed to be adequately controlled by existing pollution control regulations or use of personal protective equipment.

- **Ingestion of food produced on the farm** – Airborne chemicals might be taken up from the air or settle on plant surfaces that are later consumed. Volatile gases (e.g., ammonia) generated by carcass decomposition are given off from the storage pile and seep upward through cover materials, including soil (burial option) or wood chips (composting option). As discussed above and in Sections 3.4 and 3.5.2, available data (e.g., by Glanville et al. 2006) indicate concentrations of gases are unlikely to be hazardous for the carcass management scenarios included in this assessment and report (Table 5.1.1):

  - Temporary carcass storage, exposure pathway number 5
  - Burial, exposure pathway number 5
  - Composting, exposure pathway number 6

  The conceptual model for the food chain associated with the farm's productivity includes pathways with livestock receiving well water containing chemicals leached from combustion ash, buried carcasses, temporary carcass storage piles, or compost windrows. Only lipophilic chemicals are likely to accumulate in livestock, and as discussed in Section 5.3 below, those do not reach the groundwater well at measureable concentrations. For those reasons, four pathways in Table 5.1.1 are not assessed:

  - Temporary carcass storage, exposure pathway number 6
  - Open burning and air-curtain burning, exposure pathway number10
  - Burial, exposure pathway number 6
  - Composting, exposure pathway number 7

5.2. Characterization of Exposed Individuals

This section discusses who the assessment assumes is exposed to chemical, as well as characteristics about them (e.g., age) and their behavior (e.g., location) that affect estimated levels of exposure. Specifically, Sections 5.2.1 through 5.2.4 discuss four parameters:

- Description of exposed persons (e.g., infants, adults)
- Durations of exposures
- Distance between management option source and human receptors
- Selection of human exposure factor values

1.1.1. Description of Exposed Persons

Exposure is estimated for three types of farm residents: infants who consume drinking water in their formula, young children (age 1-2 years old), and adults who live on the farm near the carcass management unit for at least one year after carcass management. A young child (e.g., age 1 to 2 years) consumes more food per unit body weight on a daily basis than older children and adults. For the young child, exposure is calculated from estimated concentrations of chemicals a limited diet of foods produced on the farm, using assumptions about a small body weight, and higher metabolic rates (ingestion and inhalation rates). For the adult, exposure is calculated from estimated concentrations of chemicals in the drinking water and food items using mean values for various exposure factors (e.g., body weight, ingestion rates for different foods and water, inhalation rates).

1.1.2. Exposure Durations

The assessment includes two exposure routes and durations: inhalation over 48 hours and ingestion (i.e., of drinking water, home-grown food products, and fish) over one year. Although the dermal exposure route is included in Table 5.1.1, all dermal exposure pathways are negligible because of the assumed use of gloves and other PPE.

Inhalation exposures are assessed only for the combustion-based management options. As described in Section 3, Tables 3.2.1 and 3.3.1, open burning and air-curtain burning are assumed to continue for 48 hrs. Exposure concentrations in mg chemical/m^3 air are estimated as event-average concentrations. That means the assessment uses average chemical concentration present in the air during that 48 hr period (at the location of maximum air concentrations).

Ingestion exposures are evaluated for a one-year period starting with the beginning of the carcass management actions. The one-year exposure periods for the various ingestion sources do not necessarily coincide with one another. For example, drinking water exposure begins when the chemicals in groundwater reach the well. Ingestion of home-grown foods begins for the combustion-based options after chemicals are deposited from air to soil and plants, and for the composting option after finished compost is applied as a soil amendment.

All ingestion exposures are assumed to be constant and uniform throughout the one-year periods. Chemical concentrations in drinking water, home-grown produce, and fish based on the total

chemical released during the first year to an environmental medium after accounting for chemical movement to other environmental media (e.g., from surface soil to the lake) are assumed to represent the average daily exposure concentrations for one year, as described in Section 4. The exposure assumptions, such as the availability and consumption of home-grown food products, are assumed to be consistent throughout the year (i.e., data for seasonal changes not available).

Exposures to chemicals in drinking water and fish following leakage from the storage pile are the same for all seven carcass management options. They are evaluated separately from the carcass management options, which also allows the exposures from handling activities to be compared with exposures from carcass disposal.

1.1.3. Human Exposure Factor Values

This assessment uses mean life-stage-specific exposure factor values that are included in MIRC. Those values are from the most recent version of USEPA's *Exposure Factors Handbook* (USEPA 2011), its *Child-specific Exposure Factors Handbook* (USEPA 2008), and its *Child-Specific Exposure Scenarios Examples* (USEPA 2014b). These handbooks include a thorough review of relevant original data and list the USEPA-recommended values for use in exposure assessments. The handbooks provide mean, median, and percentile (e.g., 75^{th}, 90^{th}, 99^{th} percentiles) values to allow the user to determine the degree of conservatism appropriate for each factor as used in their particular type of exposure assessment (e.g., screening, ranking, refined).

The purpose of this comparative exposure assessment is to rank the management options by their exposure potential relative to each other, not to estimate possible real-world maximum individual or population exposures or risks for any of the options. As a consequence, the most appropriate value to select for each exposure factor is the mean value, not an upper percentile value as often is selected for screening-level risk assessments to represent most exposed individuals. Mean values are preferred for exposure factor values used in the ranking of carcass management options for several reasons:

- Mean values are the most robust (i.e., have the most narrow confidence limits) of the statistical descriptors of parameter distributions. The more extreme values (i.e., values near the "tails") in a natural distribution of parameter values, such as a 95^{th} or 99^{th} percentile

value, are more uncertain (i.e., and have much wider confidence limits). Upper percentile values (i.e., upper tail of a distribution) can be highly skewed by outlier values in the data set.

- The expected value, or mean, of the sum of two random variables is the sum of the means (additive law of expectation).
- The mean of the product of two parameters (with any type of distribution of values) is the product of the mean values if (and only if) the two parameters are not correlated with one another.
- If the variables are correlated (e.g., body weight positively correlates with daily quantities of food ingested), then the product of the mean values for each parameter will likely be smaller than the mean of the product of the values (e.g., the same individual). To avoid this error, original data on food ingestion rates for each individual should be expressed as kg food ingested per kg of body weight per day. The mean of that distribution should be a more accurate measure than taking the mean of food ingestion rates (kg/day) across all adults and dividing by the mean body weight of all adults (in kg).
- Percentiles for random variables generally are not additive or multiplicative whether the variables are correlated to some degree or not. Instead, reasonably accurate estimates of a percentile (e.g., 90^{th} percentile) for the sum, product, or ratio of two (or more) random variables generally requires a Monte Carlo simulation in which the distribution of each variable and its correlation with the others are well defined. For example, multiplication of upper percentile values for two independent parameters (e.g., 95^{th} percentile for exposure concentration in water in mg/L multiplied by the 95^{th} percentile water ingestion rate in L/kg body weight/day) yields a much more conservative (i.e., higher) percentile value (e.g., 99.9^{th}) than the original percentile value (e.g., 95^{th}). Moreover, using the percentile requires knowledge of the shape of the original distributions and their variances even if the two parameters are completely uncorrelated.

For the purpose of ranking the livestock carcass management options based on their relative exposure potential, *mean* values for adult and child body weight, food and water ingestion rates, and inhalation rates are used (see Table 5.2.1) as documented in Appendix K. For infants,

exposures are considered from well water used to mix with formula, with both mean and high-end exposure factor values as listed below.

Table 5.2.1. Typical and High-end Exposure Factor Values For Infant Water Consumption

Parameter	Typical or Mean Scenario mL/kg d	High end Scenario mL/kg d (95th %)	Rationale or Source
Intake by infant < 1 month	137	238	Table 3-1 in USEPA (2011) Exposure Factors Handbook, Consumers-Only drinking water
Intake by infant: 1–3 months 6–12 months	 119 53	 285 129	Table 3-1 in USEPA (2011) Exposure Factors Handbook, Consumers-Only drinking water

Abbreviations: d = day; USEPA = U.S. Environmental Protection Agency.

5.3.Exposure Estimation

This section describes the methods used to estimate chemical exposures for each carcass management option. Separate estimation methods are used for human inhalation (Section 5.3.1) and ingestion (Section 5.3.2) exposures.

1.1.1. Inhalation

Inhalation exposures are calculated for adult farm residents at a location of maximum concentrations of the chemicals in air as estimated by AERMOD on a date for which meteorological conditions resulted in the highest 48-hr average concentration. For combustion-based management options, this assessment uses only the 48-hr average exposure from chemicals released into the air (see Section 5.2.2). These average inhalation exposures are then compared with acute toxicity reference concentrations (RfCs) if available (see Section 7). Separate exposure estimates are not made for adults and children because evaluation of inhalation exposures occurs on an air-concentration basis and not an exposure-dose basis.

The conceptual model includes inhalation of aerosolized chemicals from home uses of well water (specifically showering as the worst-case home-use scenario). However, given the low ranking ratios associated with ingestion of drinking water, this inhalation exposure pathway is considered negligible, and is not estimated.

Combustion products from open burning and air-curtain burning include two groups of compounds (PAHs and dioxins/furans) with similar chemical structures in each group and toxic

health effects. Although similar, the individual compounds in each group do differ in their toxic potency. Previous researchers developed relative potency factors (for PAHs, see Appendix A) or toxicity equivalency factors (for dioxins and furans, see Appendix B) to express the toxicity of each compound relative to an index compound within the group. The compound-specific concentrations are multiplied by these factors before totaling the exposure concentration in air for the chemical groups. This assessment evaluates PAHs and dioxins/furans as a whole by totaling the maximum event-average concentrations for each chemical in these groups. The total dioxin/furan concentration in air is reported as 2,3,7,8-TCDD equivalents, and the total PAH concentration in air is reported relative to the cancer potency value of benzo(a)pyrene (BaP). This assessment assumes the location of the maximum concentration in air is the same for all of the chemicals.

Table 5.3.1 presents concentrations of chemicals in air found during open burning and air-curtain burning. Concentration differences can be explained by the different emission factors for carcass combustion and the chemical content and emission factors for the fuels. For example, concentrations of metals may be higher with open burning than air-curtain burning because of the coal used as a fuel in the pyre. Concentrations from air-curtain burning would be lower if a 2:1 wood:carcass ratio were used instead of the 4:1 ratio assumed here.

1.1.2. Ingestion Media

Ingestion media in the exposure assessment include drinking water, soil, fish caught locally in the lake, five types of home-grown produce, and five types of home-raised animals or animal products. Equations and assumptions to estimate those exposures are based on relevant portions of HHRAP as implemented in MIRC.

Table 5.3.1. Inhalation Exposure Concentrations Open Burning and Air-curtain Burning

Chemical Species	Maximum Event average Air Concentration (µg/m^3)	
	Open Burning	Air curtain Burning
Dioxins/furans	4.2E-10	7.4E-08
Total PAHs	6.8E-02	2.6E-04
Arsenic	7.7E-04	2.9E-04
Cadmium	1.4E-03	2.0E-03
Chromium	1.2E-02	9.3E-03
Copper	9.5E-03	1.0E-02
Iron	3.1E+00	5.7E-01
Lead	1.3E-02	9.3E-03
Manganese	2.9E-02	7.0E-01
Nickel	1.1E-02	4.3E-03
Zinc	9.9E-02	1.7E-01

Abbreviations: PAH = polycyclic aromatic hydrocarbon.

Average daily ingested doses (ADDs in mg/kg/day) are estimated using generic Equation 5.1:

$$ADD_{ing} = \left(C_{prod} * IR * FC * ED/BW * AT\right) * (EF/365\ days) \qquad \textbf{Eqn. 5.1}$$

where:

ADD_{ing} = Average daily ingestion dose (mg/kg/day)
C_{prod} = Concentration of chemical in ingestion medium (mg/kg or mg/L)
IR = Age-group specific ingestion rate for ingestion medium (kg/day or L/day)
FC = Fraction of food type harvested from the contaminated farm area
ED = Exposure duration (yr)
BW = Age-group-specific body weight (kg)
AT = Averaging time (yr)
EF = Annual exposure frequency for age group (days)

A version[15] of this equation is used in MIRC for each ingestion medium to calculate average daily doses (ADDs) for each receptor age group (i.e., adult or young child) and chemical.

The above equation accounts for the chemical concentration in each ingested food, the quantity of food brought into the home for consumption, how much of that food is consumed per year, the amount of the food obtained from the affected area, and the consumer's body weight (USEPA

[15] Variations of the equation include units, conversion factors, cooking loss factors, or other adjustments for the specific ingestion source.

2011). MIRC includes factors for food preparation and cooking losses account for the amount of a food product as brought into the home that is not ingested due to loss during preparation, cooking, or post-cooking (see Appendix K). Two additional exposure media are included to estimate the total daily dose of each chemical ingested: drinking water and soil (from incidental ingestion). In MIRC, ADDs are calculated separately for each chemical, ingestion medium, and receptor age group. All the ADDs for a given carcass management option are then summed for each combination of receptor age group and chemical.

For fish ingestion, the assessment assumes that farm residents catch and consume both water-column game fish (e.g., walleye, northern pike) and pan fish (e.g., yellow perch, bluegill). The fish ingestion rates are mean values for the general population developed by USEPA's Office of Air Quality Planning and Standards OAQPS for use in multimedia risk assessments in support of USEPA's Risk and Technology Review program. As described in Appendix K, OAQPS estimated the values of 7 g/person/day for adults and 1.4 g/person/day for children age 1 to 2 years (Table K.15) from data presented in USEPA's (2002) *Estimated* Per capita *Fish Consumption in the United States* and the Agency's (2008) *Child-Specific Exposure Factors Handbook*. Subsistence fish ingestion rates are not used because the farm residents also rely on home-grown plants and livestock for food.

All ingestion ADDs are calculated assuming one year of exposure to the chemicals (exposure duration [*ED*] of 1 yr), exposure that every day during the year (i.e., exposure frequency of 365 days/yr), and that all of the food or drinking water ingested is from potentially contaminated food and drinking water obtained on site (i.e., the fraction from the contaminated area is 1.0). The averaging time in the equation above (*AT* of 1 yr) is the period of time over which the average daily chemical exposure is averaged. Only the first year following management of the carcasses on site is assessed, because that is the year in which chemical concentrations will be highest in environmental media. Chemical concentrations in subsequent years will be lower as various loss processes (e.g., diffusion, dispersion, degradation, movement of chemicals to other environmental media) continue over time. Thus, exposures will continue, but decrease at a rate that is difficult to calculate across carcass management options.

For non-cancer effects, the first year of ingestion exposure is normalized to toxicity reference values—subchronic toxicity reference values (TRVs) if available, chronic TRVs if subchronic

values are not available. Strictly speaking, a subchronic exposure for humans is seven years long; however, this assessment is not calculating risks, it is ranking carcass management options after chemical exposures are normalized to inherent toxicity to the extent feasible.

For cancer, which can occur after exposure and for which USEPA assumes a 70-yr exposure duration in calculating carcinogenic potency, a 1-yr exposure duration is too short to appropriately represent a risk of developing cancer over a lifetime using cancer potency factors. Instead, to identify a risk-specific dose, the 1-yr exposure estimate is divided by 70 yrs.

For each carcass management option, chemical-specific ingestion exposures, expressed as ADDs, for each age group (i.e., adult and child aged 1-2), are summed across ingested drinking water, fish, five types of home-grown produce, and five types of home-raised animals or animal products. Total ADD for a particular age group *y* ($ADD_{(y)}$) is estimated as the sum of a given chemical ingested from all pathways from which the chemical could be consumed. The ADDs for PAHs and dioxins/furans associated with combustion options are totaled using the relative potency factor (RPFs) and toxicity equivalency factors (TEQs), respectively, described in the previous section.

Ingestion exposure estimates (i.e., ADDs) for adults and young children associated with each management option are presented in Tables 5.3.2 through 5.3.14. These tables include ADDs for each food ingested, drinking water, and incidental soil ingestion, which are added to calculate the total ingestion exposure for each chemical. The tables list "na" if the exposure is not assessed. This situation arises when either: (1) the chemical was not released by the particular management option (e.g., dioxins and PAHs are created by combustion and are not present in carcasses initially); (2) data are not available to estimate exposure to a particular chemical; or (3) there is no exposure pathway within that particular scenario or for that particular chemical. One example of the last situation is fish ingestion by infants <1 year of age is not estimated, because that age group does not consume fish (assume formula feeding for first year after birth). Farm produce exposure is not estimated for the burial option, and the drinking water exposure is not estimated for the composting option. The pathways evaluated for each option are discussed in Sections 3.1 through 3.5.

Exposure estimates for the four on-site management options do not include exposure pathways associated with the temporary carcass storage pile or with transportation on- or off-site. Each of those two possible sources of exposure are assumed to be equal across all management options (see Tables 5.3.2 and 5.3.3). Presenting possible exposures from the storage pile separately allows them to be compared with other exposures associated with the management options. In addition, exposures for the composting option are presented separately for pathways associated with leakage from the windrow to the ground below (Tables 5.3.10 and 5.3.11) and application of the finished compost to agricultural land on site (Tables 5.3.12 and 5.3.13). Table 5.3.14 presents ingestion estimates for each of the on-site management options for infants who consume powdered formula reconstituted with well water. Breast milk ingestion is an important pathway for nursing infants for lipophilic chemicals, which are limited to PAHs and dioxins and furans for the current assessment. However, this is an assessment of relative exposures across carcass management options, not of maximum individual risks (e.g., to an infant who might be more exposed to some chemicals in breast milk and less exposed to other chemicals). Breast milk ingestion and nursing infants, therefore, are not included in the conceptual models resulting from problem formulation.

Ingestion exposures estimated for adults and young children generally are within an order of magnitude. Estimated ingestion exposures for children are greater than those for adults, because children ingest more food and water per unit body weight than do adults. Many of the estimated ADDs are very small, many orders of magnitude below any toxicity reference value. All estimates are included in Tables 5.3.2 through 5.3.14, however, to show which chemical and ingestion source combinations constitute a complete pathway.

The estimates are based on the hypothetical farm setting, a standardized set of environmental conditions (e.g., meteorology), methods with considerable uncertainties, and assumptions that are not necessarily representative of site-specific carcass management efforts. For these reasons, this exposure assessment should not be regarded as providing estimates of actual exposures likely from the management options. Despite their inherent uncertainty, the exposure estimates are useful for comparing the management options relative to one another, in terms of the number of potential pathways and relative exposure levels, with each chemical exposure normalized to levels that can cause adverse effects on human and environmental health.

Table 5.3.2. Ingestion Exposure Estimates for Temporary Carcass Storage – Adults

Chemical Species	Ingestion Average Daily Dose (mg/kg d)			
	Drinking Water	Farm Produce	Fish	Total Ingestion
Total Dioxins/furans	na	na	na	na
Total PAHs	na	na	na	na
Arsenic	na	na	na	na
Cadmium	na	na	na	na
Chromium	na	na	na	na
Copper	5.0E-14	na	3.0E-12	3.1E-12
Iron	6.1E-11	na	2.9E-09	3.0E-09
Lead	na	na	na	na
Manganese	2.8E-13	na	3.3E-12	3.6E-12
Nickel	2.2E-13	na	1.8E-12	2.0E-12
Zinc	2.0E-12	na	1.9E-10	1.9E-10

Abbreviations: d = day; na = not assessed; PAH = polycyclic aromatic hydrocarbons.

Table 5.3.3. Ingestion Exposure Estimates for Temporary Carcass Storage – Children 1 to <2 Years Old

Chemical Species	Ingestion Average Daily Dose (mg/kg d)			
	Drinking Water	Farm Produce	Fish	Total Ingestion
Total Dioxins/furans	na	na	na	na
Total PAHs	na	na	na	na
Arsenic	na	na	na	na
Cadmium	na	na	na	na
Chromium	na	na	na	na
Copper	8.7E-14	na	3.8E-12	3.9E-12
Iron	1.1E-10	na	3.7E-09	3.8E-09
Lead	na	na	na	na
Manganese	4.8E-13	na	4.2E-12	4.7E-12
Nickel	3.8E-13	na	2.2E-12	2.6E-12
Zinc	3.5E-12	na	2.4E-10	2.4E-10

Abbreviations: d = day; na = not assessed; PAH = polycyclic aromatic hydrocarbons.

Table 5.3.4. Ingestion Exposure Estimates for Open Burning – Adults

Chemical Species	Ingestion Average Daily Dose (mg/kg d)			
	Drinking Water	Farm Produce	Fish	Total Ingestion
Total Dioxins/furans	4.7E-26	3.1E-12	1.4E-13	3.2E-12
Total PAHs	1.2E-16	2.8E-07	1.6E-07	4.4E-07
Arsenic	7.4E-13	2.6E-08	5.0E-07	5.3E-07
Cadmium	1.2E-13	1.5E-10	7.5E-07	7.5E-07
Chromium	1.3E-10	9.7E-16	1.8E-04	1.8E-04
Copper	3.5E-13	na	5.0E-05	5.0E-05
Iron	1.1E-09	na	2.2E-02	2.2E-02
Lead	5.2E-15	1.7E-13	3.1E-07	3.1E-07
Manganese	6.1E-10	na	1.9E-05	1.9E-05
Nickel	4.3E-12	8.1E-15	3.7E-06	3.7E-06
Zinc	2.8E-11	1.7E-12	3.2E-04	3.2E-04

Abbreviations: d = day; na = not assessed; PAH = polycyclic aromatic hydrocarbons.

Table 5.3.5. Ingestion Exposure Estimates for Open Burning – Children 1 to <2 Years Old

Chemical Species	Ingestion Average Daily Dose (mg/kg d)			
	Drinking Water	Farm Produce	Fish	Total Ingestion
Total Dioxins/furans	8.1E-26	4.6E-11	1.8E-13	4.6E-11
Total PAHs	2.1E-16	4.0E-06	2.0E-07	4.2E-06
Arsenic	1.3E-12	1.3E-07	6.4E-07	7.7E-07
Cadmium	2.0E-13	6.2E-10	9.4E-07	9.4E-07
Chromium	2.3E-10	2.8E-15	2.3E-04	2.3E-04
Copper	6.0E-13	na	6.3E-05	6.3E-05
Iron	1.9E-09	na	2.8E-02	2.8E-02
Lead	9.0E-15	5.2E-13	3.9E-07	3.9E-07
Manganese	1.1E-09	na	2.4E-05	2.4E-05
Nickel	7.5E-12	2.4E-14	4.7E-06	4.7E-06
Zinc	4.9E-11	4.3E-12	4.1E-04	4.1E-04

Abbreviations: d = day; na = not assessed; PAH = polycyclic aromatic hydrocarbons.

Table 5.3.6. Ingestion Exposure Estimates for Air-curtain Burning – Adults

Chemical Species	Ingestion Average Daily Dose (mg/kg d)			
	Drinking Water	Farm Produce	Fish	Total Ingestion
Total Dioxins/furans	8.1E-26	4.4E-11	1.0E-11	5.4E-11
Total PAHs	3.1E-16	4.1E-10	1.8E-09	2.2E-09
Arsenic	1.3E-12	2.6E-08	9.7E-08	1.2E-07
Cadmium	8.7E-14	2.2E-11	5.9E-07	5.9E-07
Chromium	2.1E-10	4.1E-16	6.8E-05	6.0E-05
Copper	4.2E-13	na	2.5E-05	2.4E-05
Iron	1.2E-09	na	1.7E-03	1.6E-03
Lead	9.2E-14	8.1E-14	1.2E-07	1.2E-07
Manganese	1.1E-09	na	1.9E-04	1.9E-04
Nickel	5.8E-12	1.9E-15	7.4E-07	7.3E-07
Zinc	9.3E-11	2.2E-12	3.6E-04	3.5E-04

Abbreviations: d = day; na = not assessed; PAH = polycyclic aromatic hydrocarbons.

Table 5.3.7. Ingestion Exposure Estimates for Air-curtain Burning – Children 1 to <2 Years Old

Chemical Species	Ingestion Average Daily Dose (mg/kg d)			
	Drinking Water	Farm Produce	Fish	Total Ingestion
Total Dioxins/furans	1.4E-25	6.7E-10	1.3E-11	6.8E-10
Total PAHs	5.4E-16	5.7E-09	2.3E-09	8.0E-09
Arsenic	2.2E-12	1.2E-07	1.2E-07	2.4E-07
Cadmium	1.5E-13	9.1E-11	7.4E-07	7.4E-07
Chromium	3.6E-10	1.2E-15	8.6E-05	7.6E-05
Copper	7.3E-13	na	3.2E-05	3.1E-05
Iron	2.1E-09	na	2.2E-03	2.0E-03
Lead	1.6E-13	2.4E-13	1.5E-07	1.5E-07
Manganese	1.8E-09	na	2.4E-04	2.4E-04
Nickel	1.0E-11	5.7E-15	9.3E-07	9.2E-07
Zinc	1.6E-10	5.9E-12	4.5E-04	4.5E-04

Abbreviations: d = day; na = not assessed; PAH = polycyclic aromatic hydrocarbons.

Table 5.3.8. Ingestion Exposure Estimates for Burial – Adults

Chemical Species	Ingestion Average Daily Dose (mg/kg d)			
	Drinking Water	Farm Produce	Fish	Total Ingestion
Total Dioxins/furans	na	na	na	na
Total PAHs	na	na	na	na
Arsenic	na	na	na	na
Cadmium	na	na	na	na
Chromium	na	na	na	na
Copper	3.6E-13	na	4.9E-11	4.9E-11
Iron	1.0E-10	na	1.1E-08	1.1E-08
Lead	na	na	na	na
Manganese	8.4E-13	na	2.3E-11	2.4E-11
Nickel	2.0E-13	na	3.7E-12	3.9E-12
Zinc	8.6E-12	na	1.8E-09	1.8E-09

Abbreviations: d = day; na = not assessed; PAH = polycyclic aromatic hydrocarbons.

Table 5.3.9. Ingestion Exposure Estimates for Burial – Children 1 to <2 Years Old

Chemical Species	Ingestion Average Daily Dose (mg/kg d)			
	Drinking Water	Farm Produce	Fish	Total Ingestion
Total Dioxins/furans	na	na	na	na
Total PAHs	na	na	na	na
Arsenic	na	na	na	na
Cadmium	na	na	na	na
Chromium	na	na	na	na
Copper	6.3E-13	na	6.2E-11	6.3E-11
Iron	1.7E-10	na	1.4E-08	1.4E-08
Lead	na	na	na	na
Manganese	1.4E-12	na	2.9E-11	3.0E-11
Nickel	3.5E-13	na	4.6E-12	5.0E-12
Zinc	1.5E-11	na	2.2E-09	2.2E-09

Abbreviations: d = day; na = not assessed; PAH = polycyclic aromatic hydrocarbons.

Table 5.3.10. Ingestion Exposure Estimates for Compost Windrow – Adults

Chemical Species	Ingestion Average Daily Dose (mg/kg d)			
	Drinking Water	Farm Produce	Fish	Total Ingestion
Total Dioxins/furans	na	na	na	na
Total PAHs	na	na	na	na
Arsenic	na	na	na	na
Cadmium	na	na	na	na
Chromium	na	na	na	na
Copper	2.7E-14	na	2.5E-12	2.5E-12
Iron	7.5E-12	na	5.5E-10	5.6E-10
Lead	na	na	na	na
Manganese	6.3E-14	na	1.1E-12	1.2E-12
Nickel	1.5E-14	na	1.8E-13	2.0E-13
Zinc	6.4E-13	na	8.9E-11	9.0E-11

Abbreviations: d = day; na = not assessed; PAH = polycyclic aromatic hydrocarbons.

Table 5.3.11. Ingestion Exposure Estimates for Compost Windrow – Children 1 to <2 Years Old

Chemical Species	Ingestion Average Daily Dose (mg/kg d)			
	Drinking Water	Farm Produce	Fish	Total Ingestion
Total Dioxins/furans	na	na	na	na
Total PAHs	na	na	na	na
Arsenic	na	na	na	na
Cadmium	na	na	na	na
Chromium	na	na	na	na
Copper	4.7E-14	na	3.1E-12	3.1E-12
Iron	1.3E-11	na	6.9E-10	7.0E-10
Lead	na	na	na	na
Manganese	1.1E-13	na	1.4E-12	1.5E-12
Nickel	2.6E-14	na	2.3E-13	2.6E-13
Zinc	1.1E-12	na	1.1E-10	1.1E-10

Abbreviations: d = day; na = not assessed; PAH = polycyclic aromatic hydrocarbons.

Table 5.3.12. Ingestion Exposure Estimates for Compost Application – Adults

Chemical Species	Ingestion Average Daily Dose (mg/kg d)			
	Drinking Water	Farm Produce	Fish	Total Ingestion
Total Dioxins/furans	na	na	na	na
Total PAHs	na	na	na	na
Arsenic	na	na	na	na
Cadmium	na	7.0E-09	9.7E-06	9.7E-06
Chromium	na	7.7E-10	1.8E-03	1.8E-03
Copper	na	na	5.0E-03	5.0E-03
Iron	na	na	2.0E+00	2.0E+00
Lead	na	4.0E-07	1.5E-04	1.5E-04
Manganese	na	na	2.2E-03	2.2E-03
Nickel	na	1.1E-08	1.6E-04	1.6E-04
Zinc	na	3.5E-06	2.0E-02	2.0E-02

Abbreviations: d = day; na = not assessed; PAH = polycyclic aromatic hydrocarbons.

Table 5.3.13. Ingestion Exposure Estimates for Compost Application – Children 1 to <2 Years Old

Chemical Species	Ingestion Average Daily Dose (mg/kg d)			
	Drinking Water	Farm Produce	Fish	Total Ingestion
Total Dioxins/furans	na	na	na	na
Total PAHs	na	na	na	na
Arsenic	na	na	na	na
Cadmium	na	2.3E-08	1.2E-05	1.2E-05
Chromium	na	2.3E-09	2.3E-03	2.3E-03
Copper	na	na	6.3E-03	6.3E-03
Iron	na	na	2.5E+00	2.5E+00
Lead	na	1.2E-06	1.9E-04	1.9E-04
Manganese	na	na	2.7E-03	2.7E-03
Nickel	na	3.4E-08	2.1E-04	2.1E-04
Zinc	na	9.0E-06	2.5E-02	2.5E-02

Abbreviations: d = day; na = not assessed; PAH = polycyclic aromatic hydrocarbons.

Table 5.3.14. Ingestion Estimates for Infants with Formula Made Using Well Water[a]

Chemical Species	Ingested Daily Dose (mg/kg d)							
	Open Burning		Air Curtain		Burial [(b)]		Composting	
	Avg	95th%	Avg	95th%	Avg	95th%	Avg	95th%
Total Dioxins/furans	2.8E-22	6.6E-22	5.1E-22	1.2E-21	na	na	na	na
Arsenic	4.4E-09	1.0E-08	7.8E-09	1.8E-08	na	na	na	na
Cadmium	7.1E-10	1.6E-09	5.2E-10	1.2E-09	nd	nd	nd	nd
Chromium	7.9E-07	1.8E-06	1.3E-06	3.0E-06	nd	nd	nd	nd
Copper	2.1E-09	4.9E-09	2.6E-09	6.0E-09	2.2E-09	5.1E-09	1.7E-10	3.8E-10
Iron	6.7E-06	1.6E-05	7.4E-06	1.7E-05	6.1E-07	1.4E-06	4.5E-08	1.0E-07
Lead	3.1E-11	7.2E-11	5.5E-10	1.3E-09	na	na	na	na
Manganese	3.7E-06	8.5E-06	6.4E-06	1.5E-05	5.1E-09	1.2E-08	3.8E-10	8.7E-10
Nitrates/nitrites[b]	nd	nd	nd	nd	6.6E-04	1.5E-03	2.3E-06	5.3E-06
Zinc	1.7E-07	3.8E-07	5.6E-07	1.3E-06	5.1E-08	1.2E-07	3.9E-09	9.0E-09

Abbreviations: Avg = average; d = day; na = not assessed; PAH = polycyclic aromatic hydrocarbons.
[a] Avg columns calculated using a time-weighted mean water ingestion rate of 0.0919 L/kg-day for an infant less than 1 year of age (original data listed in Table 6.2.1; an intermediate ingestion rate of 0.146 L/d was assumed for infants 3 to 6 months of age). 95th % = ingested daily dose assuming time-weighted 95th percentile water ingestion rate for infant less than 1 year (original data in Table 6.2.1; an ingestion rate of 0.167 L/kg-day for infants was assumed 3 to 6 months).
[b] For burial, groundwater concentration as drawn from the on-site well during the first year (Table 4.3.2), except for nitrates/nitrites for which the concentration during the first week is used to be conservative. Contribution to lifetime cancer risk from PAHs not evaluated for a 1-year exposure via formula; PAHs not included in table. No reference doses (RfD) for nickel; hence, nickel not included in table.

5.4. Livestock and Environmental Exposures

This section discusses exposures of livestock (Section 5.4.1) and environmental exposures of organisms in the on-site lake and in contact with on-site soil (Section 5.4.2).

1.1.1. Livestock Exposure

The conceptual model diagrams for the on-site carcass management options (Figure 3.2.1, Figure 3.3.1, Figure 3.4.1, and Figure 3.5.1) include pathways by which livestock might be exposed to chemicals from on-site combustion, burial, and composting (Table 5.4.1). They include exposure to air-borne vapor- and particle-phase chemicals through inhalation, incidental ingestion of chemicals deposited to soils (e.g., cattle grazing), ingestion of drinking water provided from an on-site groundwater well, and ingestion of plants grown on site, including grains, silage, and forage. Except in two major ways, these livestock pathways are the same as previously considered for human exposure pathways. The first exception is that humans and livestock consume different plant products. The second exception is that incidental soil ingestion by

livestock while grazing on short grasses, particularly by cattle, allows greater exposures than incidental soil ingestion by humans (e.g., through hand-to-mouth contact).

Table 5.4.1 Exposure Pathways and Routes for Livestock Carcass Management Options

Exposure Source	Conceptual Model Pathways for Carcass Management Options			
	Combustion based Options	Burial	Composting	Off site Options
Inhalation	1) Air → Livestock	1) Air → Livestock	1) Air → Livestock	—
Incidental Soil Ingestion	2) Air → Soil→ Livestock	—	—	—
Groundwater Ingestion	3) Ash → Groundwater → Livestock	2) Leachate → Groundwater → Livestock	2) Leachate → Groundwater → Livestock	—
Ingestion of Food Produced on the Farm	4) Air → Plants → Livestock 5) Air → Soil → Plants → Livestock	3) Air → Plants → Livestock 4) Air → Soil → Plants → Livestock	3) Air → Plants → Livestock 4) Air → Soil → Plants → Livestock	—

"—" = no exposure pathways.

Both on-site combustion-based options result in chemical ingestion by livestock. For on-site combustion options, the MIRC-estimated concentrations of arsenic, cadmium, total PAHs, and total dioxins/furans (by weight, not by toxic equivalency factors) in beef, pork, poultry, milk, and eggs are listed in Tables 5.4.2 and 5.4.3. Data are not listed for chromium, copper, iron, lead, manganese, nickel, or zinc because there are no available empirical transfer factors. Open-burning results in somewhat higher concentrations released to air than air-curtain burning, particularly for PAHs. One exception is that estimates of dioxins/furans created are slightly higher for the air-curtain burning scenario because of the large quantities of wood burned assuming a 4:1 ratio of wood to carcasses.

Table 5.4.2. Chemical Concentrations in Beef, Pork, and Poultry After Carcass Management by Open Burning (550°C)

Chemical Species	Beef (mg/kg wet wt.)	Total Dairy (mg/kg wet wt.)	Pork (mg/kg wet wt.)	Poultry (mg/kg wet wt.)	Eggs (mg/kg wet wt.)
Arsenic	1.2E-05	5.5E-07	na	na	na
Cadmium	8.4E-09	6.8E-10	5.8E-10	5.2E-13	1.2E-14
Zinc	na	na	na	2.5E-12	2.5E-12
Total PAHs[a]	1.1E-03	3.6E-04	9.5E-05	3.0E-09	1.7E-09
Total Dioxin/furans[b]	1.5E-09	4.7E-10	1.2E-10	4.6E-17	2.6E-17

Abbreviations: wt = weight; na = not assessed; PAH = polycyclic aromatic hydrocarbons.
[a] Total PAHs calculated as sum of the products of individual congener concentrations and relative potency factors (RPFs).
[b] Total dioxins/furans calculated the same way using toxicity equivalency factors (TEFs or TEQs).

Table 5.4.3. Chemical Concentrations in Beef, Pork, and Poultry After Carcass Management by Air-Curtain Burning (850°C)

Chemical Species	Beef (mg/kg wet wt.)	Total Dairy (mg/kg wet wt.)	Pork (mg/kg wet wt.)	Poultry (mg/kg wet wt.)	Eggs (mg/kg wet wt.)
Arsenic	1.2E-05	5.4E-07	na	na	na
Cadmium	1.2E-09	1.0E-10	8.4E-11	5.1E-13	1.2E-14
Zinc	na	na	na	3.5E-12	3.5E-12
Total PAHs[a]	2.7E-06	8.5E-07	2.2E-07	9.8E-12	5.6E-12
Total Dioxin/furans[b]	2.1E-08	6.8E-09	1.8E-09	2.2E-15	1.3E-15

Abbreviations: wt = weight; na = not assessed; PAH = polycyclic aromatic hydrocarbons.
[a] Total PAHs calculated as sum of the products of individual congener concentrations and relative potency factors (RPFs).
[b] Total dioxins/furans calculated the same way using toxicity equivalency factors (TEFs or TEQs).

MIRC-estimated concentrations are not compared to tissue-based toxicity benchmark concentrations for livestock or wildlife for several reasons:

- Tissue-based toxicity values for animals usually are specified in terms of the concentration in specific organs or tissues, often kidney, liver, brain, and fat deposits, because few if any chemicals distribute equally throughout the body. HHRAP-MIRC-estimated concentrations are based on soil-livestock transfer factors intended to reflect concentrations in muscle/meats (and in milk, cheese, and eggs) as consumed by humans. Those concentrations are likely to differ from those in kidney, liver, brain, or lungs, which often are the initial organs damaged by toxic chemicals.

- Although dose-response toxicity reference values are available for some chemicals for birds and small mammals, scaling of those doses to large-bodied, herbivorous, ungulates would introduce uncertainty arising from substantial differences in digestive processes. The available TRVs derived for wildlife, the highest no-observed-adverse-effect levels and the lowest-observed-adverse-effect levels (LOAELs) from laboratory toxicity tests for growth, reproduction, and survival are not necessarily indicative of herd- or population-level impacts. The relationships to doses that might impact agricultural productivity or livestock marketability would introduce another source of error.

- Inhalation of air-borne chemicals by livestock is not likely to cause adverse health effects given the short (48-hr) exposure duration. Moreover, inhalation benchmarks to protect individual humans from irritation (eyes, nose, throat, lungs) are likely to be much lower than inhalation benchmarks to protect long-term health of humans or livestock.

1.1.2. Environmental Exposure

To examine the potential for adverse effects in wildlife exposed to chemicals originating from the on-site carcass management options, the estimated concentrations of chemicals in soils and the lake associated with each option are compared to available ecological benchmarks.

For soils, this assessment uses USEPA's Superfund *Ecological Soil Screening Levels* (EcoSSLs). The EcoSSLs are intended to screen chemical concentrations in surface soils for potential impacts on wildlife, vegetation, and soil biota (e.g., earthworms, other soil invertebrates important to soil aeration and nutrient recycling). Chemical bioavailability in soils to plants, invertebrates, and vertebrates that ingest soils incidentally as they forage, depends on many factors, including soil-specific characteristics. Some of the EcoSSLs are near background levels (conservative assumptions used in their calculation); those values are of limited utility as a screening tool. Despite the conservative nature of the EcoSSLs, they are several orders of magnitude greater than the estimated concentrations of contaminants in surface soil resulting from the carcass management options (Table 5.4.4). This suggests that use of any of the analyzed carcass management options is not likely to pose risks to wildlife from the estimated concentrations of chemicals in surface soil.

Under the CWA, USEPA's Office of Water develops National Ambient Water Quality Criteria for the Protection of Aquatic Life (NAWQC-AL) and their uses. Criteria for many metals depend on water characteristics, such as hardness or pH. NAWQC-AL for chronic exposures (assuming neutral pH and hardness of 100 mg/L as $CaCO_3$ for chemicals for which those influence toxicity) are provided in Table 5.4.5 along with estimated contaminant concentrations in the on-site lake for each of the four on-site livestock carcass management options. For all chemicals and livestock carcass management options, the estimated surface water concentrations are lower than the chronic NAWQC-AL (Table 5.4.5). This suggests that chemicals reaching surface waters from use of any of the analyzed carcass management options are unlikely to cause toxic effects in aquatic life.

Table 5.4.4 Estimated Surface Soil Concentrations Compared with Ecological Soil Screening Levels

Chemical Species	Ecological Soil Screening Levels (mg/kg)[a]				Estimated Soil Concentration (mg/kg)			
	Invertebrate	Mammalian	Avian	Plant	Open Burning	Air Curtain Burning	Initial Applied Compost	Applied Compost at 1 Year
Arsenic	nd	4.6	43	18	1.3E-12	3.2E-13	na	na
Cadmium	nd	nd	nd	nd	1.4E-10	1.4E-10	1.3E-03	6.9E-05
Chromium	nd	130	nd	nd	3.0E-10	1.3E-10	2.2E-02	2.4E-04
Copper	nd	230	120	13	6.9E-10	4.2E-10	8.9E-02	2.8E-03
Iron	nd	nd	nd	nd	4.0E-04	3.3E-05	1.6E+00	7.8E-01
Lead	1,700	56	11	120	2.0E-08	9.6E-09	1.4E-01	4.8E-02
Manganese	450	4,000	4,300	220	3.8E-06	4.2E-05	3.3E-02	1.6E-02
Nickel	280	130	210	38	1.3E-09	3.2E-10	3.3E-02	1.9E-03
Zinc	120	79	46	160	8.8E-09	1.2E-08	3.4E-01	1.9E-02
PAHs	nd	nd	nd	nd	5.4E-06	1.7E-08	na	na
Dioxin/ Furans	nd	nd	nd	nd	1.1E-13	5.4E-12	na	na

Abbreviations: wt = weight; nd = no data; na = not assessed; PAH = polycyclic aromatic hydrocarbons.
[a] Chemical-specific Eco-SSL reports can be found https://rais.ornl.gov/documents/eco-ssl_[chemical].pdf. For example, the Eco-SSL document for nickel can be found at https://rais.ornl.gov/documents/eco-ssl_nickel.pdf. Also theoretically at http://www.epa.gov/ecotox/ecossl/; however, that link seems to lead to ECOTOX only.

Water quality criteria for nutrients like phosphorus and nitrogen in lakes depend on attributes of the ecoregion in which the lakes are located. For this reason, there are no NAWQC for nutrients, so instead, this assessment uses nutrient criteria from the USEPA Ecoregions in which livestock are raised in large numbers. These include USEPA Regions 4, 5, 6, 8, 9, 12, and 14. Total phosphorus criteria ranged from 8–33 µg/L while total nitrogen criteria ranged from 240–560 µg/L across those six regions. The criteria are based on the 25th percentile reference conditions for the region.

This assessment used the minimum values for each nutrient as criteria (Table 5.4.5). Nutrient criteria exist for 10 of the 12 USEPA Ecoregions. For any given lake, the effect of added nitrogen or phosphorus depends on the limiting factor for algal growth, which in turn depends on surrounding land use, air deposition patterns, and hydrogeology. Although the burial option might be expected to result in nutrients leaching to groundwater, and excessive concentrations of chemicals in surface water, the estimated surface water concentrations did not exceed the lowest nutrient criteria from any of the six USEPA Ecoregions. Ecoregional nutrient criteria for lakes

and reservoirs are published by ecoregion at http://www.epa.gov/nutrient-policy-data/ecoregional-nutrient-criteria-documents-lakes-reservoirs.

In contrast to the estimated concentrations of a chemical in water pumped from a groundwater well, which are constrained to a well-intercept diameter of 0.2 m, surface water concentrations depend entirely on the relative volume and configuration of the chemical's source and the volume and shape of the surface water. Ponds less than 91 m in diameter (e.g., a few acres total) might intercept almost all of a groundwater plume from carcass burial (see Figure 5.4.1; note different scales for the single lake on the left and the two smaller lakes on the right side of the figure). In a worst-case environmental setting with evaporation and no additional water sources, a pond might develop chemical concentrations close to the original leachate concentrations. Lakes larger than the 40.5 ha (100 ac, more than 600 m diameter) lake assumed in this assessment would accumulate less. Larger, longer burial trenches could result in higher amounts of chemicals transported to nearby surface waters. Many additional factors, including geometry and size of the source and those of the lake, influence the process of groundwater recharge and the potential for contamination of a lake.

This assessment qualitatively considers disruption of a lake ecosystem, with possible eutrophication from nutrient loading and possible oxygen depletion and fish kills from increased biological oxygen demand (BOD) and chemical oxygen demand (COD) discharge to the water column. The major source of BOD and COD discharged to the lake is expected to be an on-site burial trench. The degree to which a surface water can maintain equilibrium in the presence of

Table 5.4.5. Chemical Concentrations in Surface Water compared to National Ambient Water Quality Criteria for Aquatic Life – Criterion Continuous Concentration (CCC) (i.e., for chronic exposures)

Chemical Species	NAWQC-AL (µg/L)	Concentrations in Surface Water (µg/L), Large Lake (40.5 ha)					
		Storage Pile	Open Burning	Air curtain Burning	Burial	Compost Windrow	Compost Application
Total Dioxins/furans[a]	nd	na	9.3E-13	3.2E-11	na	na	na
Total PAHs[b]	nd	na	2.0E-04	4.7E-07	na	na	na
Arsenic	1.5E+02	na	2.3E-04	4.3E-05	na	na	na
Cadmium	nd	na	1.4E-04	1.1E-04	na	na	1.9E-03
Chromium	1.1E+01	na	6.1E-03	2.1E-03	na	na	6.3E-02
Copper	9.0E+00	1.6E-10	2.6E-03	1.3E-03	2.5E-09	1.3E-10	2.6E-01
Iron	1.0E+03	1.9E-07	1.4E+00	1.0E-01	7.1E-07	3.5E-08	1.3E+02
Lead	2.5E+00	na	1.2E-04	4.5E-05	na	na	5.9E-02
Manganese	nd	8.6E-10	5.0E-03	4.9E-02	5.8E-09	2.9E-10	5.6E-01
Nickel	5.2E+01	6.9E-10	1.4E-03	2.8E-04	1.4E-09	7.1E-11	6.3E-02
Zinc	1.2E+02	6.3E-09	1.1E-02	1.2E-02	6.0E-08	3.0E-09	6.8E-01
Ammonium	—	2.5E-03	na	na	6.6E-02	3.3E-03	na
Chloride	2.3E+05	1.2E-03	na	na	1.5E-02	7.4E-04	na
Phosphorus	8.0E+00[c]	4.4E-04	na	na	7.0E-03	3.5E-04	na
Potassium	Nd	9.0E-04	na	na	1.2E-02	6.2E-04	na
Sodium	Nd	7.6E-04	na	na	1.2E-02	6.0E-04	na
Sulfate	Nd	2.7E-03	na	na	4.6E-02	2.3E-03	na
Sulphur	Nd	5.7E-04	na	na	1.0E-02	5.0E-04	na
Total Nitrogen	2.4E+02[c]	2.2E-02	na	na	2.8E-01	1.4E-02	na

Abbreviations: NAWQC-AL = National Ambient Water Quality Criterion – Aquatic Life; ha = hectares; nd = no data; na = not assessed; PAHs = polycyclic aromatic hydrocarbons.

[a] Human toxicity equivalency factors (TEFs or TEQs) relative to 2,3,7,8-TCDD are applied to individual congeners then concentrations are summed for the group.

[b] Totaled from individual congeners using human relative potency factors (RPFs) relative to benzo(a)pyrene (BaP).

[c] Lowest of six USEPA regional nutrient criteria expressed at the 25th percentile of observed effects (USEPA Regions 4, 5, 8, 9, 12, and 14 considered representative of livestock raising states).

excess nutrients, without changes to the balance of aquatic plant and animal life, depends on many factors. These factors include the nutrient status of the water body, which nutrient(s) are limiting for aquatic plant growth, and whether other nutrient sources (e.g., fertilizer, manure runoff) are present. The degree to which oxygen might be depleted with input of materials with measureable BOD and COD also depends on many factors, particularly temperature (colder waters can hold more oxygen at saturation than warmer waters). Stress from BOD and COD would be expected only for smaller ponds. The larger lake simulated in this assessment (40 ha or 100 ac) is unlikely to be disrupted by the types or amounts of chemicals associated with the carcass management options. This suggests that use of any of the analyzed on-site carcass management options is not likely to pose risks of eutrophication or disruption of lakes 40 ha or

larger from the estimated amounts of chemicals that might enter the environment when setbacks of 30.5 m (100 ft) or more are followed, including the area where compost is applied.

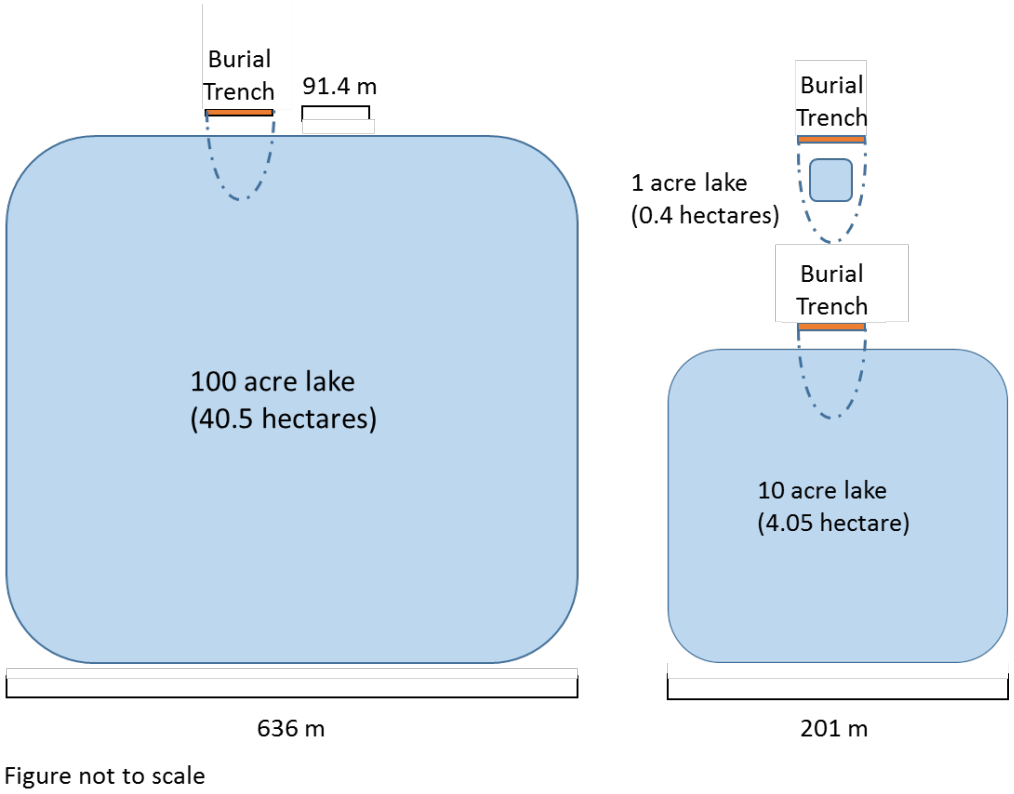


Figure 5.4.1 Relationship between emerging contaminant groundwater plume from carcass burial trench to surface water bodies of various sizes.

6. Exposure Estimation for Microbes

As living organisms, microbial dynamics and fate in the environment are very different from chemicals. Their survival is modified by environmental conditions, and various microbes might be affected very differently by the same conditions. In addition, measurements of the number of microorganisms present in a contamination source (in this instance, livestock carcasses) and at the time of human exposure are rarely available (Lammerding and Fazil 2000; Joung et al. 2013). Because of differences in the behavior of microbes and chemicals in the environment and in data availability, the chemical fate and transport models and methods described in Section 4 are not suitable for estimating microbial exposures associated with livestock carcass storage and handling, transportation, or the livestock carcass management options. This section describes the methods used to estimate human, livestock, and ecological exposures to microbes.

Human and livestock exposure to microbes is likely only from ingestion of groundwater from the drinking water well; all other routes of exposure to microbes were determined to be negligible or to be unquantifiable. Ecological exposure to microbes may occur through multiple routes and mediums and these routes were unable to be quantitatively assessed. Published screening-level models for estimating exposure to pathogens, with many parameter values selected to be representative nationwide like chemical screening models (e.g., USEPA 2005a), are not available for microbes. Existing pathogen fate and transport models are limited in number and require a significant amount of refinement and user input of parameter values, many of which are unknown in Phase 1. In addition, each of the microbes identified as a potential hazard in Table 2.4.4 could have unique inputs for these models (e.g., initial loading at the time of death, microbial suspension in porous media, surface attachment, survival curves), many of which have not been defined for some of the pathogens identified in Table 2.4.4. Assumptions for any of these input values could significantly alter the modeling results.

In the absence of quantitative data on important modeling inputs such as the initial loading concentration associated with healthy livestock and rate of growth/die-off for each pathogen, the assessment uses less refined quantitative approaches relying on simplified assumptions about the initial loading, decay rate, ingestion rate (human and cattle, where appropriate), adult body weight, and vertical fate and transport efficiency. Data for those parameters were gathered for three pathogens: prions (a highly thermotolerant microorganism with a high rate of

environmental survival and small diameter); *Bacillus anthracis* (a spore-forming bacterium also with high thermal tolerance and high environmental survival); and *E. coli* O157:H7 (a pathogenic zoonotic species of bacteria commonly found in the gut of cattle and swine and frequently identified as the etiologic agent in cases of waterborne and foodborne illnesses in humans).

The assessment estimates initial loading concentration in two ways depending on the availability of quantitative data for the specific pathogen. This assessment uses land-applied Class B biosolids measurements as the loading concentration, if these data are available. In the absence of measured concentrations of the pathogen in biosolids, the assessment estimates initial loading concentration based on published values for the infectious dose in 50% of cattle. The initial loading concentration is assumed to be one-half of the infectious dose, because the cattle are assumed free of signs or symptoms of illness when the natural disaster strikes. Human exposure factor values (e.g., for body weight, water ingestion) are mean values obtained from the most recent version of USEPA's *Exposure Factors Handbook* (USEPA 2011). A step-wise equation is used to calculate the density of prions, *B. anthracis*, and *E. coli* O157:H7 in groundwater at the time of ingestion from the initial release to groundwater through one year of exposure.

Simple methods evaluate exposures to livestock and wildlife that survive the natural disaster. For microbes, a step-wise equation estimates the ingestion of the three selected pathogens with groundwater used for watering livestock. The variables in this equation reflect the ingestion rate and body weight of livestock, and there are separate calculations for cattle for winter and summer because the ingestion rate varies during the course of a year.

An initial list of potential microbial hazards that could be present in livestock that are not exhibiting symptoms of infection or disease (and are not known to have been exposed to a foreign animal disease agent or other infectious agent) is presented in Section 2.4.2, Table 2.4.4. Some of the agents in that list are not expected to survive carcass storage and handling, transportation, and management. For example, microbes that would not survive the thermal processes associated with combustion-based and rendering processes were removed from the list of potential microbial hazards for those management options. For the reasons given below, a subset of representative microbes was selected from the larger set of microbes identified in Section 2.4.2 for inclusion in the exposure assessment:

- **Prions** – Prions (proteinaceous infectious particles) are unique pathogens that have no nucleic acid and thereby differ from viruses, bacteria, and other pathogens. Prions are resistant to procedures that break down nucleic acid; they are considered the most resistant microbial agents in the list of potential hazards presented in Table 2.4.4. Prions also can survive relatively high combustion temperatures. For this reason, prions are likely to survive temporary storage, handling, and transportation for all management options. Prions also are likely to survive carcass open-burning, burial, and composting. The concentration of prions in environmental media in areas where TSEs are endemic is largely unknown due to the limited ability to detect prions in or extracted from environmental samples. Natural biotic and abiotic mechanisms of protein degradation might reduce prion infectivity in the environment.

- ***Bacillus anthracis*** – While spore-forming organisms such as *B. anthracis* are destroyed by the combustion processes characteristic of some management options, they can survive the temperatures reached during livestock composting even though these temperatures can inactivate other pathogens. In addition to surviving the composting process, spores of *B. anthracis* can also persist in air, soil, and water, and are assumed to be present during carcass storage and handling, transportation, and on-site unlined burial (Stanford et al., 2015). In the United States, inhalation anthrax generally is associated with exposure to wool, bone, animal hides, and bioterrorist attacks (Griffith et al. 2014).

- ***Escherichia coli* strain O157:H7** – *E. coli* O157:H7 can account for up to 1% of the bacterial population of the gut in ruminant animals, including cattle. The gastrointestinal system can act as a reservoir for the pathogenic bacterium *E. coli* strain O157:H7 (Callaway et al. 2009). Approximately 30% of feedlot cattle shed *E. coli* O157:H7, and high concentrations of *E. coli* O157:H7 are reported in cattle manure (Callaway et al. 2009). *E. coli* O157:H7 has been detected in cattle feces and Class B land-applied biosolids (Hutchinson et al. 2005; Pepper et al. 2010). Hutchinson et al. (2005) reported a concentration of 1,200 colony forming units (CFU) of *E. coli* O157:H7 per gram of cattle feces and Pepper et al. (2010) reported a concentration of 1 CFU of *E. coli* O157:H7 per 1 gram dry biosolid. *E. coli* O157:H7 excreted in cattle feces can be transmitted to humans and cause illness (Matthews et al. 2013). The incidence of human illness caused by *E. coli*

O157:H7 is high, with an estimated 63,000 cases occurring in the United States each year (Scallan et al. 2011). However, it is unclear how many of these illnesses are associated with transmission from cattle feces. *E. coli* O157:H7 can persist in air, soil, and water, but is inactivated by the thermal processes characteristic of the open-burning, air-curtain burning, and composting processes. However, *E. coli* O157:H7 could remain viable during the burial process and during storage, handling, and transportation.

Assessment of pathogen exposure considers properties related to the fate and transport of microbes in the environment. It is not feasible to identify and consider every parameter that affects fate and transport for every pathogen mentioned in this exposure assessment. Instead, data on four properties of pathogens are aligned with the variables identified in the equations used in the exposure estimation for pathogens (described, when available, in Section 6.2 and 6.3 for each media compartment). The assessment uses quantitative data from the literature for four properties (presented in Table 6.1.1):

- **Size of the microorganism:** Particle size affects rates of diffusion and movement of the microbes with fluids through soil, dispersion in air, and suspension in water.
- **Survival/persistence:** The growth and/or inactivation of the microbe in the environment outside of livestock carcasses affect its ability to reach living animals or humans. Pathogens can become dormant or shift to environmentally long-lived forms, such as endospores. For some types of microbes, the concentration of viable agents can be significantly reduced after release to the environment. For example, viruses are not able to replicate outside of a host cell and therefore are not expected to multiply in air, water, or soil. Microbial survival in the environment is often linked to the ambient pH. In contrast, microbial growth and reproduction is linked to the availability of water and/or nutrients. For those reasons, the broad criterion of "survival" facilitates assessment rather than focusing on variability among microbial populations or precise survival mechanisms.
- **Illness(es) caused and infectious dose:** Infection with a specific microbe is typically associated with specific illnesses and health effects. Infectious dose (ID) is the number of microbes required to cause infection in the host, in this case in healthy adult humans or healthy adult cattle. The ID_{50} refers to the dose of an infectious organism required to

Table 6.1.1. Evaluation Factors Included in the Exposure Assessment for Microbes.

Category	Organism Name	Size	Illness(es) Caused; Infectious Dose (ID)	Survival Rate	References
Bacteria – Gram negative	*Escherichia coli* O157:H7	0.25 – 1 µm wide; 2 µm long	**Illness:** Range from mild gastrointestinal illness, life-threatening disease hemolytic uremic syndrome (HUS) **ID_{50}[a] Humans:** 10 –100 organisms **ID_{50} Cattle:** <300 organisms	**Cattle manure amended soil:** 1.25 x 10^{-3} organisms/hr **Air:** 0.2 organisms/hr **Water:** 3.12 x 10^{-3} organisms/hr; 1.31 x 10^{-2} organisms/ hr with a 90% reduction in 3.18 days	Filip et al. 1988; Himathongkham et al. 1999; Besser et al. 2001; Hutchinson et al. 2005; Nyberg et al. 2010; Gurian et al. 2012
Bacteria – Spore-forming	*Bacillus anthracis*	1 – 2 µm (diameter)	**Illness:** Cutaneous anthrax, gastrointestinal anthrax, inhalational anthrax **ID_{50} Humans:** 8,000-50,000 (inhalation); generally in the 1,000s or 10,000s spores for other exposure routes **ID_{50} Cattle:** < 10 spores in susceptible herbivores to > 107 spores in more resistant livestock species(administered parenterally)	**Human Sewage:** 1.74 x 10^{-4} organisms/hr **Soil (moist):** 8.42 x 10^{-5} organisms/hr **Water:** 1.14 x 10^{-4} organisms/hr **Air:** 4.64 x 10^{7} organisms/hr	Sinclair et al. 2008; WHO 2008
Prion	PrP^{Sc}	10 – 20 nm wide; 100 – 200 nm long	**Illness:** In cattle, BSE; In humans, vCJD or nvCJD **ID_{50} Humans:** Unknown **ID_{50} Cattle:** 5.5 x 10^{-3} particles	**Soil:** 7.61 x 10^{-5} organisms/hr **Air:** Unknown **Water:** 0.0069 organisms/hr	Brown and Gajdusek 1991; Miller et al. 2004; Yamamoto et al. 2006; Miles et al. 2011

Abbreviations: CFU = colony forming units; hr = hour; BSE, bovine spongiform encephalopathy; CJD, Creutzfeldt–Jakob disease; v, variant; nv, new-variant.
[a] The infective dose of microorganisms that will cause 50% of exposed individuals to become ill.

produce infection in 50 percent of the experimental subjects. In some instances, the ID_{50} is only available for healthy adult cattle and is not available for humans.

- **Available loading data**: The concentration and distribution of the microbe in livestock carcasses is an important element of evaluating exposure. Data on the concentration of microbes in cattle manure should be representative of materials in the gastrointestinal tract. For prions and *B. anthracis*, measured data on the concentration of these agents in cattle or biosolids was limited. Many laboratory studies relied on spiked samples with known starting concentrations selected by the researchers (e.g., a concentration associated with an adverse effect on human health or livestock. The laboratory-spiked samples did not reflect loading associated with natural populations present in healthy cattle (Kinckley et al. 2008; Jacobson et al. 2009). Assumptions are made on initial carcass concentrations or prions and *B. anthracis* using ID_{50} values. This approach has been used in other published risk assessments and exposure analyses (Gale et al. 1998; Grist 2005). The loading value for *E. coli* O157:H7 is based on its reported concentration in land-applied Class B biosolids (Pepper et al. 2010).

The use of data on surrogates[16] for assessing fate and transport is common when quantitative data on a specific pathogen is not available (Sinclair et al. 2012). In Phase 1 of this assessment of carcass management options (i.e., mass livestock mortality from a natural disaster), initial loading for pathogens are levels that could occur in healthy livestock. Concentrations of common surrogates for *B. anthracis* and *E. coli* O157:H7 would result in a gross overestimation of the initial loading in healthy livestock. Fecal coliforms and total coliforms, common surrogates for *E. coli* O157:H7, are abundant in the environment and their presence does not necessarily indicate the presence of virulent pathogens (Ashbolt et al. 2001). Measured concentrations of fecal coliforms or total coliforms present in healthy cattle would likely be greater than concentrations of *E. coli* O157:H7 present in healthy livestock killed during a natural disaster. *B. anthracis* is generally not measured because it presents a significant threat to public health. Instead, surrogates of *B. anthracis*, including other species of *Bacillus* such as, *B. cereus, B. putida, B. arvi, B. pumilus, B. sphaericus, B. psychodurans, B. subtilis,* and *B. foetidans*, have

[16] A surrogate is an organism, particle, or substance used to evaluate the fate of a pathogen in a specific environment. Pathogenic organisms, nonpathogenic organisms, and innocuous particles have been used as surrogates for a variety of purposes, including studies on survival and transport as well as for method development and as "indicators" of certain conditions (Sinclair et al. 2012).

been studied to understand the fate and transport of *B. anthracis* spores in the environment (Greenberg et al. 2010). However, investigators have measured decay rates for *B. anthracis* (i.e., inactivation of spores) in a variety of media; thus data from surrogate microbes were not needed. Although data on *B. anthracis* loading in healthy livestock populations was not available, data on surrogates would not have provided an accurate measure of *B. anthracis* in healthy livestock. Like fecal coliforms and total coliforms, *Bacillus* species are abundant in cattle and use of a surrogate would overestimate the initial concentration for *B. anthracis* in healthy cattle (Wu et al. 2005). Therefore, data specific to the three pathogens assessed were favored over the use of data on general surrogates which are more abundant in the natural flora of livestock

The remainder of this section is organized in three subsections. A summary of the exposure pathways included in the microbial exposure assessment is provided in Section 6.1. Evaluations of source conditions and microbial properties allowed elimination of several pathways because they pose negligible risks of illness in humans or livestock in this scenario. For the remaining exposure pathways, availability of quantitative data determined whether a quantitative or qualitative assessment of exposure can be done. The decision criteria used for these determinations are also discussed in Section 6.1.

Section 6.2 describes how potential human exposures to the three microbes could occur, and where data allow, how possible microbial exposures were estimated for livestock carcass storage, handling, and transportation for each of the carcass management options.

Section 6.3 discusses livestock and wildlife exposures to microbes.

There were insufficient data to quantitatively compare possible exposure levels to health protective benchmarks.

6.1. Summary of Human Exposure Pathways for Microbes

Pathways of human exposure to microbes assessed for this report are highlighted in bold in Table 6.1.2. Pathways with quantified exposures are indicated with bold type and endnote “a.” Exposure pathways indicated by endnote “b” in Table 6.1.2 are assumed to be negligible. Exposure pathways indicated by endnote “c” are assumed to be adequately controlled by existing pollution control regulations or use of PPE (i.e., gloves, dust mask). The rationale for excluding

Table 6.1.2. Human Exposure Pathways for Livestock Carcass Management Options – Microbes

Exposure Route and Medium	Exposure Pathways Transportation and Handling Activities			Exposure Pathways Management Options						
	Carcass Handling	Temporary Carcass Storage	Carcass Transportation	Open Burning	Air curtain Burning	Burial	Composting	Off site Incineration	Off site Landfilling	Rendering
Inhalation	1) Air → Inhalation[c]	1) Air → Inhalation[c] 2) Leachate → Soil → GW → Aerosol	1)Aerosol[b]	1) Air[b] 2) Ash → GW → Aerosol[b]	1) Air[b] 2) Ash → GW → Aerosol[b]	1) Air[b] 2) Leachate → GW → Aerosol[b]	1) Air[b] 2) Compost → GW → Aerosol[b]	1) Air[c]	1) Air[c]	1) Air[c]
Direct Ingestion	2) Hand-to-mouth oral contact[c]	—	—	—	—	—	—	—	—	—
Incidental Soil Ingestion	—	—	—	3) Air → Soil[b]	3) Air → Soil[b]	—	—	2) Air → Soil[c]	—	—
Fish Ingestion	—	3) Leachate → Soil → GW → SW → Fish ingestion[b]	—	4) Air → SW → Fish[b] 5) Air → soil → SW → Fish[b] 6) Ash → GW → SW → Fish[b]	4) Air → SW → Fish[b] 5) Air → Soil → SW → Fish[b] 6) Ash → GW → SW → Fish[b]	3) Leachate → GW → SW → Fish[b]	3) Compost → Soil → SW → Fish[b] 4) Compost → GW → SW → Fish[b]	3) Air → SW → Fish[c] 4) Air → Soil → SW → Fish[c]	—	—
Ground-water Ingestion	—	**4) Leachate → Soil → GW → Drinking water ingestion[a]**	—	**7) Ash → GW[a]**	7) Ash → GW[b]	**4) Leachate → GW[a]**	**5) Compost →Leachate → GW[a]**	—	—	—
Ingestion of Food Produced on the Farm	—	—	—	8) Air → Plants/ Livestock[b] 9) Air → Soil → Plants/ Livestock[b] 10) Ash → GW → Livestock[b]	8) Air → Plants/ livestock[b] 9) Air → Soil → Plants/ Livestock[b] 10) Ash → GW → Livestock[b]	5) Air → Plants/ Livestock[b] 6) Leachate → GW → Livestock[b]	6) Air → Plants/ Livestock[b] 7) Compost → Soil → GW → Livestock[b]	5) Air → Plants/ Livestock[c] 6) Air → Soil → Plants/ Livestock[c]	2) Air → Plants/ Livestock[c]	2) Air → Plants/ Livestock[c]
Dermal Contact	3) Dermal contact[c]	--	—	—	—	—	—	—	—	—

Abbreviations: "—" = no exposure pathways; SW = surface water; GW = groundwater.
Note: Exposure pathways shown in bold were included in the quantitative exposure assessment.
[a] Quantitative assessment conducted; results are presented in Section 6.2. [b] Potential exposures are assumed to be negligible based on source conditions or microbial properties.
[c] Environmental releases or exposures are assumed to be adequately controlled by existing pollution control regulations or use of personal protective equipment.

pathways from further evaluation (endnotes "b" and "c") is discussed in more detail below.

Exposures along pathways in Table 6.1.2 indicated by Table endnote "b" are assumed to be negligible for the reasons discussed below. To avoid repetition, the reasons are grouped by exposure pathway and medium. Thermal inactivation is discussed first, however, because it affects pathways associated with five carcass management options: the on-site open-pyre burning, air-curtain burning, composting, and the off-site incineration and rendering options.

- **Thermal Inactivation** – The temperatures reached and the duration of high temperatures for on-site air-curtain burning and off-site incineration management options are high enough to destroy the microbes identified as potential hazards, including prions. However, the burn temperature reached during on-site open burning (e.g., 550°C) is lower than the temperatures reached during on-site air-curtain burning (e.g., 850°C) and off-site incineration (e.g., >1,000°C). While most pathogens would be inactivated or destroyed at 550°C over two days, more heat-resistant prions would not be inactivated. Similarly, many pathogens are inactivated by the temperatures characteristic of on-site composting (e.g., at least 55°C for three or more days), but prions or spores formed by some types of bacteria (e.g., *B. anthracis*) are unlikely to be inactivated by the lower heat associated with composting. Thermal inactivation of pathogens sufficient to pose a negligible risk of illness is likely for four carcass management options and some or all of the associated pathways identified in Table 6.1.2:
  - Open burning, exposure pathways 1–10; two of the three pathogens considered for the natural disaster scenario are excluded, prions are included
  - Air-curtain burning, exposure pathways 1–10; all three pathogens considered for the natural disaster scenario are excluded
  - Composting, exposure pathways 1–7; one pathogen, *E. coli* O157:H7, is included; two are excluded from further evaluation: spore-forming bacteria and prions
  - Off-site incineration, exposure pathways 1– 6; all three pathogens considered for the natural disaster scenario are excluded

- **Inhalation** – Pathways that can lead to inhalation of aerosolized well water by humans (e.g., showering, boiling) are not quantified for exposure pathways associated with carcass

transportation and handling activities or the management options. For temporary carcass storage and the combustion-based, composting, and burial options, those pathways are assumed to be insignificant compared with ingestion of well water (e.g., drinking, reconstituting dried foods). Boiling foods would inactivate bacteria in the well water, but not inactivate prions and bacterial spores. Based on simulated combustion studies, prions generally are not released directly to air during the burning process (Brown et al. 2004). Although survival of prions in air has been observed (Haybaeck et al. 2011; Xavier 2014), the small initial concentration in healthy livestock suggests that a negligible concentration of viable prions would be released to air from an open pyre. Moreover, humans are assumed to be at least 100 feet from the pyre (Turnbull et al 1998). Inhalation exposures, therefore, are *not assessed* for the management options, exposure pathways, and potential microbial hazards specified below:

- Open burning, exposure pathways 1 – 2; prions
- Temporary carcass storage, exposure pathway 2; all three pathogens considered for the natural disaster scenario
- Burial, exposure pathway 1; all three pathogens considered for the natural disaster scenario
- Composting, exposure pathways1 – 2; all three pathogens considered for the natural disaster scenario

- **Soil ingestion** – With the on-site open-burning option, microbes initially released to air with soot are assumed to be deposited onto soils surrounding the pyre during the 48 hours of combustion. Accidental ingestion by workers (e.g., via hand-to-mouth contact) could occur during carcass combustion activities. Accidental ingestion by farm residents could occur either during or after those activities. For workers, the exposure is avoided by using disposable gloves and other personal protective equipment (as required in this assessment). Farm residents are unlikely to spend significant time on a daily basis in contact with the soil near the combustion site which effectively limits the risk of soil ingestion exposure. Children should not be allowed access the work site, so even if they engage in geophagy, they are unlikely to directly consume contaminated soil. Consequently, ingestion of soil is considered an incidental and negligible exposure pathway for workers and adult and child farm

residents. Incidental soil ingestion, therefore, is *not* assessed for the one possible remaining management option, exposure pathway, and type of microbe:

- Open burning, exposure pathway 3; prions.

- **Fish ingestion** – Fish in the on-site farm lake can be exposed to pathogens if contaminated groundwater enters the lake or when pathogens are deposited via air to the lake's surface. Groundwater could be contaminated if pathogens move from the carcasses through the soil and reach groundwater. Pathogens can reach surface soils via direct deposition from air or can reach subsurface soils from percolation of rainwater through buried ash or leaching of fluids from buried livestock carcasses. A significant reduction in the concentration of viable microbes released from carcasses is expected for microbes that require a living host to be active. Microbes also are likely to adhere to particles in the environment. Inactivation and attachment to soil particles can significantly reduce the number of viable microbial agents transported from buried carcasses or buried ash through the subsurface soil to groundwater. Therefore, the discharge of groundwater to the lake, and the subsequent entry of pathogens into the aquatic food web, is considered negligible.

  Some pathogens can bioaccumulate in fish when fish consume bacteria and phytoplankton (to which microbes can adhere) are present in the aquatic environment. Microbes can also accumulate in filter-feeding benthic organisms, including shellfish, that might be collected for human consumption. Shellfish supported by freshwater ponds, like the one at the hypothetical farm, and consumed by humans, appear to be limited to crayfish, which are detritus feeders and scavengers. The consumption of undercooked or raw crayfish has been linked to human illness from pathogens in the crayfish, but not to any of the pathogens included in our list of potentially hazardous microbes associated with on-site open burning and on-site unlined burial. Some pathogens associated with livestock, including *Mycobacterium* spp., *E. coli* O157:H7, *Salmonella* spp., *Clostridium perfringens*, and *Campylobacter* spp., are linked to foodborne illness in humans following the consumption of fish (Novotny et al. 2004). Outbreaks usually occur if the fish are inadequately cooked, or fish products are contaminated after/during their processing (Novotny et al. 2004).

There have been concerns that scrapie-causing prion protein (PrP^{Sc}) can cause diseases in animals of different taxa, such as fish; however, the passage of disease is usually impaired by a taxonomic barrier. Laboratory research indicates that prions for mammalian diseases do not infect fish (see Ingrosso et al. 2006). Moreover, if fish were to become infected, they could not spread this disease to mammalian species. Several *in vitro* and *in vivo* experiments have concluded that fish tissues taken at different times after parenteral or oral inoculation with scrapie-causing prion protein (PrP^{Sc}) did not induce disease in mice directly inoculated with these infected fish tissues (Ingrosso et al. 2006). Should prions produce infection in fish, the brain and nervous system would be targeted. Humans would need to consume those tissues to become infected, and those parts of the fish are generally not consumed. It is unlikely that prions would pose a risk to humans if fish from the on-site pond were consumed.

Fresh water sources that support harvesting of bivalves and fish for human consumption would be negligibly affected by even mass-morality carcass management locations. Fish and shellfish harvesting areas provide substantial dilution water. Many species/strains of microbes that cause infection in cattle do not produce infection in fish or shellfish. In addition, the use of proper cooking temperatures and holding times is highly likely to inactivate all pathogens that might be present in fish. Thus, human exposure via aquatic animals is not evaluated for any of the carcass management options. Specifically, the fish ingestion pathway was not evaluated for the management options and potential microbial hazards specified below:

- Temporary carcass storage, exposure pathway 3; all three pathogens considered for the natural disaster scenario
- Open burning, exposure pathways 4 – 6; prions only
- Burial, exposure pathway 3; all three pathogens considered for the natural disaster scenario
- Composting, exposure pathways 3 – 4; all three pathogens considered for the natural disaster scenario

- **Ingestion of food produced or grown on the farm** – Pathways were identified by which farm-grown produce might be contaminated with pathogens for on-site open burning, air-

curtain burning, burial, and composting options. Unlike chemicals, well-defined models for deposition of pathogen particles on plant surfaces or uptake of pathogens by plant roots are not available for microbes. Potential human exposures depend on loading concentrations, survival, and transport of microbes in each segment of food production. Initial loading concentrations are assumed to be low for all of the microbes considered in this exposure assessment. The assessment also assumes an initial reduction in the concentration of viable infectious microbes when the microbes are released to air, followed by additional reductions due to dilution as the microbes move along the pathways presented in Table 6.1.2.

Our conceptual model includes pathways with aerosolized microbes deposited on the surface of plants. There is some evidence that human enteric pathogens interact with plants and the plant environment (Lim et al. 2014). Human enteric pathogens can trigger plant defenses, but recent evidence shows that some human pathogens, such as *Salmonella* spp. and *E. coli*, can overcome plant defenses (Lim et al. 2014). However, a significant reduction in the concentration of pathogens reaching plants for human consumption is anticipated because pathogen movement in the soil is limited, and *Salmonella* spp. and *E. coli* O157:H7 lose viability when in air instead of in a living host. Thus, only a small concentration of viable pathogens could potentially reach crops and become part of the food chain. Plants harvested for human consumption are assumed to be washed, cooked, and/or peeled as appropriate, which would reduce the likelihood of pathogen ingestion. Exposure pathways associated with uptake of microbes via food produced on the farm are excluded from further evaluation for the management options and microbes specified below:

- Open burning, exposure pathways 8 – 9; prions only
- Burial, exposure pathway 5; all three microbes considered in the exposure assessment for the natural disaster scenario
- Composting, exposure pathways 6 – 7; all three microbes considered in the exposure assessment for the natural disaster scenario

Exposure pathways in Table 6.1.2 and indicated by endnote “c” in are assumed to be adequately controlled by existing pollution technologies (particularly for releases to water). In addition, workers should be protected by use of PPE.

Exposure pathways for the off-site management options are not discussed in Sections 3 and 4 because, as explained in Section 2.2, releases to the environment from those options are from pollution control systems that are assumed to operate within permitted levels. Controlled emissions include releases to air and water. Residues on plant surfaces must meet tolerance requirements. Management options, exposure pathways, and microbial hazards excluded from further analysis are listed below:

- Off-site landfilling, exposure pathways 1 – 2; all three pathogens considered for the natural disaster scenario
- Rendering, exposure pathways 1 – 2; all three pathogens considered for the natural disaster scenario

As described in Section 3.1.1, this assessment assumes that recommended PPE includes gloves and a dust mask and that PPE will be used by workers involved in the handling, storage, and transportation of livestock carcasses prior to their disposal. Use of PPE mitigates exposure to microbes for some of the exposure pathways identified in Table 6.1.2:

- Carcass handling, exposure pathways 1 – 3; all three pathogens considered for the natural disaster scenario
- Temporary carcass storage, exposure Pathway 1; all three pathogens considered for the natural disaster scenario

1.2. Estimated Human Ingestion Exposures

The only ingestion source included in the microbial exposure assessment is drinking water pulled from an on-site groundwater well. Drinking water ingestion exposures were estimated for microbes from temporary carcass storage, the on-site unlined burial, and on-site open burning carcass management options. For the first two activities, microbes can be released to the soil and then move with percolating water during precipitation events toward groundwater or move with leachate from carcasses toward groundwater. Microbes that survive open burning and are buried with the bottom ash also can move toward groundwater during precipitation events.

As noted in Table 2.4.4, there are a wide range of microbes associated with temporary carcass storage and on-site unlined burial. For the temporary carcass storage pile, approximately 10 tons of carcasses are placed in contact with bare earth where decomposition begins. During the burial

process, those same carcasses are transferred to an unlined pit, where decomposition continues. As part of the decomposition processes, bodily fluids are released as leachate. All of the microbes listed in Table 2.4.4 (e.g., viruses, bacteria, protozoa, and prions) could remain viable in these fluids. The presence of extensive microbial contamination of subsurface soil surrounding cattle decomposition pits and burial sites is supported by published microbial analyses of these sites (Davies and Wray 1996; Joung et al. 2013). Davies and Wray (1996) placed two calves' carcasses in a deep burial pit and two calves' carcasses in a decomposition pit, each measuring 2.5 m in depth. During pit construction, sampling pipes were inserted in the soil, with two pipes adjacent to the carcasses within the pit and with the remainder in surrounding soils radiating away from the carcasses at distances of 2 cm to 3 m. For each pit (10 sampling pipes per pit), swabs were placed in the pipes and removed one week later. Swab samples were collected before the calves' carcasses were placed in the pit and then weekly for two years after. *Salmonella typhimurium, C. perfringens,* and *Bacillus cereus* (a potential surrogate for *B. anthracis*) were isolated from these samples (Davies and Wray 1996). Pathogens released to soil could enter groundwater with leachate from the carcass storage pile or buried carcasses. Joung et al. (2013) collected groundwater samples from 1,200 sites following the mass burial of livestock carcasses (e.g., cattle, swine, and poultry) after outbreaks of foot and mouth disease and highly pathogenic avian influenza. The samples were collected within a 0–200 m radius from the burial site; the depth of sample collection was not specified. *C. perfringens, Salmonella* spp., and *Shigella* spp. were all isolated from these samples (Joung et al. 2013).

As stated in earlier sections, focus on three microbes (prions, *B. anthracis,* and *E. coli* O157:H7) facilitates this analysis. Their presence is considered when evaluating groundwater ingestion associated with temporary carcass storage, with unlined burial, and with burial of ash from open burning. For the composting option, *E. coli* O157:H7 are expected to be inactivated; therefore, exposure by drinking the groundwater would not occur. Table 2.4.4 illustrates the survival of thermally-resistant pathogens, including prions and bacterial spores. Review of the available literature, however, did not reveal quantitative data on the concentration of those pathogens in leachate from decomposing livestock.

The on-site combustion-based livestock carcass management options yield ash, which is buried on-site. Although the combustion processes are expected to inactivate and/or destroy most

pathogens, viable prions could remain in buried ash from open-burning. Review of the available literature did not reveal any data by which to estimate the concentration of prions in ash or the possible reduction in viable prion concentration that might be associated with open burning. This represents a significant data gap in evaluating this pathway.

Modeling the processes that influence fate and transport of microbes in groundwater is complex. Considerations include (1) the reduction in pathogen populations in both soil and water when there are no available hosts, (2) the ability of the organisms to survive as saprophytes or acquire nutrients from dissolved organic matter, (3) characteristics of the microbes and soils that affect sorption of microbes to soil particles, (4) the porosity of various soil types, and (5) the potential presence of channels created by plant roots or freeze and thaw cycles. In the absence of established models, this assessment uses a multi-step approach to estimate the concentration of the three selected microbes (i.e., prions, *B. anthracis*, and *E. coli* O157:H7) in groundwater and to estimate human ingestion of these agents via drinking water from a well. As part of this approach, it is assumed that there will be no re-growth of the agent in either soil or groundwater prior to exposure.

To quantify exposure, this assessment uses information on four parameters for prions, *B. anthracis*, and *E. coli* O157:H7 (see Table 6.1.1):

- Initial loading concentrations of prions, *B. anthracis*, and *E. coli* O157:H7 in cattle carcasses
- Concentrations of prions, *B. anthracis*, and *E. coli* O157:H7 in leachate and/or ash from cattle carcasses
- Fate of viable prions, spores of *B. anthracis*, and *E. coli* O157:H7 cells in both soil and water
- Vertical fate and transport efficiency[17] for microbes in soil

Prions are expected to be hardiest of the microbes identified as potential hazards. They have a small diameter, are resistant to heat and other environmental stressors, and have been shown to survive for long periods of time in multiple media compartments (Miles et al. 2011; Smith et al.

[17] Vertical fate and transport refers to the vertical migration of microbes as they travel vertically (down) from a source (in this case carcasses) through the soil.

2011). Smith et al. (2011) reviewed the fate and transport of prions in soil and concluded that prion attachment to soil particle surfaces protects them from enzymatic, chemical, or physical degradation. While some soil types can serve as an environmental reservoir for prions for up to three years, mobility in soil is limited (Miller et al. 2004; Smith et al. 2011). Moreover, soil-bound prions are less bioavailable when ingested than free-prion particles. It is plausible that prions released to the soil from buried ash could move toward groundwater (Miller et al. 2004; Smith et al. 2011). Miles et al. (2011) evaluated the fate of prions in water. They reported an approximate 90% reduction of infectious prions at 25°C, 37°C, and 50°C (ranging between 0.5-$\log_{10}$ and 1.4-$\log_{10}$) in one week, with continued reductions over eight subsequent weeks. In the study, higher organic matter in the soil protected prions, allowing them to remain infectious for a longer period of time. Nevertheless, there was a significant reduction in the number of viable prions, and few might be viable by the time they reach groundwater. For the purpose of this assessment, prions are assumed to survive, but are filtered out by soil particles, resulting in few prions that reach groundwater.

In the absence of quantitative data, the starting concentration of microbes in carcasses is assumed to be less than the infectious dose of the microbe associated with their respective illness(es). This assumption applies to all the pertinent pathway assessments. As reported in Table 6.1.1, the populations of all three representative pathogens decrease over time in soil and water without the presence of hosts. This means the concentration of each microbe decreases after the initial release from the decomposing carcass or ash, during the microbe's movement through the soil toward groundwater, and between the transfer of the microbe from the groundwater source to the drinking water well. Estimates of the concentration of each microbe ingested via drinking water from the groundwater well are limited by the assumptions required to develop a starting concentration for the agent in the carcasses and in the groundwater following the agents' transport through the soil. Viable pathogen cells (e.g., *E. coli* O157:H7) are likely to decrease in groundwater over time if they cannot survive through dormancy (e.g., as a spore), as a saprobe, or otherwise take up nutrients from the environment. Pathogen concentrations in groundwater are estimated by multiplying the concentration of each microbe in soil by a vertical fate and transport efficiency factor which accounts for physical loss during downward migration in soil. The major loss process is straining or filtration by soil particles (Bitton and Gerba 1984; Yates et al. 1988). Quantifying vertical transport for microbes is challenging because it depends on soil

properties and weather conditions, including precipitation, which vary substantially. Yates et al. (1988) reported bacterial migration in various types of subsurface materials and provided vertical fate and transport efficiency values for *E. coli* O157:H7 based on a variety of considerations, including temperature, microbial activity, soil type, soil moisture content, pH, organic matter, conductivity, and hydraulic condition among others. The authors reported a maximum travel distance for *E. coli* O157:H7 of 4 m and assumed a vertical fate and transport efficiency of 0.01(Yates et al. 1988, Table 6). That means that if the density of *E. coli* O157:H7 in soil is equal to 100 organisms per m^3, then only 1 *E. coli* O157:H7 cell per m^3 reaches groundwater.

Table 6.2.1. Quantitative Assumptions for the Groundwater Exposure Pathway for Microbes

Pathogen	Estimated Initial Loading Concentration (organisms/m^3)	Decay Rate (hour 1)	Reference
Prions (PrP^{Sc})	5.50E-03	6.90E-03	Yamamoto et al. (2006); Based on 0.5 $\log_{10}$ in a week from Table 7.1 in Miles et al. (2011)
Bacillus anthracis	5.50E+01	1.14E-04	Sinclair et al. (2008); WHO (2008)
Escherichia coli O157:H7	1.25E+01	1.25E-03	Flip et al. (1988); Pepper et al. (2010)

The values provided in Table 6.2.1 are used to calculate the concentration of each respective microbe in groundwater using the following equation:

$$C_{agent_{groundwater}}(t) = C_{agent\_soil}\,(t) \times Eff_{vertical} \times e^{-decay\_water \times t} \qquad \textbf{Eqn. 6.1}$$

where:

$C_{agent_{groundwater}}(t)$ = Pathogen groundwater concentration at time *t* (particles/m^3)

$C_{agent\_soil}\,(t)$ = Pathogen soil concentration at time *t* (particles/m^3)

$Eff_{vertical}$ = Pathogen vertical fate and transport efficiency (m^3 soil/m^3 groundwater)

$decay\_water$ Agent decay rate in soil pore water (hr-1)

t time (hr)

The equation includes loss of viability (rate of decay over time) and assumes that there will be no re-growth of the agent in either soil or groundwater prior to humans ingesting the well water. The above equation calculates the density of prions, *B. anthracis*, and *E. coli* O157:H7 in

groundwater over time (initial concentration through 1 year), and the results are in Table 6.2.2 for each pathogen.

Table 6.2.2. Concentration of Pathogens in Groundwater over Time (particles/m^3)

Pathogen	Initial	1 hr	24 hr	72 hr	1 week	4 weeks	3 months	6 months	1 year
Prions (PrP^{Sc})	1.21E-01	1.21E-01	1.03E-01	7.39E-02	3.81E-02	1.18E-03	4.09E-08	1.38E-14	1.56E-27
Bacillus anthracis	1.21E+03	1.21E+03	1.21E+03	1.20E+03	1.19E+03	1.13E+03	9.49E+02	7.42E+02	4.54E+02
Escherichia *coli* O157:H7	1.25E+00	1.25E+00	1.16E+00	9.99E-01	7.40E-01	1.54E-01	1.48E-03	1.75E-06	2.45E-12

Abbreviations: hr = hour.

As illustrated in Table 6.2.2, the concentration of each evaluated pathogen decreases over time. For *E. coli* O157:H7 and prions, the initial concentrations themselves are less than 1 particle per m^3, which is equivalent to less than 1 particle per 1,000 L or 1,000,000 mL. The initial concentration of *B. anthracis* was the highest and the loss of infectivity over time was the smallest.

The presence of even small concentrations of pathogens in groundwater sources used for drinking water presents a serious concern. USEPA regulates public water systems, and does not have the authority to regulate private drinking water wells serving less than 25 users. Although USEPA sets maximum contaminant levels (MCLs) for public water systems serving more than 25 users under the Safe Drinking Water Act (SDWA), the MCLs do not apply to public water systems with fewer than 25 users or to private wells. As part of the implementation of the SDWA, USEPA protects groundwater sources used for drinking water through implementation of the Ground Water Rule and requires monitoring of groundwater sources under the Revised Total Coliform Rule (RTCR). The RTCR establishes MCLs for total coliforms and *E. coli* (USEPA 2013c). If routine monitoring results in a sample positive for total coliforms, then the sample must be tested for *E. coli*. If the sample is positive for *E. coli*, and the MCL has been exceeded, additional site assessment is required. Therefore, corrective action is required if any samples test positive for *E. coli* (USEPA 2013c). Similar regulations are not explicitly available for *B. anthracis* or prions, but the MCL values for other regulated pathogens are zero.

For the purpose of making comparisons in this assessment, any detection of *E. coli* in the groundwater well would be considered problematic for a drinking water source, private or

public. Private wells are sampled for bacterial contamination less frequently public water systems regulated by the SDWA. Private drinking water wells might continue to be used even if pathogens are present in groundwater at detectable concentrations (USEPA 2014a). If the pathogens were detected during water quality monitoring efforts, corrective action would be needed before users could drink from the well. Like *E. coli*, the presence of any quantifiable level of *B. anthracis* or prions in drinking water sources also indicates danger to human health, even though enumeration of these pathogens is not part of routine water quality monitoring efforts.

Whether or not a groundwater monitoring sample yields a positive result depends on the limit of detection for the analysis method. Water quality assays typically used to detect *E. coli* in groundwater include multiple tube fermentation, membrane filtration, and enzyme substrate based-assays (California WRCB 2016). For example, USEPA Method 1604 (Total Coliforms and *Escherichia coli* in Water by Membrane Filtration Using a Simultaneous Detection Technique (MI Medium)) has a detection limit of 1 *E. coli* and/or 1 total coliform per 100 mL sample volume. The concentrations of *E. coli* estimated in Table 6.2.2 are reported as particles, not as the total number of organisms. It is possible that one particle could contain more than one organism and that the concentration of particles detected by this method would underestimate the concentration of individual *E. coli* cells. Therefore, it is unclear if all of the concentrations of *E. coli* estimated in Table 6.2.2 fall below the limit of detection for common *E. coli* detection assays. However, even if a groundwater sample tests negative for *E. coli*, particularly virulent strains of *E. coli* could still pose a risk of illness in humans drinking the well water.

The principal described above for *E. coli* would also apply for prions, for which estimated concentrations in groundwater are also below 1 prion per 100 mL sample. Even if samples tested negative for prions, they could still be present in groundwater at lower concentrations than could be detected and pose a risk of illness in humans drinking the groundwater.

The estimated concentrations of *B. anthracis* are greater than 1 colony forming unit (CFU) per liter water sampled at all time intervals. Although groundwater samples are not routinely tested for the presence of *B. anthracis*, culture-based assays have reported a limit of detection of 1 CFU per L of water sampled (Herzog et al. 2009). Therefore, groundwater samples from the on-site

well could yield positive results for *B. anthracis* if managed cattle were infected but asymptomatic.

1.2.1. Estimated Ingestion

Using the concentration data in Table 6.2.2, Equation 6.2 estimates the ingested dose of each of the three pathogens from drinking water from a groundwater well:

$$Dose_{agent_{groundwater}}(t) = C_{agent_{groundwater}}(t) \times V_{ing\_human\_groundwater} \qquad \textbf{Eqn. 6.2}$$

where:

$Dose_{agent_{soil}}(t)$	Pathogen exposure dose from groundwater ingestion (particles /day)
$C_{agent\_soil}\ (t)$	Pathogen soil concentration over time (particles/m^3)
$V_{ing\_human\_groundwater}$	Human daily groundwater ingestion rate (m^3/day/person)

The groundwater ingestion rate and the adult body weight are reported in the USEPA Exposure Factors Handbook (2011) as 42 mL/kg day and 80 kg, respectively. The results of this analysis are presented in Table 6.2.3. The estimated ingestion of microbes from a groundwater well is calculated as higher for *B. anthracis* than for *E. coli* O157:H7 or prions.

Table 6.2.3. Estimated Human Ingestion of Microbes from a Groundwater Well (particles/time interval)

Pathogen	Initial	1 hr	24 hr	72 hr	1 week	4 weeks	3 months	6 months	1 year
Prions (PrP^{Sc})	4.08E-04	4.05E-04	3.46E-04	2.48E-04	1.28E-04	3.95E-06	1.37E-10	4.63E-17	5.25E-30
Bacillus anthracis	4.08E+00	4.08E+00	4.07E+00	4.05E+00	4.00E+00	3.78E+00	3.19E+00	2.49E+00	1.52E+00
Escherichia coli O157:H7	4.20E-03	4.19E-03	3.90E-03	3.35E-03	2.49E-03	5.16E-04	4.97E-06	5.88E-09	8.24E-15

Abbreviations: hr = hour.

The values presented in Table 6.2.3 are very conservative because the concentrations for each microbe presented in Table 6.2.2 are likely much higher than the likely concentrations reaching groundwater. This analysis assumed the same concentrations for the microbial load expected to reach groundwater sources used for drinking water ingestion and exposure for the storage pile, on-site burial, and composting. As stated in Section 3, the analysis assumed the groundwater well is 30.5 m downgradient from the carcass disposal site.

Estimates of human ingestion for *B. anthracis* and *E. coli* O157:H7 are below their reported ID_{50} values; therefore illness in farm residents is unlikely (see Table 6.1.1). For *B. anthracis,* the ID_{50} value is 3–4 orders of magnitude higher than the estimated ingested dose. For *E. coli* O157:H7, the ID_{50} value is 5–6 order of magnitude higher than the estimated ingested dose at initial exposure. Particularly sensitive individuals, including children, the elderly, and immunocompromised persons, might become ill (Percival and Williams 2014).

For prions, an ID_{50} value in humans is not available, but an ID_{50} value is available for cattle. The initial estimated ingested dose in Table 6.2.3 is less than the ID_{50} value in cattle by one order of magnitude. Illness in farm residents could occur if groundwater is ingested soon after the initial prion release reaches groundwater and if the human ID_{50} values is close to the ID_{50} value for cattle.

1.2.2. Conclusions

Estimated exposure to *E. coli* O157:H7 and *B. anthracis* in drinking water would be below the ID_{50} in humans. For prions, exposure in drinking water might be close to the ID_{50} for cattle. If the ID_{50} for humans is similar to that of cattle, some farm residents might fall ill.

Microbial populations are expected to be highest in temporary carcass storage piles, and reduced in buried or composted carcasses over time as the pathogens are shed from the carcasses and their food supplies diminish.

Decreases in viable microbe concentrations should be most rapid during the initial stages of carcass decomposition. Ultimately, there may be only survival forms (e.g., prions and spores) of pathogens present at the collection and disposal sites. Air-curtain burning could inactivate even survival forms. Based on the efficacy of the various carcass management options to kill these pathogens, no pathogens are expected to be viable in buried ash from air-curtain burning, and fewer pathogens would be present in buried ash from an open pyre (prions only) than in leachate from untreated buried carcasses or composted carcasses. This means that drinking water contaminated by leachate from buried or composted carcasses is likely have more microbial contamination than water contaminated by leachate from buried ash.

In summary:

- The concentration of pathogens in ash would be lower than the concentration of pathogens in leachate from other carcass management options due to thermal inactivation of pathogens. Only prions are likely to remain viable in ash from open burning while no pathogens are expected to remain infectious in ash from air-curtain burning.
- The concentration of viable pathogens released to the soil in leachate from the storage pile could be higher than the concentration of pathogens released to the soil in leachate from carcass composting and on-site burial. Pathogen viability would be highest in the first two days post mortality, when the carcasses are stored in a pile on bare ground. After that, the infectivity of pathogens would decrease over time owing to several processes.
- Leachate from the temporary storage pile and buried carcasses would contain a broad range of pathogens, whereas finished compost is likely to only contain spores of spore-forming pathogens and prions. The composting process will develop populations of a wide variety of non-pathogenic microbial flora.
- The potential for contamination of drinking water supplies would reflect the initial microbial populations present in the carcasses as attenuated by the specific carcass management option and over time.

6.2. Livestock and Environmental Exposures

This section discusses livestock and wildlife exposures to microbes. Both qualitative and quantitative approaches assess exposure of livestock and wildlife to microbes. In general, exposure of livestock and wildlife is considered negligible due to source conditions and microbial properties. However, livestock exposure to microbes following the ingestion of contaminated groundwater was plausible. This potential exposure was quantified for one transportation and handling activity, and two management options in Section 6.3.1. Some species of wildlife might be exposed directly by ingesting parts of carcasses in the temporary storage pile or via other pathways, as discussed in Section 6.3.2.

1.2.1. Livestock Exposure

Livestock on the farm might be exposed to microbes released to the environment during the on-site management options via several pathways, as summarized in Table 6.3.1. Pathways include exposure through inhalation, incidental soil ingestion while grazing, ingestion of drinking water provided from an on-site groundwater well, and ingestion of plants grown on site, including

grains, silage, and forage. All of these pathways are in common with human exposure pathways, except that humans and livestock consume different plant products, and incidental soil ingestion.

Table 6.3.1. Livestock Exposure Pathways for Livestock Carcass Management Options – Microbes

Exposure Source	Exposure Pathways Transportation and Handling Activities			Exposure Pathways Management Options			
	Carcass Handling	Temporary Carcass Storage	Carcass Transportation	Open Burning	Burial	Composting	Air Curtain Burning
Inhalation	1) Air → Livestock[b]	1) Air → Livestock[b]	—	1) Air → Livestock[b]	1) Air → Livestock[b]	1) Air → Livestock[b]	—
Incidental Soil Ingestion	2) Air → Soil→ Livestock[b]	2) Air → Soil→ Livestock[b]	—	2) Air → Soil→ Livestock[b]	—	—	—
Groundwater Ingestion	—	**3) Leachate → GW → Livestock[a]**	—	**3) Ash → GW → Livestock[a]**	**2) Leachate → GW → Livestock[a]**	**2) Leachate → GW → Livestock[a]**	—
Ingestion of Food Produced on the Farm	3) Air → Plants → Livestock[b] 4) Air → Soil → Plants → Livestock[b]	4) Air → Plants → Livestock[b] 5) Air → Soil → Plants → Livestock[b]	—	4) Air → Plants → Livestock[b] 5) Air → Soil → Plants → Livestock[b]	3) Air → Plants → Livestock[b] 4) Air → Soil → Plants → Livestock[b]	3) Air → Plants → Livestock[b] 4) Air → Soil → Plants → Livestock[b]	—

Abbreviations: "—" = No exposure pathways; SW = surface water; GW = groundwater.
Note: Exposure pathways shown in bold were included in the quantitative exposure assessment.
[a] Quantitative methods were available for exposure assessment; results are presented below in Section 6.3.1.
[b] Potential exposures were assumed to be negligible based on source conditions or microbial properties.

by livestock while grazing, particularly by cattle, is a greater potential source of exposure than incidental soil ingestion by humans (e.g., through hand-to-mouth contact).

Exposure pathways with quantified exposures are indicated with bold type and endnote "a." The remaining pathways of livestock exposure, indicated by endnote "b" in Table 6.3.1, were assumed to be negligible and not quantified for the following reasons:

- **Thermal Inactivation** – The burn temperature and duration of the on-site open burning option inactivates the pathogens with the exception of prions. Similarly, the duration of the high temperatures characteristic of the on-site composting option can inactivate or destroy many microbes, except for prions or spores from spore-forming bacteria (e.g., *B. anthracis*). Because of the impact of temperature on the survival of microbes, many exposure pathways that were assessed for chemicals were not evaluated for microbes. Air-curtain burning is not included in Table 6.3.1 because the usual burn temperatures of this option is likely to completely inactivate all three categories of pathogens included in the natural disaster scenario.

- **Inhalation** – Microbes could be released to air during carcass transportation and handling activities (i.e., carcass handling and temporary carcass storage) and several management options (i.e., on-site open burning, burial, and composting). However, the probability of direct inhalation by cattle is low, as it is for humans (see Section 6.1). Similar reasoning can be applied to the assessment of livestock exposure. Livestock are assumed to be at least 30.5 m from the on-site open burning pyre, burial pit, composting pile, and temporary storage pile. Microbial populations decrease with increasing distance from the site of livestock carcasses and over time. Farm livestock are expected to be excluded from the area around the temporary carcass storage pile and consequently not exposed to microbial populations in that area. Microbes survive being buried or composted; however, livestock downwind of burial or composting activities are likely to inhale few or no pathogens. During the composting process, microbes in leachate from the carcasses are adsorbed to the underlying woodchips and soil, and are not expected to be released to air. Similarly, microbes in leachate from a burial pile are not expected to become aerosolized. Releases to air from windrow turning are not evaluated because windrows for cattle composting are not turned.

- **Incidental soil ingestion** – Aerosolized microbes could be deposited onto soil during (1) all carcass handling activities, (2) temporary carcass storage, and (3) on-site open burning processes (assumed to be for a 48-hr duration). However, many bacterial cells become desiccated in air, which could kill the population in air (see Table 6.1.1). Livestock often accidentally ingest soil during grazing. The number of microbes deposited downwind onto soil or plant matter after open-burning carcass management activities is unknown. Given the low number of viable microbes expected to be deposited on soil or plant matter, this exposure pathway is assumed to be negligible for livestock as it is for humans.

- **Ingestion of contaminated feed produced on the farm** – Low initial microbial populations, the relatively short time-frame for source emissions, and low likelihood that grazing pastures would be directly downwind of carcass management activities, suggest livestock exposure through their feed is unlikely. The impact of microbial aerosol emissions (the highest deposition is over a limited area – within 600 m from the source in the direction of prevailing winds based on AERMOD particulate dispersion modeling) – also suggests exposure via this pathway is unlikely. For these reasons, the exposure of livestock to microbial contaminants in their feed is considered to be negligible.

The food chain on the farm also includes pathways with livestock drinking groundwater (i.e., well water) containing prions that leached from buried combustion ash, and microbes in leachate from buried carcasses or the temporary carcass storage pile. Watering of surviving livestock using groundwater from the well will continue during the following carcass management stages: temporary carcass storage, on-site open burning, on-site unlined burial, and composting. The temperatures reached during the composting process are expected to inactivate most pathogens with the exception of prions and spores of *B. anthracis*.

Exposures of livestock that drink water supplied by a groundwater well on the hypothetical farm are quantitatively assessed below using a step-wise approach similar to that used to estimate human exposure to microbes via drinking water ingestion. Data to differentiate the transportation and handling activities and management options are not available, so the same starting concentration for each of the microbes was used for all of the transportation and handling activities and management options where exposure is possible. The concentration of microbes ingested by livestock was assumed to be similar to the concentration that reached

humans as described above in Section 6.2.1; however, the ingestion rates differ for humans and cattle. Dairy cattle drink more water than beef cattle (Agriculture and Agri-Food Canada undated):

- Dairy cattle: 95 L/day (summer), 77 L/day (winter); and
- Beef cattle: 86 L/day (summer), 55 L/day (winter).

Quantitative estimates of dairy and beef cattle ingestion of water supplied by a groundwater well are calculated for prions, *B. anthracis*, and *E. coli* O157:H7. Equation 6.3 estimates cattle ingestion of pathogens with well water:

$$Animal_{Dose_{agent_{groundwater}}}(t) = C_{agent_{groundwater}}(t) \times V_{ing\_animal\_groundwater} \quad \textbf{Eqn. 6.3}$$

where:

$Animal_{Dose_{agent_{groundwater}}}(t)$	Pathogen exposure dose for dairy and beef cattle from groundwater ingestion at time *t* (organisms/day)
$C_{agent\_soil}\ (t)$	Agent soil concentration at time *t* (particles/m^3)
$V_{ing\_animal\_groundwater}$	Cattle daily groundwater ingestion volume (m^3/animal/day)

Table 6.3.2 presents the estimated ingestion of prions, *B. anthracis*, and *E. coli* O157:H7 by dairy cattle drinking water supplied by a groundwater well in both the summer and winter seasons.

Table 6.3.3 presents the estimated ingestion of prions, *B. anthracis* spores, and *E. coli* O157:H7 by beef cattle drinking water supplied by a groundwater well in both the summer and winter seasons. Based on the results presented in Table 6.3.2 and Table 6.3.3, the estimated ingestion of *B. anthracis* is expected to be higher than the ingestion of prions or *E. coli* O157:H7 for both dairy and beef cattle in both summer and winter seasons. The initial estimated ingestion of microbes from a groundwater well is higher for prions, *E. coli*, and *B. anthracis* in humans compared with cattle.

Table 6.3.2 Estimated Ingestion of Microbes from a Groundwater Well – Dairy Cattle (particles/time interval)

Agent	Season	Initial	1 hr	24 hr	72 hr	1 week	4 weeks	3 months	6 months	1 year
Prions (PrP^{Sc})	Summer	1.15E-02	1.15E-02	9.78E-03	7.02E-03	3.62E-03	1.12E-04	3.89E-09	1.31E-15	1.48E-28
	Winter	9.35E-03	9.29E-03	7.92E-03	5.69E-03	2.93E-03	9.06E-05	3.15E-09	1.06E-15	1.20E-28
Bacillus anthracis	Summer	1.15E+02	1.15E+02	1.15E+02	1.14E+02	1.13E+02	1.07E+02	9.02E+01	7.05E+01	4.31E+01
	Winter	9.35E+01	9.35E+01	9.33E+01	9.28E+01	9.17E+01	8.66E+01	7.31E+01	5.72E+01	3.49E+01
Escherichia coli O157:H7	Summer	1.19E-01	1.18E-01	1.10E-01	9.49E-02	7.03E-02	1.46E-02	1.41E-04	1.66E-07	2.33E-13
	Winter	9.63E-02	9.60E-02	8.93E-02	7.69E-02	5.70E-02	1.18E-02	1.14E-04	1.35E-07	1.89E-13

Abbreviations: hr = hour.

Table 6.3.3 Estimated Ingestion of Microbes from a Groundwater Well – Beef Cattle (particles/time interval)

Agent	Season	Initial	1 hr	24 hr	72 hr	1 week	4 weeks	3 months	6 months	1 year
Prions (PrP^{Sc})	Summer	1.04E-02	1.04E-02	8.85E-03	6.36E-03	3.28E-03	1.01E-04	3.52E-09	1.18E-15	1.34E-28
	Winter	6.68E-03	6.63E-03	5.66E-03	4.06E-03	2.10E-03	6.47E-05	2.25E-09	7.57E-16	8.59E-29
Bacillus anthracis	Summer	1.04E+02	1.04E+02	1.04E+02	1.04E+02	1.02E+02	9.68E+01	8.17E+01	6.38E+01	3.90E+01
	Winter	6.68E+01	6.68E+01	6.66E+01	6.63E+01	6.55E+01	6.19E+01	5.22E+01	4.08E+01	2.49E+01
Escherichia coli O157:H7	Summer	1.08E-01	1.07E-01	9.97E-02	8.59E-02	6.36E-02	1.32E-02	1.27E-04	1.51E-07	2.11E-13
	Winter	6.88E-02	6.85E-02	6.38E-02	5.49E-02	4.07E-02	8.45E-03	8.14E-05	9.63E-08	1.35E-13

Abbreviations: hr = hour.

Available ID_{50} values for cattle for *B. anthracis*, prions, and *E. coli* O157:H7 are presented in Table 6.1.1. Estimates of ingestion for *E. coli* O157:H7 are below the reported ID_{50} value, whereas estimates of ingestion for prions and *B. anthracis* are higher than the reported ID_{50} values at certain times and seasons. For *E. coli* O157:H7, the ID_{50} value is 6 orders of magnitude higher than the estimated ingested dose for dairy and beef cattle in both the summer and winter months. However, for prions, the estimated ingestion is greater than the ID_{50} during the summer months for both dairy and beef cattle. The estimated ingestion falls below the ID_{50} value for prions from 1 to 24 hours following the initial release to groundwater. Ingestion of drinking water 24 hours after release results in exposure to prions one order of magnitude below the ID_{50} value.

The estimated ingestion of *B. anthracis* in drinking water is greater than the ID_{50} value for dairy and beef cattle in both summer and winter for all evaluated time points. *B. anthracis* has a fairly low ID_{50} value (<10 spores) in cattle. Estimates of ingestion are calculated in Table 6.3.3 from initial release to groundwater through one year after that release. Exposure to *B. anthracis* in water provided to cattle could pose a threat to public health for at least one year following the

release of this pathogen to the groundwater. Thus, burial, composting, and allowing an uncovered temporary storage pile on bare ground might pose risks of illness to cattle and to humans from *B. anthracis*.

6.2.3. Wildlife Exposure

The organisms most susceptible to adverse health effects from the three microbes evaluated, other than humans and livestock, would be vertebrate wildlife. For this assessment, only animals, and not plants, should be susceptible to falling ill from microbes that are pathogenic in humans and livestock and that originate in the carcasses of healthy livestock.

One principal pathway/route of exposure of wildlife (e.g., birds, mammals, reptiles) to microbes in livestock carcasses that is not evaluated for humans and livestock would be ingestion of bits of carcasses from the temporary storage pile. Scavenging wildlife (e.g., crows, ravens, gulls, raccoons, rats) could ingest microbes with bits of carcass from an uncovered temporary storage pile. The risks to wildlife from the storage pile, however, would be the same across all seven carcass management options. Direct ingestion of microbes with pieces of carcasses, therefore, is not evaluated further in Phase 1, livestock mortality following a natural disaster. This pathway *is* assessed for Phase 2, mortality from livestock disease outbreak.

Other exposure pathways and routes to a variety of types of organisms are possible. Wildlife of concern are:

- Wider-ranging animals that might frequent the affected property and feed on less mobile animals (e.g., soil invertebrates, small rodents) and plants as food sources
- Benthic invertebrates within waters in a region and the fish that feed on them

For the purpose of this assessment, the hypothetical farm includes an on-site lake. The lake could lead to exposures of several types of animals:

- Fish that feed on aquatic plants, planktonic organisms, benthic invertebrates, or smaller fish
- Semi-aquatic animals (e.g., amphibians, water birds, beavers, muskrat, and piscivorous mammals such as mink)
- Terrestrial animals (e.g., soil-dwelling invertebrates, other insects, passerine birds that feed on above or below-ground insects to provision their young, small mammals that feed on

seeds (e.g., mice) or on soil invertebrates (e.g., shrews), and larger grazing or predatory mammals)

- Other organisms in soils (e.g., plants and soil microbes)

The assessment assumes that animals and their foods are not exposed to microbes from the three off-site management options, because releases from off-site commercial facilities are regulated to be within health-protective limits and to be environmentally responsible. The three off-site carcass management options are commercial incineration, landfilling, and rendering. For example, landfills should be covered with tarps to prevent excess infiltration by precipitation and to prevent scavenging by animals (most notoriously gulls along the Great Lakes and east and west coasts).

Exposure of wildlife might occur during transportation of carcasses to off-site carcass management facilities from accidents with spills or from leaks. However, as described in Section 3.1.3, the likelihood of a vehicle accident with livestock carcasses spilled onto a road is very remote. Leaks of leachate along the travel route might deposit viable microbes along the roadway; ground-feeding wildlife might incidentally ingest the microbes and scavenging mammals might be attracted by the smell. The chance of an animal ingesting an infectious dose, however, is small. A total of 160 liters of leachate might leak from a truck during off-site transportation of 50 tons of carcasses (8 trips with 20 L leaked per trip), but the leachate would be spread over many miles of roadway. Additional wildlife exposure pathways are possible for the following management options and potential microbial hazards:

- **On-site open-burning** – Prions could be released to air during the burn and buried with the remaining ash after. Pathways to the on-site lake are the same as those identified in Sections 6.2 and 6.3.1.
- **Composting** – Prions and spores from spore-forming bacteria (i.e., *B. anthracis*, *Clostridium perfringens*, and *Coxiella burnetii*) could reach the lake as described in Section 6.2.
- **On-site unlined burial** – All of the potential microbial hazards evaluated could be released to subsurface soils; however, it is unlikely that microbes could reach the lake in sufficient concentrations to reach wildlife at infectious doses (substantial soil filtering both vertical and horizontal, dilutions along a food chain).

Further consideration of the frequency of accidents and the potential volume of leachate caused by leaks or spills from carcass transportation vehicles (discussed in detail in Section 3.1.3) indicate these activities would not cause exposure to ecological receptors. Consequently, the combination of transport and off-site carcass management are not sources of exposure for ecological receptors.

One key consideration in assessing ecological effects from exposures to microbes originating with transportation and handling activities and on-site carcass management options is the pathogen's host range. As listed in Table 2.4.4, a wide range of pathogenic microbes are associated with the carcass management options listed above, including several groups of bacteria, viruses, protozoa, and prions. Many of these microbes have complex host ranges where multiple, unique strains that can produce infection in some hosts but are not infective in others. Many of the microbes included in Table 2.4.4 produce zoonotic diseases, meaning they can cause illness in animals and humans. For example, humans, cattle, sheep, goats, horses, pigs, dogs, cats, and other mammalian wildlife can become infected with *B. anthracis*; however, amphibians, reptiles, fish, and most birds are not directly susceptible to infection with *B. anthracis* (Spickler 2007). Additionally, vultures and flies can disseminate *B. anthracis* mechanically after feeding on carcasses (Spickler 2007). To adequately assess possible ecological effects, the pathways for transmission among species and infectivity of each of the microorganisms in Table 2.4.4 would need to be investigated.

Plants can be exposed to microbes in a variety of ways including direct deposition on foliage followed by surface adhesion, uptake by the roots, and through irrigation with well water. It is assumed that crops grown for human consumption are be washed, cooked, and/or peeled as appropriate. These processes would remove or inactivate many of the microorganisms that may have been deposited to the surface of any edible plants. However, foodborne outbreak research indicates that some human pathogens can become internalized into plant tissues, which reduces the effectiveness of conventional processing and chemical sanitizing methods in preventing transmission from contaminated produce (Lynch et al. 2009). Foodborne illnesses are associated with the following pathogens included in Table 2.4.4: norovirus, *Clostridium perfringens, Cryptosporidium* spp., *Campylobacter* spp., *E. coli* O157:H7, *Listeria monocytogenes, Salmonella* spp., *Shigella* spp., *Yersinia enterocolitica, Giardia* spp., *Mycobacterium bovis*

Toxoplasma gondii, and *Vibrio* spp. (Scallan et al. 2011). These potential microbial hazards are associated with carcass handling, temporary carcass storage, and on-site unlined burial. It is unclear if foodborne illnesses caused by these agents were due to human consumption of internally contaminated plant materials, a failure to practice proper food handling practices, or a combination of both possibilities. Wildlife that might feed on plants in the vicinity of carcass handling and storage or carcass management sites could be exposed to pathogens incorporated into the plants or simply deposited on the surfaces of foliage or grains as consumed by the wildlife. Pathogens that cause illness in humans, livestock, and wildlife, however, are unlikely to adversely affect plants owing to taxonomic distance and marked differences in physiology. Similarly, the host ranges for the vast majority of plant pathogens do not include humans (USDA 2016).

Ecological receptors could be exposed to potential microbial hazards via the carcass handling, temporary carcass storage, burial, on-site open burning, and composting management options. Exposure to fewer microbes is expected for composting (i.e., prions and *B. anthracis*) and open burning (i.e., prions) because these carcass management options kill or inactivate many microbes. The specific number of ecological receptors impacted by each handling activity and management option is unknown as is the frequency and duration of exposure. The expected exposure concentration is unknown, but thought to be lower than the initial loading concentration as some microbes die, while others adhere to soil particles. For these reasons, it is unclear what concentration of microbes would reach a given ecological receptor.

In summary, the highest potential for exposure to a higher number of microbes is associated with the following:

- Temporary on-site carcass storage
- On-site unlined burial

7. Comparative Risks for Livestock Management Options

This section compares the livestock carcass management options relative to each other in a two-tiered approach. Tier 1 (Section 7.1) groups the seven carcass management options in two categories of potential exposure based on the level of regulatory pollution controls that limits releases of chemicals and microbes to the environment. Tier 1 also considers the number of potential exposure pathways identified in the conceptual models for each management option (Appendix C) and describes why the three off-site carcass management options present minimal to negligible relative risks. In Tier 2, the four on-site management options are evaluated further based on the quantitative exposure assessments presented in Sections 3 through 6. Exposures are normalized to inherent toxicity or infectious dose in Section 7.2, and results of the Tier 2 comparison are presented separately for chemicals (Section 7.2.1) and microbes (7.2.2). Sections 7.3 and 7.4 provide further information to help readers understand and use the findings of this assessment. Section 7.3 discusses the uncertainties and limitations of the assessment, including information about how different assumptions or site-specific circumstances could affect the estimated exposures. Section 7.4 summarizes the livestock carcass management options, potential exposure mitigation strategies, and research needs.

Readers of this document should recognize that the relative risks calculated for the hypothetical site might differ from relative risks of the different carcass management options in specific locations and under various conditions. This document does not replace the need for county or statewide planning for natural disasters with mass livestock mortality based on availability of off-site management options and suitability of on-site options for the region.

7.1. Tier 1 Comparison of the Seven Carcass Management Options

As discussed in Section 2, this assessment considers seven well-established carcass management options with documented use following natural disasters or with sufficient capacity for large scale carcass management. With the three off-site options, releases to the environment (e.g., incinerator emissions to air, rendering facility discharge to surface water) are restricted by, and are assumed to comply with, applicable regulations. Therefore, chemical and microbial releases from off-site commercial facilities are assumed to be adequately controlled. The on-site management options all include uncontrolled or minimally controlled chemical and possibly microbial releases to air, soil, or water, for which exposures are modeled as described in Sections

3 through 6. Moreover, the conceptual models (Appendix C) show that on-site management options tend to have more potential exposure pathways than the off-site options, with the possible exception of off-site transportation. Following a natural disaster, however, transport of carcasses off-site is unlikely to result in hazardous environmental releases, because the probability of an accident that dumps carcasses on a roadway is very small (see Section 3.1.3). Acknowledging the distinction between off-site and on-site options based on regulatory pollution control constitutes the first tier ranking of the seven carcass management options. Table 7.1.1 presents that ranking and lists the numbers of conceptual model pathways for chemicals and for microbes. Table 7.1.1 also describes controlling legislation and technologies to limit releases to permitted levels or below. The table shows that the three off-site options are ranked higher (i.e., less potential for exposure and risk) than the four on-site options based on these considerations.

Table 7.1.1. Tier 1 Ranking of Livestock Carcass Management Options

Tier 1 Ranking	Management Options	Chemical Exposure Pathways	Microbial Exposure Pathways	Controls and Limits to Environmental Releases
Rank 1: Negligible to minimal exposure — releases regulated to levels safe for human health and the environment	Incineration	6	6	Air emissions regulated under the Clean Air Act (CAA), including pollution control equipment (e.g., scrubbers, filters), with tall stacks to prevent localized deposition; residuals (i.e., ash) managed under the Resource Conservation and Recovery Act (RCRA); wastewater managed under the Clean Water Act (CWA).
	Rendering	3	2	Releases to air and to water regulated under the CAA and CWA, respectively.
	Landfilling	2	2	Landfill design and operation regulated under RCRA; controls include leachate collection and management and methane recovery.
Rank 2: Higher exposure potential — uncontained releases to the environment	Open Burning	10	10	Uncontrolled and unregulated combustion emissions; possible releases from combustion ash if managed on site.
	Air-curtain Burning	10	10	Partially controlled but unregulated combustion emissions, possible releases from combustion ash if managed on site.
	Composting	8	7	Partially controlled releases from compost windrow (minor leaching, runoff, and gas release to air); where finished compost is tilled into soils, potential runoff and erosion from amended soil.
	Burial	6	6	Uncontrolled leaching from unlined burial; slow gas release to air.

7.2. Tier 2 Ranking of On-site Carcass Management Options

In Tier 2, the four on-site carcass management options are compared based on estimates of chemical (Section 7.2.1) and microbial (Section 7.2.2) exposures normalized to inherent toxicity and infectious dose, respectively.

1.2.1. Tier 2 Ranking Based on Chemical Exposures

For chemicals, the Tier 2 ranking of the four on-site carcass management options uses the chemical exposure estimates presented in Section 5. As discussed previously, chemical exposures are not estimated for all of the exposure pathways in the conceptual models. The pathways for which chemical exposures were quantified are shown in bold type in Table 5.1.1. For convenience, Table 5.1.1 is repeated here in Table 7.2.1. The exposure pathways that were not quantified for one or more reasons are included in Table 7.2.1 in plain (not bold) type. The reasons that certain pathways were not assessed were discussed in Section 5.1.

Although each of the on-site management options includes preceding carcass transportation and handling steps, Table 7.2.1 shows that chemical exposures associated with those steps are evaluated in Tier 2 separately from the management options themselves. That allows one to distinguish their contribution to the overall chemical exposures. The on-site carcass transportation and handling steps, and their resulting chemical exposures, are assumed to be the same for all seven management options, and therefore do not need to be included for comparison of the four on-site management options.

By itself, an exposure concentration does not indicate whether adverse effects on human health or environmental quality are possible or likely. To support a risk-based comparison of the exposure estimates, they are normalized to inherent toxicity using toxicity reference values (TRVs). A TRV is a concentration- or dose-based estimate of the exposure level below which adverse health effects are not expected for individual humans in the population evaluated. TRVs are chemical-specific and are developed by various agencies (e.g., USEPA, ATSDR) using agency- or program specific-methods and definitions. TRVs also are developed for various exposure durations. For example, the USEPA NHSRC established Provisional Advisory Levels (PALs) for both inhalation and oral exposures in the event of an accidental or deliberate release

Table 7.2.1. Human Exposure Pathways for Livestock Carcass Management – Chemicals

Exposure Source	Carcass Transportation and Handling			Carcass Management Options		
	Carcass Handling	Temporary Carcass Storage	Carcass Transportation	Open Burning and Air curtain Burning	Burial	Composting
Inhalation	1) Air[b]	1) Air[b] 2) Leachate → GW → In-home Aerosol[c]	1) Air[b]	**1) Air**[a] 2) Ash → GW → In-home Aerosol[b]	1) Air[b] 2) Leachate → GW → In-home Aerosol[b]	1) Air[b] 2) Compost → GW → In-home Aerosol[b]
Incidental Ingestion	2) Hand-to-mouth ingestion [b,c]	—	2) Accident → soil[b,c]	3) Air → soil[b]	—	—
Dermal	3) Direct dermal contact[c]	—	3) Accident → soil[c]	—	—	—
Fish Ingestion	—	**3) Leachate → GW → SW → Fish**[a]	—	**4) Air → SW → Fish**[a] **5) Air → soil → SW → Fish**[a] **6) Ash → GW → SW → Fish**[a]	**3) Leachate → GW → SW → Fish**[a]	**3) Compost → soil → SW → Fish**[a] **4) Compost → GW → SW → Fish**[a]
Groundwater Ingestion	—	**4) Leachate → GW**[a]	—	**7) Ash → GW**[a]	**4) Leachate → GW**[a]	**5) Compost → GW**[a]
Ingestion of Food Produced on the Farm	—	5) Air → Plants/livestock[b] 6) Leachate → GW → Livestock[b]	—	**8) Air → Plants/livestock**[a] **9) Air → Soil → Plants/ Livestock**[a] 10) Ash → GW → Livestock[b]	5) Air → Plants/ Livestock[b] 6) Leachate → GW → Livestock[b]	**6) Compost → Soil → Plants/ Livestock**[a] 7) Air → Plants/ Livestock[b] 8) Compost → soil → GW → Livestock[b]

Abbreviations: "—" = no exposure pathways; SW = surface water; GW = groundwater.
Exposure pathways shown in bold were included in the quantitative exposure assessment. Pathways were not quantitatively assessed for the following reasons:
[a] Quantitative methods were available for exposure assessment; Results are presented in Section 6.3.
[b] Potential exposures were assumed to be negligible based on source conditions or chemical properties.
[c] Environmental releases or exposures were assumed to be adequately controlled by existing pollution control regulations or use of personal protective equipment.

of chemicals to air or water over periods of 24 hours, 30 days, 90 days, or two years. The chemicals for which USEPA PALs are available, however, are not among those evaluated for carcass management options. USEPA and other agencies often prepare separate TRVs for acute, subchronic, and chronic exposures (see Appendix L).

The TRVs used for this assessment are listed in the Oak Ridge National Laboratory's Risk Assessment Information System (RAIS).[18] In addition, TRVs differ for each chemical and each route of exposure (i.e., oral or inhalation) and for cancer and non-cancer health effects. Preferred TRVs are those most appropriate for the modeled exposure durations (e.g., 24-hr to 48-hr acute inhalation benchmarks for inhalation exposures during a 48-hr on-site open or air-curtain burn) and those developed by USEPA.

The available TRVs and those chosen for the assessment are documented in Appendix L. Non-cancer effects associated with two-day inhalation exposures are normalized to (i.e., divided by) acute (24-hr to 30-day) inhalation reference concentrations (RfCs) where available. As described in Appendix L, RfCs derived for shorter exposure durations (e.g., 10, 30, or 60 minutes, or 8 hours) are not used because they would not necessarily be safe for a 48-hr exposure. None of the chemicals assessed for the combustion-based management options have 24-hr inhalation criteria. If acute inhalation RfCs are not available, a subchronic or chronic RfC is used, with preference in that order. Because cancer benchmarks are based on increased cancer risk from a lifetime exposure, cancer health effects are not evaluated for the single, 48-hr inhalation exposure during on-site combustion events.

As discussed in Section 5.1.2, ingestion exposures are assumed to occur over the first year of maximum exposures, with subsequent ingestion exposures declining over time as the chemical mass at the carcass management location is depleted and less chemical mass is available to reach exposure media. Moreover, chemicals in the environment become more dispersed over time. Accordingly, the preferred TRVs for evaluating non-cancer health effects from ingestion exposures are subchronic oral reference doses (RfDs), which are developed for periods up to 7 years (USEPA 1989). Chronic oral RfDs are selected when subchronic RfDs are unavailable. For

[18] The Risk Assessment Information System is available at: https://rais.ornl.gov/

cancer health effects, oral slope factors are selected, when available, to normalize ingestion exposures, as described in more detail below.

The selected TRVs are referred to by the general term "benchmarks," because they include values for cancer and non-cancer endpoints, are developed by various agencies for various exposure durations, and differ for inhalation and oral exposures. The benchmarks for inhalation exposure are expressed as air concentrations, whereas the benchmarks for ingestion exposures are expressed as the ingested dose (i.e., mg[chemical]/kg[human body weight] per day). As described below, exposure estimates for each management option, chemical, and exposure route are compared to the cancer and non-cancer benchmarks for purpose of comparing or ranking the management options relative to one another.

Even in comparative or relative risk assessments, cancer and non-cancer endpoints are not grouped into one category. There are no consensus guidelines at USEPA by which risk assessors can combine estimates of cancer risk (a probability or incidence rate) with a hazard quotient (ratio of a point estimate of exposure to the appropriate benchmark, either >1.0 indicating adverse effect are possible or ≤1.0 indicating adverse effects are unlikely). Some health effects upon which non-cancer toxicity RfCs or RfDs are based are more severe than others. Some types of cancer are associated with limited expected future survival whereas others have better prognoses.

For this relative risk ranking of the four on-site carcass management options, ratios of exposure to benchmarks for non-cancer and cancer endpoints are calculated. Given the data limitations and generic assumptions for this assessment, risk managers and the public should not interpret any numeric results in this document as "actual likely" exposures (Section 5) or risks (this section).

The estimated exposures (Section 5) are compared with the relevant benchmarks by calculating the ratios of exposure to benchmarks, as shown in Tables 7.2.2 through 7.2.11. These ratios are referred to as "ranking ratios." For these calculations, only the exposures estimated for children 1 to <2 years of age are used, because that age group is more highly exposed (e.g., ingest more food per unit body weight) than older children and adults. The first data column in each of these tables presents the estimated magnitude of exposure for the young children. The next column for inhalation tables presents the non-cancer inhalation (RfC) benchmarks, as documented in

Appendix L. For the ingestion tables, both cancer and non-cancer benchmarks, as documented in Appendix L, are presented after the estimated ingested dose. The final columns present the ratio(s) of the estimated exposure to the benchmark(s).

Table 7.2.2. Ingestion Exposure Assessment for Temporary (48-hr) Carcass Storage

Chemical Species	Estimated Ingestion ADD (mg/kg d)	Benchmarks		Ranking Ratios	
		RfD (mg/kg d)	RSD (mg/kg d)	ADD/RfD	LADD[a]/RSD
Total Dioxins/furans	na	2.0E-08	7.7E-10	na	na
Total PAHs	na	nb	1.4E-05	na	na
Arsenic	na	3.0E-04	6.7E-05	na	na
Cadmium	na	1.0E-03	nc	na	na
Chromium	na	3.0E-03	nc	na	na
Copper	3.9E-12	1.0E-02	nc	3.9E-10	na
Iron	3.8E-09	7.0E-01	nc	5.4E-09	na
Lead	na	nb	1.2E-02	na	na
Manganese	4.7E-12	1.4E-01	nc	3.3E-11	na
Nickel	2.6E-12	1.1E-02	nc	2.3E-10	na
Zinc	2.4E-10	3.0E-01	nc	8.1E-10	na

Abbreviations: d = day; ADD = average daily dose; RfD = reference dose; RSD = risk-specific dose for carcinogenic chemicals for a target risk of 1E-04assuming ingestion of contaminated media occurs over a year of daily exposures; LADD = lifetime average daily dose; PAH = polycyclic aromatic hydrocarbon; nb = benchmark (non-cancer) not available for oral exposure; na = not assessed; nc = not considered carcinogenic by ingestion exposures.
Note: Ingestion sources include fish caught from the on-site lake and drinking water drawn from an on-site well.
[a] Cancer TRVs represent cancer risk over a lifetime of exposure. Therefore, average daily exposure dose for the first year (i.e., the ADD) is divided by 70 years to calculate the LADD.

For inhalation exposures (Tables 7.2.3 and 7.2.5), which are estimated only for the combustion-based management options, both exposures and benchmarks are expressed as air concentrations ($\mu g/m^3$). Dose-based ingestion exposures (i.e., remaining tables from 7.2.2 through 7.2.11) are in units of mg/kg-day. Non-cancer TRVs used as benchmarks can be compared directly to the estimated ingestion exposures, which are average daily doses (ADDs) for the first year of maximum exposures following carcass management.

The cancer oral TRVs (oral slope factors) require a transformation for direct comparison to exposure estimates. Oral slope factors are in units of per mg/kg-day (i.e., $(mg/kg\text{-}day)^{-1}$). A target risk level of 1E-04 is divided by the oral slope factor to calculate the corresponding risk-specific dose (RSD), that is, the dose that corresponds to a target risk level of 1E-04 (one in 10,000) over a lifetime of exposure. This risk target is selected because, in general, USEPA considers excess cancer risks above 1E-04 to be sufficiently large that some response action is merited (USEPA 1991).

Table 7.2.3. Inhalation Exposure Assessment for the Open-burning Option

Chemical Species	Estimated Inhalation Exposure Concentration (µg/m^3)	Benchmarks, RfC (µg/m^3)	Ranking Ratios: Exposure/RfC
Total Dioxins/furans	4.2E-10	4.0E-05	1.1E-05
Total PAHs	6.8E-02	nb	na
Arsenic	7.7E-04	1.5E-02	5.1E-02
Cadmium	1.4E-03	3.0E-02	4.7E-02
Chromium	1.2E-02	1.0E-01	1.2E-01
Copper	9.5E-03	1.0E+02	9.5E-05
Iron	3.1E+00	nb	na
Lead	1.3E-02	nb	na
Manganese	2.9E-02	5.0E-02	5.8E-01
Nickel	1.1E-02	6.0E-02	1.8E-01
Zinc	9.9E-02	nb	na

Abbreviations: RfC = reference concentration; PAH = polycyclic aromatic hydrocarbon; nb = no benchmark available for inhalation exposure; na = not assessed.
Notes: Exposure duration is 48 hours. Cancer risk is not evaluated for this short-term exposure.

Table 7.2.4. Ingestion Exposure Assessment for the Open-burning Option

Chemical Species	Estimated Ingestion ADD (mg/kg d)	Benchmarks		Ranking Ratios	
		RfD (mg/kg d)	RSD (mg/kg d)	ADD/RfD	LADD[a]/RSD
Total Dioxins/furans	4.6E-11	2.0E-08	7.7E-10	2.3E-03	8.5E-04
Total PAHs	4.2E-06	nb	1.4E-05	na	4.3E-03
Arsenic	7.7E-07	3.0E-04	6.7E-05	2.6E-03	1.6E-04
Cadmium	9.4E-07	1.0E-03	nc	9.4E-04	na
Chromium	2.3E-04	3.0E-03	nc	7.7E-02	na
Copper	6.3E-05	1.0E-02	nc	6.3E-03	na
Iron	2.8E-02	7.0E-01	nc	4.0E-02	na
Lead	3.9E-07	nb	1.2E-02	na	4.6E-07
Manganese	2.4E-05	1.4E-01	nc	1.7E-04	na
Nickel	4.7E-06	1.1E-02	nc	4.3E-04	na
Zinc	4.1E-04	3.0E-01	nc	1.4E-03	na

Abbreviations: d = day; ADD = average daily dose; RfD = reference dose; RSD; risk-specific dose for target risk of 1.0E-04; LADD = lifetime average daily dose; PAH = polycyclic aromatic hydrocarbon; nb = benchmark (non-cancer) not available for oral exposure; na = not assessed; nc = not considered carcinogenic by ingestion exposures.
Notes: Ingestion sources include agricultural products grown on site, fish caught from the on-site lake, and drinking water drawn from an on-site well.
[a] Cancer oral slope factors represent cancer risk over a lifetime of exposure. Therefore, average daily exposure dose for the first or maximum year of exposure (i.e., the ADD) is divided by 70 years to calculate the LADD.

Table 7.2.5. Inhalation Exposure Assessment for the Air-curtain Burning Option

Chemical Species	Inhalation Exposure Concentration (µg/m³)	Benchmarks	Ranking Ratios
		RfC (µg/m³)	Exposure/RfC
Total Dioxins/furans	7.4E-08	4.0E-05	1.8E-03
Total PAHs	2.6E-04	nb	na
Arsenic	2.9E-04	1.5E-02	2.0E-02
Cadmium	2.0E-03	3.0E-02	6.6E-02
Chromium	9.3E-03	1.0E-01	9.3E-02
Copper	1.0E-02	1.0E+02	1.0E-04
Iron	5.7E-01	nb	na
Lead	9.3E-03	nb	na
Manganese	7.0E-01	5.0E-02	1.4E+01
Nickel	4.3E-03	6.0E-02	7.1E-02
Zinc	1.7E-01	nb	na

Abbreviations: RfC = reference concentration; PAH = polycyclic aromatic hydrocarbon; nb = no benchmark (non-cancer) for inhalation exposure; na = not assessed.
Note: Exposure duration is 48 hours. Cancer risk is not evaluated for this short-term exposure.

Table 7.2.6. Ingestion Exposure Assessment for the Air-curtain Burning Option

Chemical Species	Ingestion ADD (mg/kg d)	Benchmarks		Ranking Ratios	
		Reference Dose (mg/kg d)	Risk specific Dose (mg/kg d)	ADD/RfD	LADD[a]/RSD
Total Dioxins/furans	6.8E-10	2.0E-08	7.7E-10	3.4E-02	1.3E-02
Total PAHs	8.0E-09	nb	1.4E-05	na	8.2E-06
Arsenic	2.4E-07	3.0E-04	6.7E-05	8.1E-04	5.1E-05
Cadmium	7.4E-07	1.0E-03	nb	7.4E-04	na
Chromium	7.6E-05	3.0E-03	nb	2.5E-02	na
Copper	3.1E-05	1.0E-02	nb	3.1E-03	na
Iron	2.0E-03	7.0E-01	nb	2.9E-03	na
Lead	1.5E-07	nb	1.2E-02	na	1.8E-07
Manganese	2.4E-04	1.4E-01	nb	1.7E-03	na
Nickel	9.2E-07	1.1E-02	nb	8.4E-05	na
Zinc	4.5E-04	3.0E-01	nb	1.5E-03	na

Abbreviations: d = day; ADD = average daily dose; RfD = reference dose; RSD; risk-specific dose for target risk of 1.0E-04; LADD = lifetime average daily dose; PAH = polycyclic aromatic hydrocarbon; nb = benchmark (non-cancer) not available for oral exposure; na = not assessed;
Notes: Ingestion sources include agricultural products grown on site, fish caught from the on-site lake, and drinking water drawn from an on-site well.
[a] Cancer oral slope factors represent cancer risk over a lifetime of exposure. Therefore, average daily exposure dose for the first or maximum year of exposure (i.e., the ADD) is divided by 70 years to calculate the LADD.

Because oral slope factors are developed to estimate the likelihood of cancer in a 70-yr lifetime, the estimated exposure (i.e., ADD) for the first year or year of maximum exposure is divided by 70 years before calculating the ranking ratio for a chemical and management option. Although ingestion exposures are likely to continue after the first year (or year of maximum exposure) for

Table 7.2.7. Ingestion Exposure Assessment for the Burial Option

Chemical Species	Ingestion ADD (mg/kg d)	Benchmarks		Ranking Ratios	
		Reference Dose (mg/kg d)	Risk specific Dose (mg/kg d)	ADD/RfD	LADD[a]/RSD
Total Dioxins/furans	na	2.0E-08	7.7E-10	na	na
Total PAHs	na	nb	1.4E-05	na	na
Arsenic	na	3.0E-04	6.7E-05	na	na
Cadmium	na	1.0E-03	nb	na	na
Chromium	na	3.0E-03	nb	na	na
Copper	6.3E-11	1.0E-02	nb	6.3E-09	na
Iron	1.4E-08	7.0E-01	nb	2.0E-08	na
Lead	na	nb	1.2E-02	na	na
Manganese	3.0E-11	1.4E-01	nb	2.2E-10	na
Nickel	5.0E-12	1.1E-02	nb	4.5E-10	na
Zinc	2.2E-09	3.0E-01	nb	7.4E-09	na

Abbreviations: d = day; ADD = average daily dose; RfD = reference dose; RSD = risk-specific dose for target risk of 1.0E-04; LADD = lifetime average daily dose; PAH = polycyclic aromatic hydrocarbon; nb = no benchmark (non-cancer) available for ingestion exposures; na = not assessed.
Note: Ingestion sources include fish caught from the on-site lake and drinking water drawn from an on-site well.
[a] Cancer oral slope factors represent cancer risk over a lifetime of exposure. Therefore, average daily exposure dose for the first or maximum year of exposure (i.e., the ADD) is divided by 70 years to calculate the LADD.

some pathways, the decline in exposure over subsequent years should be exponential, with the continuing depletion of chemical mass at the source and dispersion in the environment. With annual declines of chemical mass at the source ranging from 0.01 to 0.99 of the mass from the preceding year, the likely lifetime ADD (i.e., LADD) might exceed the maximum one-year ADD by up to a factor of 2 (i.e., for a 0.5 annual decline) at most. Loss rates of 0.1 and 0.9 per year would yield a LADD only 1.1 times the ADD. Given the uncertainty associated with estimating the decline in exposure over subsequent years, for purposes of ranking relative risks, each LADD is assumed to equal its one-year ADD. Ranking ratios for cancer health effects are estimated by dividing the LADDs by the RSDs.

The composting management option includes two distinct sets of activities that take place at different on-site locations and times: composting carcasses in the windrow and application of the finished compost to a portion of the farm. Findings for both of these activities combined are shown in Table 7.2.8, and findings for the compost windrow only and compost application only are shown in Tables 7.2.9 and 7.2.10, respectively. Evaluating the contributions of the composting phase and application of the finished compost shows that overall exposures for this management option appear to be driven by application of the finished compost. One reason for this is that chemical releases to groundwater from the windrow are largely contained by the

Table 7.2.8. Ingestion Exposure Assessment for the Composting Option

Chemical Species	Ingestion ADD (mg/kg d)	Benchmarks		Ranking Ratios	
		RfD (mg/kg d)	RSD (mg/kg d)	ADD/RfD	LADD[a]/RSD
Total Dioxins/furans	na	2.0E-08	7.7E-10	na	na
Total PAHs	na	nb	1.4E-05	na	na
Arsenic	na	3.0E-04	6.7E-05	na	na
Cadmium	1.2E-05	1.0E-03	nb	1.2E-02	na
Chromium	2.3E-03	3.0E-03	nb	7.7E-01	na
Copper	6.3E-03	1.0E-02	nb	6.3E-01	na
Iron	2.5E+00	7.0E-01	nb	3.6E+00	na
Lead	1.9E-04	nb	1.2E-02	na	2.3E-04
Manganese	2.7E-03	1.4E-01	nb	1.9E-02	na
Nickel	2.1E-04	1.1E-02	nb	1.9E-02	na
Zinc	2.5E-02	3.0E-01	nb	8.3E-02	na

Abbreviations: d = day; ADD = average daily dose; RfD = reference dose; RSD = risk-specific dose for target risk of 1.0E-04; LADD = lifetime average daily dose; PAH = polycyclic aromatic hydrocarbon; nb = no benchmark available; na = not assessed.
Notes: Table includes results associated with the compost windrow and the 4.05 ha compost application area. For the windrow, 5% of the liquid released from carcasses seeps to the ground below. Compost is tilled into soil to a depth of 20 cm. No offset distance separates the compost application area and the lake. Ingestion sources include agricultural products grown on site, fish caught from the on-site lake, and drinking water drawn from an on-site well.[a] Cancer oral slope factors represent cancer risk over a lifetime of exposure. Therefore, average daily exposure dose for the first or maximum year of exposure (i.e., the ADD) is divided by 70 years to calculate the LADD.

carbon bulking material that underlies the carcasses, and a portion of the leached chemicals from the windrow are "filtered" out by soil before the leachate reaches groundwater. In addition, because the windrow is effective at retaining metals and other chemicals present in the carcasses, these are present in the finished compost when it is applied to surface soil.

When the finished compost is tilled into surface soil, the chemicals are available for plant uptake, incidental ingestion by livestock, and erosion and runoff to surface water. As shown in Table 7.1.10, exposures estimated for finished compost application are below benchmark values, with the exception of the estimated exposure for iron. The modeling approach for compost application, however, did not include an offset distance between the 4.05 ha application area and the lake. Thus, chemicals in eroded soils from the application area could not be filtered out by vegetated soil between the compost application area and the lake.

Table 7.2.9. Ingestion Exposure Assessment for the Composting Option – Windrow Only

Chemical Species	Ingestion ADD (mg/kg d)	Benchmarks		Ranking Ratios	
		RfD (mg/kg d)	RSD (mg/kg d)	ADD/RfD	LADD[a]/RSD
Total Dioxins/furans	na	2.0E-08	7.7E-10	na	na
Total PAHs	na	nb	1.4E-05	na	na
Arsenic	na	3.0E-04	6.7E-05	na	na
Cadmium	na	1.0E-03	nb	na	na
Chromium	na	3.0E-03	nb	na	na
Copper	3.1E-12	1.0E-02	nb	3.1E-10	na
Iron	7.0E-10	7.0E-01	nb	1.0E-09	na
Lead	na	nb	1.2E-02	NA	na
Manganese	1.5E-12	1.4E-01	nb	1.1E-11	na
Nickel	2.6E-13	1.1E-02	nb	2.3E-11	na
Zinc	1.1E-10	3.0E-01	nb	3.7E-10	na

Abbreviations: d = day; ADD = average daily dose; RfD = reference dose; RSD = risk-specific dose for target risk of 1.0E-04; LADD = lifetime average daily dose; PAH = polycyclic aromatic hydrocarbon; nb = no benchmark available; na = not assessed.
Note: Chemicals released from the windrow are contained in the 5% of the liquid released from carcasses that seeps to the ground below. Ingestion sources include drinking water drawn from an on-site well and fish caught from the on-site lake.
[a] Cancer oral slope factors represent cancer risk over a lifetime of exposure. Therefore, average daily exposure dose for the first or maximum year of exposure (i.e., the ADD) is divided by 70 years to calculate the LADD.

Table 7.2.10. Ingestion Exposure Assessment for the Composting Option – Soil Amended with Finished Compost

Chemical Species	Ingestion ADD (mg/kg d)	Benchmarks		Ranking Ratios	
		RfD (mg/kg d)	RSD (mg/kg d)	ADD/RfD	LADD[a]/RSD
Total Dioxins/furans	na	2.0E-08	7.7E-10	na	na
Total PAHs	na	nb	1.4E-05	na	na
Arsenic	na	3.0E-04	6.7E-05	na	na
Cadmium	1.2E-05	1.0E-03	nb	1.2E-02	na
Chromium	2.3E-03	3.0E-03	nb	7.7E-01	na
Copper	6.3E-03	1.0E-02	nb	6.3E-01	na
Iron	2.5E+00	7.0E-01	nb	3.6E+00	na
Lead	1.9E-04	nb	1.2E-02	na	2.3E-04
Manganese	2.7E-03	1.4E-01	nb	1.9E-02	na
Nickel	2.1E-04	1.1E-02	nb	1.9E-02	na
Zinc	2.5E-02	3.0E-01	nb	8.3E-02	na

Abbreviations: d = day; ADD = average daily dose; RfD = reference dose; RSD = risk-specific dose for target risk of 1.0E-04; LADD = lifetime average daily dose; PAH = polycyclic aromatic hydrocarbon; nb = no benchmark available; na = not assessed.
Notes: Compost is tilled into 4.05 ha of soil to a depth of 20 cm. No offset distance between the compost application area and the lake. Ingestion sources include agricultural products produced at the compost application site and fish caught from the on-site lake.
[a] Cancer oral slope factors represent cancer risk over a lifetime of exposure. Therefore, average daily exposure dose for the first or maximum year of exposure (i.e., the ADD) is divided by 70 years to calculate the LADD.

Figure 7.1 provides a visual comparison of the chemical ranking ratios by management option and exposure route (i.e., inhalation or ingestion). For the combustion-based options, which are

the only options with estimated inhalation exposures, the figure shows that exposures normalized to TRVs via inhalation and ingestion pathways are comparable to each other. These ranking ratios tend to be well above ranking ratios estimated for ingestion pathways associated with leaching from burial, the compost windrow, and the temporary carcass pile. Ranking ratios estimated for pathways following the application of compost to surface soil are more similar in magnitude to the ranking ratios for pathways associated with open and air-curtain burning than for burial and the compost windrow. These patterns reflect differences between the exposure pathways (e.g., surface versus subsurface fate and transport) associated with the management options. In addition, differences in data sources available and methods used for different exposure pathways are likely to contribute to the patterns of chemical ranking ratios across options.

Infants under the age of 1 year might be bottle fed with powdered formula reconstituted with water drawn from an on-site groundwater well. Estimated infant ingestion exposures for the livestock carcass burial option included in Table 6.3.14 are compared with the TRVs shown in the last column of Table 7.2.11. Ingestion of nitrates/nitrites, of particular concern for infants, appear to be well below the RfD even using the highest 1-week concentration estimated (for the first week following burial). Nitrate/nitrite concentrations in well water averaged over the first two months are estimated to be one order of magnitude lower than during the first week after an on-site burial. Estimated nitrate/nitrite concentrations averaged over the first year are two orders of magnitude lower than for the first week after on-site burial.

For the remaining chemicals, the estimated concentrations averaged over the first year are compared with the RfD values (last column in Table 7.2.11) as described in Appendix L. All exposure estimates are below RfDs, which indicates that non-cancer health effects are not expected in infants.

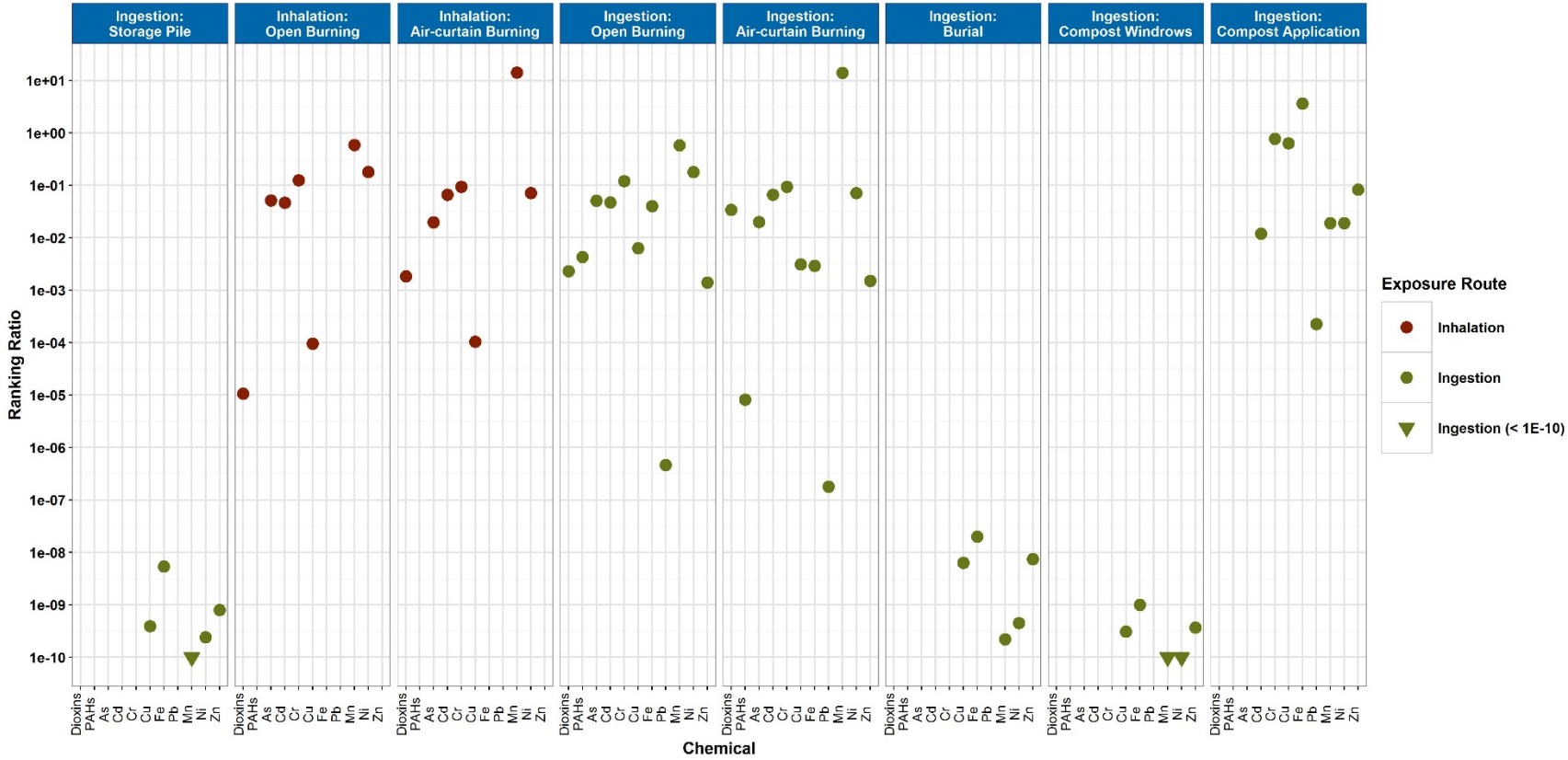


Figure 7.1. Chemical ranking ratios by management option and exposure route.

7.2.11 Ingestion Ranking Ratios for Infants with Formula Made Using Well Water[a]

Chemical Species	Ranking Ratio								Toxicity Reference Dose (mg/kg day)
	Open Burning		Air Curtain		Burial[b]		Composting		
	Avg	95th%	Avg	95th%	Avg	95th%	Avg	95th%	
Total Dioxins/furans	1.4E-14	3.3E-14	2.5E-14	5.9E-14	na	na	na	na	2.0E-08
Arsenic	8.8E-07	2.0E-06	1.6E-06	3.6E-06	na	na	na	na	5.0E-03
Cadmium	1.4E-06	3.3E-06	1.0E-06	2.4E-06	na	na	na	na	5.0E-04
Chromium[b]	2.6E-04	6.1E-04	4.3E-04	9.9E-04	na	na	na	na	3.0E-03
Copper	2.1E-07	4.9E-07	2.6E-07	6.0E-07	2.2E-07	5.1E-07	1.7E-08	3.8E-08	1.0E-02
Iron	9.6E-06	2.2E-05	1.1E-05	2.4E-05	8.7E-07	2.0E-06	6.4E-08	1.5E-07	7.0E-01
Lead	na	na	na	na	na	na	na	na	No RfD
Manganese	2.6E-05	6.1E-05	4.6E-05	1.1E-04	3.6E-08	8.4E-08	2.7E-09	6.2E-09	1.4E-01
Nitrates/nitrites	na	na	na	na	6.6E-04	1.5E-03	2.3E-06	5.3E-06	1.0E+00
Zinc	5.5E-07	1.3E-06	1.9E-06	4.3E-06	1.7E-07	4.0E-07	1.3E-08	3.0E-08	3.0E-01

Abbreviations: Avg = average; 95th = 95th percentile; d = day; nd = no data; na = not assessed.

[a] Avg (average) columns calculated using the mean water ingestion rate of 0.137 L/kg-day for an infant less than 1 month old (highest mean ingestion rate for infants less than 1 year of age, see Table 6.2.1. 95th% = ingested daily dose assuming 95th percentile water ingestion rate for infant 1 to 3 months old (highest 95th percentile ingestion rate reported for infants less than 1 year).

[b] The chromium reference dose (RfD) of 3.0E-03 is for a chronic USEPA RfD documented in IRIS for chromium IV. The most likely form of chromium to reach groundwater has not been evaluated.

The following factors were used to compare the management options on the basis of the chemical ranking ratios:

- **Two highest ranking ratios** – The highest ranking ratios (i.e., highest estimated exposures relative to toxicity benchmarks) indicate the exposure pathways and chemicals that might be "risk drivers" for a management option. When using a maximum value of a distribution, particularly when there is significant uncertainty in the data and methods used to calculate values in the distribution, there is a potential for biasing conclusions based on an unreasonable outlier for a parameter in the calculations. To reduce that possibility when comparing management options, the two highest ranking ratios for each management option are compared across management options.
- **Median ranking ratio** – The median ranking ratio represents a central-tendency of the distribution of the chemical ranking ratios for a management option. The median allows comparisons of the magnitude of the ranking ratios calculated for the options that is less likely to be influenced by outliers. First, for each chemical assessed for a management option, as stated above, ranking ratios are determined for each exposure route (i.e., inhalation or ingestion) and each health endpoint (i.e., cancer or non-cancer). In theory, a single chemical might have three ranking ratios associated with it: inhalation non-cancer, ingestion non-cancer, and ingestion cancer. The maximum of those three ratios (or possibly the only ratio assessed for a given chemical) is assumed to be the "risk driver" for that chemical. Thus, each chemical has a single ranking ratio associated with it. After the single maximum ranking ratio was selected for each chemical, the median ranking ratio across all chemicals was calculated for each carcass management option.

The values of the two highest ranking ratios and the median value across all chemicals for each management option are listed in Table 7.2.12. The table provides a brief summary of the exposure potential for each option. Exposures associated with carcass transportation and handling are listed separately so that differences among the management options are not obscured by exposures that are assumed to be the same for all management options.

Table 7.2.12. Chemical Ranking Ratio Summary

Carcass Management Scenario	Ranking Evaluation		
	Top Two Ranking Ratios	Median Ranking Ratio	Summary of Exposure Potential
Temporary Carcass Storage Pile	▪ 5.4E-09 iron ingestion; ▪ 8.1E-10 zinc ingestion	Median of 5 chemical ratios: 3.9E-10	Exposures from carcass transportation and handling were assumed to be negligible except those arising from storage pile leaching. The estimated exposures are well below those estimated for the carcass management options.
Open Burning	▪ 5.8E-01 manganese inhalation; ▪ 1.8E-01 nickel inhalation	Median of 11 chemical ratios: 4.0E-02	The combustion-based carcass management options have equivalent exposure pathways, and these include more chemical releases to the environment than other options. They are the only options with potentially significant inhalation exposures. While air-curtain burning has higher top ratios than open burning, the median ranking ratio is higher for open burning.
Air-curtain Burning	▪ 1.4E+01 manganese inhalation; ▪ 9.3E-02 chromium inhalation	Median of 11 chemical ratios: 2.0E-02	
Burial	▪ 2.0E-08 iron ingestion; ▪ 7.4E-09 zinc ingestion	Median of 5 chemical ratios: 6.3E-09	For the assumed site setting and carcass burial scenario evaluated, burial has the potential to result in chemical exposures through groundwater and fish ingestion. The estimated ingestion exposures normalized to toxicity are lower than the three other on-site carcass management options and are similar to the ranking ratios for the windrow component of the composting option and the temporary carcass storage pile.
Composting	<u>Windrow</u> ▪ 1.0E-09 iron ingestion; ▪ 3.7E-10 zinc ingestion <u>Compost Application</u> ▪ 3.6E+00 iron ingestion; ▪ 7.7E-01 chromium ingestion	<u>Windrow</u> Median of 5 chemical ratios: 3.1E-10 <u>Compost Application</u> Median of 8 chemical ratios: 5.1E-02	The scenario considered both leaching from the windrow and application of finished compost without erosion controls or an offset distance between the application site and the lake. The highest exposures for this option are for children's ingestion of fish caught in the lake near the compost application field. Exposures from compost-amended soils can be made negligible by using of erosion controls at the compost application site or by adhering to a setback distance between application and the lake.

Based on the information presented in Table 7.2.12, Tier 2 rankings for chemical exposures only are presented below, with rank or number 1 indicating the on-site management option with the least potential for adverse health effects from chemical exposures.

1. **Compost Application.** The highest median ranking ratio and highest two chemical-specific ranking ratios were estimated for the application of finished compost. As shown in Figure 7.1 and Table 7.2.12, the ranking ratios for compost application are, collectively, similar to and only slightly above the ranking ratios for the combustion-based options. Composting does not destroy metals and other persistent chemicals in the carcasses. Thus, almost all of the chemical mass for persistent chemicals remains in the finished compost. That contrasts with the combustion options, where the fate of persistent chemicals is split between air emissions and land-disposed ash. In addition, with compost applied to a 4.05 ha (10 ac) area, the chemicals contained in the compost are added to soil in higher concentrations (e.g., in units of mg/m^3) in that area than chemicals deposited from air to surface soils over much larger areas from the combustion-based options. Runoff and erosion from the area to which compost is applied can move more chemical from that area to surface water than runoff and erosion from the entire watershed receiving deposition from air for the combustion options.

   Although compost application is ranked highest among the on-site management options, it is very likely that exposures are overestimated by a limitation of the modeling approach. In particular, the model used to estimate erosion from the compost application site provides no means to specify an offset distance between the 4.05 ha compost application area and the on-site lake. In actual practice, compost rarely would be applied immediately adjacent to a lake, especially without the use of erosion control. When a distance separates the compost application field and the water body, the intervening land area acts as a buffer that retains soil and compost particles eroded from the compost application area. Potential exposures through these pathways can be controlled with mitigation measures described in Table 7.4.1.

2. **Combustion-based Options.** The two on-site combustion-based management options included in the exposure assessment had the highest estimated exposure levels. These options include direct inhalation exposure to chemicals produced by combustion over 48 hours.

Between the two combustion-based options, open burning has a higher median ranking ratio than air-curtain burning, although air-curtain burning appears to have a higher maximum ranking ratio than open burning. If the coal added to the open pyre is bituminous or subbituminous, the ranking ratio for PAHs for open burning would be higher than in Figure 7.1 by as much as a factor of 14 (see Appendix A); however, that small difference would not affect the overall pattern of ranking ratios. Thus, the distributions of ranking ratios for the two combustion-based options are similar, that is, not distinguishable from each other given the uncertainties in estimating exposures. For this reason, the combustion-based options are ranked together.

Emissions from air-curtain burning are sensitive to the assumed quantity of wood burned. This assessment assumes a fuel-to-carcass ratio of 4:1 on a weight basis. This assumption was obtained from the expert workshop discussed in Section 2.5. However, information available from the literature (see Section 3.3) indicates that air-curtain burning might require fuel-to-carcass ratios from 1:1 to greater than 4:1. Emissions rates (not shown) calculated with a 2:1 fuel ratio resulted in lower estimated concentrations of PAHs compared with open burning and lower concentrations of dioxins/furans than predicted for air-curtain burning based on the 4:1 ratio.

3. **Burial.** On-site burial is one of three carcass management activities with potential "below ground" exposure pathways through groundwater, the other two being temporary carcass storage and the windrow phase of composting. As shown in Figure 7.1 and Table 7.2.12, ranking ratios estimated for those three activities tend to be several orders of magnitude below the ranking ratios for the management options with above ground exposure pathways. In addition, the ranking ratios are at least 8 orders of magnitude below 1.0, which indicates a very low likelihood of adverse health effects, particularly with the conservative assumptions of this assessment (e.g., no dilution or attention of chemicals in groundwater, drinking water obtained from a shallow, unconfined aquifer). Ranking ratios are greater for burial than for temporary carcass storage and the compost windrow because burial releases more leachate to soils than the other activities.

   One reason that exposures via groundwater are lower than exposures via above-ground pathways is that chemicals in the liquids released from the carcasses can be filtered out by

the soil before they reach groundwater. Partitioning to soil is estimated with chemical-specific soil-water partition coefficients. The effect of partitioning on chemical fate is consistent with field experiments by Glanville et al. (2006), who found chloride ion (Cl^-) concentrations above background in soil below a compost windrow to a depth of 120 cm, but other leachate components declined more quickly with depth than Cl^-. Chloride ions do not sorb to soils particles (which also have a net negative charge), and so are good markers of maximum leaching distance. Concentrations of total nitrogen, ammonia, and nitrates decreased with increasing depth and were significantly different from background only in the top 15 cm of soil when corn stalks were used as the bulking agent. As discussed in Section 7.3, differences between the ranking ratios estimated for the different pathways is attributable in part to unavoidable differences in the uncertainty and conservatism of the source data and modeling approaches.

4. **Temporary Carcass Storage.** The temporary carcass storage pile is assumed to be on bare ground with no containment of liquids released by the carcasses during two days of storage. The median and maximum two ranking ratios for the storage pile are very low for the reasons discussed above for the burial option, as well as the very short duration of releases (two days) compared with burial.

5. **Compost Windrow.** Among the carcass management activities evaluated, the lowest potential exposures were estimated for the windrow phase of the composting option. Chemical exposures from the composting windrow are several orders of magnitude lower than those from compost application. Properly constructed and maintained windrows are effective at containing chemicals from carcass decomposition while allowing the water in leachate to evaporate from the bulking materials. Although, composting is effective at breaking down organic matter, metals and other persistent chemicals are not destroyed and remain in the windrow and finished compost.

7.2.3. Tier 2 Ranking for Microbial Exposures

For microbes, the Tier 2 ranking of the four on-site carcass management options uses the microbial exposure estimates presented in Section 5. As discussed previously, microbial exposures are not estimated for all of the exposure pathways in the conceptual models; the pathways that were quantified are shown in bold type in Table 6.1.2. For convenience, Table 6.1.2 is repeated here in Table 7.2.13. The exposure pathways that were not quantified for one or more reasons are included in Table 7.2.13 in plain (not bold) type. The reasons that certain pathways were not assessed were discussed in Section 6.1.

Like chemical exposures, microbial exposures associated with carcass transportation and handling steps that precede each of the on-site management options are evaluated in Tier 2 separately from the management options themselves (Table 7.2.13).. The carcass transportation and handling steps, and their resulting microbial exposures, are assumed to be the same for all carcass management options.

Unlike chemicals, TRVs are not available for microbes. To allow a relative risk-based evaluation of the exposures for microbes, exposures are compared to available ID_{50} values reported in the literature for the three microbes selected for this assessment. The three microbes should represent three subsets of the potential microbial hazards identified in Table 2.4.4 (Section 2) – prions, spore-forming bacteria, and non-spore forming bacteria. The ID_{50} values for *B. anthracis, E. coli* O157:H7, and scrapie-inducing prions (PrP^{Sc}) are provided in Table 6.1.1 (and included in Table 7.2.14). A human ID_{50} value is not available for prions, so the reported ID_{50} value for cattle is used instead.

As stated above, for microbes, only human exposures associated with groundwater ingestion are quantified. The exposure estimates are compared to the reported ID_{50} values. Exposure estimates at or above the ID_{50} indicate that possibly half of the farm residents, especially sensitive populations, might fall ill following the ingestion of groundwater. Values many orders of magnitude below the reported ID_{50} value are unlikely to result in illness in a small population of farm residents.

Table 7.2.13. Potential Human Exposure Pathways and Routes for Livestock Carcass Transportation and Handling Activities and Management Options – Microbes

Exposure Source	Carcass Transportation and Handling			Carcass Management Options			
	Carcass Handling	Temporary Carcass Storage	Carcass Transportation	Open Burning	Air curtain Burning	Burial	Composting
Inhalation	1) Air[b]	1) Air[b] 2) Leachate → Soil → GW → Aerosol[b]	1) Air[b]	1) Air[b] 2) Ash → GW → In-home Aerosol[b]	1) Air[b] 2) Ash → GW → In-home Aerosol[b]	1) Air[b] 2) Leachate → GW → In-home Aerosol[b]	1) Air[b] 2) Compost → GW → In-home Aerosol[b]
Incidental Ingestion	2) Hand-to-mouth ingestion [b,c]	—	2) Accident → soil[b,c]	3) Air → Soil[b]	3) Air → Soil[b]	—	—
Dermal Contact	3) Dermal contact[c]	—	3) Accident → soil[c]	—	—	—	—
Fish Ingestion	—	3) Leachate → Soil → GW → SW → Fish[b]	—	4) Air → SW → Fish[b] 5) Air → soil → SW → Fish[b] 6) Ash → GW → SW → Fish[b]	4) Air → SW → Fish[b] 5) Air → Soil → SW → Fish[b] 6) Ash → GW → SW → Fish[b]	3) Leachate → GW → SW → Fish[b]	3) Compost → Soil → SW → Fish[b] 4) Compost → GW → SW → Fish[b]
Groundwater Ingestion	—	**4) Leachate → Soil → GW[a]**	—	**7) Ash → GW[a]**	7) Ash → GW[b]	**4) Leachate → GW[a]**	**5) Compost → Leachate → GW[a]**
Ingestion of Food Produced on the Farm	—	5) Air → Plants/livestock[b] 6) Leachate → GW → Livestock[b]	—	8) Air → Plants/ Livestock[b] 9) Air → Soil → Plants/ Livestock[b] 10) Ash → GW → Livestock[b]	8) Air → Plants/ livestock[b] 9) Air → Soil → Plants/ Livestock[b] 10) Ash → GW → Livestock[b]	5) Air → Plants/ Livestock[b] 6) Leachate → GW → Livestock[b]	6) Air → Plants/ Livestock[b] 7) Compost → Soil → GW → Livestock[b]

Abbreviations: "—" = no exposure pathways; SW = surface water; GW = groundwater.

Note: Exposure pathways shown in bold were included in the quantitative exposure assessment.

[a] Quantitative methods were available for exposure assessment; results are presented in Section 5.

[b] Potential exposures were assumed to be negligible based on source conditions or microbial properties.

[c] Environmental releases or exposures were assumed to be adequately controlled by existing pollution control regulations or the use of personal protection equipment (PPE).

For humans, all exposure estimates for ingestion were below the reported ID_{50} values for all microbes at all time intervals (from initial exposure to 1 year). The lowest and highest microbial exposure estimates for groundwater ingestion, the ID_{50} values associated with these microbes, and the transportation and handling activities and management options associated with the exposure estimates, are summarized in Table 7.2.14.

Table 7.2.14. Ingestion Exposure Assessment for Microbes

Microbe	Management Option	ID_{50}	Highest Exposure Estimate/ Time Interval	Lowest Exposure Estimate/ Time Interval	Reference
Bacillus anthracis	Temporary carcass storage	1,000s – 10,000s spores	4.08E+00 particles/ initial	1.52E+00 particles/ 1 year	WHO (2008)
	Burial				
	Composting				
Escherichia coli O157:H7	Temporary carcass storage	10 –100 organisms	1.35E-05 particles/ initial	2.64E-17 particles/ 1 year	Gurian et al. (2012)
	Burial				
Prions (PrP^{Sc})	Temporary carcass storage	Unknown for humans; value for cattle 5.5E-03 particles	4.08E-04 particles/ initial	5.25E-30 particles/ 1 year	Yamamoto et al. (2006)
	Open pyre				
	Burial				
	Composting				

Abbreviations: ID_{50} = infectious dose at which 50% of the exposed population falls ill; PrP^{Sc} causes the disease scrapies.

As illustrated in Table 7.2.14, the exposure estimates for *E. coli* O157:H7 are significantly lower than the associated ID_{50} value for humans (>7 orders of magnitude). It is unlikely that exposure to those concentrations of *E. coli* O157:H7 in drinking water would result in illness in local healthy human populations. *E. coli* O157:H7 is representative of a larger group of non-spore forming bacteria that are expected to be released from livestock carcasses present in the storage pile and the burial pit (see Table 2.4.4). Compared with the ID_{50} value for this non-spore forming species of bacteria, the estimated exposure indicates that human illness is very unlikely.

The exposure estimates for *B. anthracis* are also below the reported ID_{50} value for humans. Exposure estimates after the initial release and over the first year of exposure to groundwater is 3–4 orders of magnitude less than the ID_{50}. Like *E. coli* O157:H7, it is unlikely that exposure to those concentrations of *B. anthracis* would result in illness in a small, localized, population of humans. *B. anthracis* represents a larger group of spore-forming agents that are expected to be

released from livestock carcasses in the storage pile, the compost pile, and the burial pit (see Table 2.4.4). Compared with the ID_{50} value for *B. anthracis*, the estimated exposure indicates that human illness is possible, but unlikely in a relatively small population of farm residents. It should be noted that the sensitive populations are more vulnerable than others (Gerba et al 1996).

The exposure estimate for scrapie-inducing prions at the initial exposure is closer to its ID_{50} value than *E. coli* O157:H7 or *B. anthracis*; however, an ID_{50} value is available only for cattle, not humans. The exposure estimate after the initial release to groundwater (time 0) is only one order of magnitude less than the ID_{50} value for cattle. However, the estimated exposure one year later is 27 orders of magnitude less than the ID_{50} value for cattle. Prions were not selected to represent other microbial hazards identified in Table 2.4.4; they were selected because they are the most resistant to inactivation by environmental stressors of the microbial categories. In contrast to the first two microbes, releases of infectious prions are possible for three of the on-site carcass management options (i.e., composting, burial, and open-burning), as well as for the carcass storage pile. The estimates of exposure at most time intervals are not likely to result in illness in local healthy human populations, but illness might occur if groundwater is ingested following the initial release of prions to this medium and if the human ID_{50} value is close to the ID_{50} value for cattle. Each management option includes exposure to microbes via carcass handling, transportation, and the temporary carcass storage pile; however, those exposures are associated with all carcass management options equally.

Given the assumptions and methods of this assessment, the ratio of exposure estimate to ID_{50} values for each of the three microbes evaluated did not distinguish among the four on-site livestock carcass management options. Thus, to rank those options relative to each other, one key criterion was used: efficacy of each management option in thermally inactivating the pathogens examined. Based on that criterion, the four on-site management options are ranked from the potentially lowest microbial exposure (1) to the highest (4) below.

1. **Air-curtain Burning.** Air-curtain burning at temperatures approximating 850°C is likely to destroy or inactivate essentially all three types of pathogens, including spore-forming bacteria and prions. Thus, no exposure pathways are likely for microbes associated with air-curtain burning.

2. **On-site Open Burning.** The temperatures reached in an open pyre (e.g., approximately 550°C) should inactivate bacterial cells and spores; the exception is that prions could survive. Subsequent burial of the remaining ash eliminates above ground exposure pathways for surviving prions. **U**neven burning across an open pyre could allow survival of other thermotolerant spore-forming bacteria and other microbes.

3. **On-site Composting, Windrow.** The heat produced by thermophilic bacterial decomposition of composted livestock carcasses can raise the temperature of materials in the compost pile to 55°C for several days. Even that modest temperature is sufficient to inactivate virus particles and bacterial cells, although not spores from the spore-forming species of bacteria. Particles in leachate released from the compost pile should be contained in the bulking material below the windrow, with perhaps 5% leaking to subsurface soils during precipitation events. Prions and spore-forming bacteria identified in Table 2.4.4, like *B. anthracis*, *Clostridium perfringens,* and *Coxiella burnetii,* could survive the composting process and be present in finished compost in which the bulking materials surrounding the carcasses are mixed in with the carcass remains. Viable prions and bacterial spores could, therefore, be applied in finished compost to soils on the farm. If a windrow is allowed to sit for several additional weeks, the additional heating could provide for more complete inactivation of spore-forming bacteria (Schwarz and Bonhotal 2014). In the field, most human exposures to *B. anthracis* are via spores on the skin or fur of mammals (wool, hides, or hair) and not via consumption of crops that might have come in contact with infectious spores (CDC 2015). Persons handling infected mammals might contract inhalation anthrax (e.g., spores aerosolized during industrial processing of contaminated materials) or cutaneous anthrax (e.g., if spores contact an open cut or scrape on the persons' skin). Ingestion anthrax could occur if raw or undercooked meat from infected animals is consumed; however, that generally occurs where livestock are not vaccinated against anthrax and where food animals are not inspected before slaughter (CDC 2015).

4. **Burial.** Although the fewest exposure pathways were identified in the conceptual model for burial, this option is associated with the greatest potential for pathogen survival over the long term. In addition, no thermal inactivation of microbes is expected. The conditions of the

burial pit impact pathogen viability in different ways, adding a high level of variability to pathogen survival. For some pathogens, the anaerobic conditions of the burial pit favor a shift to survival forms (e.g., spores). The spores can remain viable for long periods of time and are environmentally resistant. Analyses of livestock carcass burial sites have reported the detection of a wide range of microbes in and soil samples surrounding these burial sites (Davies and Wray 1996; Joung et al. 2013). However, for other pathogens, the conditions of a burial trench might prevent sporulation or regrowth. Some microbes in leachate from buried carcasses might escape adsorption to soil particles when traveling from the burial trench toward groundwater. If microbes do not reach groundwater, then risks from this key exposure pathway for both humans and livestock becomes negligible. If microbes reach groundwater, recharge of groundwater into the on-site lake similarly would result in very low concentrations in the water column. Even small lakes would dilute concentrations of pathogens reaching the lake via groundwater recharge to negligible concentrations.

In conclusion, for microbes the four on-site carcass management options can be ranked by their ability to thermally inactivate microbes as shown in Table 7.2.15, with rank 1 indicating the option with the lowest exposure potential. Table 7.2.13 identified the exposure pathways evaluated for microbes with bold text. The temporary carcass storage pile would be used prior to the management of carcasses for each option, and exposures originating from the pile should affect each management option equally. Similarly, on-site carcass handling is the same across management options. Therefore, temporary carcass storage and handling do not affect the ranking of management options.

Table 7.2.15. Ranking the Four On-site Carcass Management Options by Relative Risk from Microbes

	Carcass Management Option	Rationale
1	Air-curtain burning	All microbes inactivated or destroyed, lowest relative risk
2	Open-pyre burning	Prions survive, other microbes inactivated or destroyed
3	Composting: windrow & application	Prions and spores survive, *E. coli* can be inactivated
4	Burial	No thermal destruction; leachate not impeded

The temperatures and burn durations associated with combustion-based management options are expected to destroy most pathogens. Air-curtain burning subjects particles to multiple burn cycles and high temperatures in the burning carcasses. No microbe exposure is anticipated. On-

site open burning might not inactivate prions, but otherwise can inactivate most types and species of microbes.

Of the two land-based on-site options, composting and burial involve the same pathways, but the interactions with the normal microflora would lead to different overall microbial populations and effects. Pathogens could be present in leachate produced at the burial site and during the composting process. The aerobic environment maintained during the composting process is likely to favor the ability of native thermophilic microflora to outcompete pathogen populations. The final compost product is likely to have very low populations of prions and spore-forming bacteria remaining as contaminants, and allowing the windrow to sit for more time before application decreases the likelihood that viable spore-forming bacteria would be present in finished compost. Leachate from a poorly sited composting process could introduce spore-forming bacteria and prions to groundwater sources. The anaerobic environment that accompanies many burial sites is likely to favor pathogens shifting to survival forms that subsequently die, are inactivated, or become diluted below an infective dose over time. Release to groundwater via contaminated leachate is the only pathway assessed quantitatively for burial.

Microbial releases were also identified for carcass transportation and handling activities; however, the use of PPE and other transportation-related common practices (such as the use of tarps) should prevent exposure to microbes from carcass handling and transportation. Four exposure pathways were identified for temporary carcass storage. Like on-site unlined burial, leachate produced from temporary carcass storage piles can release a broad range of pathogens, including prions, viruses, and bacteria. Those might reach groundwater sources used for drinking water; however, the short duration of storage should help mitigate that possibility. Of the transportation and handling activities, the temporary carcass storage pile is associated with the highest potential exposure to pathogens (see Section 6.1). Exposures to microbes are mitigated through the use of PPE and other measures (e.g., tarp, lined trucks) for other carcass transportation and handling activities.

7.3. Conclusions and Discussion of Uncertainty

Throughout the analysis, chemicals and microbes were assessed independently, because of fundamental differences in the two types of potentially hazardous agents and differences in the availability of suitable data and approaches (e.g., models, methods). The final rankings of the

seven livestock carcass management options differ for chemicals and pathogenic microbes, as described in Section 7.3.1.

Section 7.3.2 discusses key uncertainties in the exposure assessments for both chemicals and pathogenic microbes. It also describes activities or modifications of the carcass management processes and options that can mitigate exposures along certain pathways.

1.2.1. Conclusions

The qualitative Tier 1 assessment distinguished the three off-site management options as releasing fewer chemicals and fewer microbes (or at lower concentrations) than the on-site options because of regulatory emission controls (Section 7.1, Table 7.1.1). For the on-site management options, the Tier 2 assessment quantified relative risks from chemical releases (Sections 4 and 5), but not microbial releases (Section 6).

For chemicals, the Tier 1 and Tier 2 assessments are summarized in Table 7.3.1. The Tier 1 summary shows that (1) the off-site options are considered to pose lower risk than the on-site options as discussed above, and (2) the off-site options are not ranked relative to each other. The Tier 2 summary shows numerical rankings for the on-site options, with the rank of 1 posing the lowest relative risk. Some options (e.g., air-curtain burning and open burning) were not distinguishable from others given data gaps and uncertainty in modeling. Those options have, therefore, the same relative rank.

The Tier 2 rankings for chemicals are based on the quantitative assessment in which different methods were applied to model combustion releases to air and to assess fate and transport in surface and subsurface soils, groundwater, and an on-site lake. Initial emissions of chemicals to air and in leachate were based on measured data reported in the literature under conditions similar to the assumptions for the hypothetical farm. Conservative assumptions filled other data gaps, including environmental characteristics with high variation nationwide.

Table 7.3.1. Ranking of Livestock Carcass Management Options for Chemicals

Tier 1 Description	Management Option		Principal Rationale
The qualitative Tier 1 assessment distinguishes the off-site options from the on-site options based on level of regulatory control. The off-site options are considered to pose lower risk than the on-site options, which have uncontrolled environmental releases. The off-site options are not ranked relative to each other.	Off-site Rendering		Carcasses processed into useful products; wastes released under permits; availability decreasing
	Off-site Landfill		Carcass leachate contained and methane captured; landfills at capacity are closed and new ones built
	Off-site Incinerator		Destruction of materials; air emissions are regulated; ash is landfilled
Tier 2 Description	**Rank [a]**	**Management Option**	**Principal Rationale**
The quantitative Tier 2 assessment ranks the on-site options relative to each other by comparing ratio of estimated exposures (from data on source emissions and fate and transport modeling) with toxicity reference values (TRVs).	1	Compost Windrow	Bulking material retains most chemicals
	1	Burial	Soils filter out chemicals traveling toward groundwater
	2	Air-curtain burning	Similar release profiles; emissions sensitive to type and quantity of fuels used and burn temperature
	2	Open Pyre burning	
	3	Compost Application	If no offset from lake; mitigate with offset and erosion controls

[a] Rank 1 poses the lowest relative risk and higher numbers indicate higher relative risk.

The Tier 1 and Tier 2 assessments for microbes are summarized in Tables 7.3.2 and 7.3.3, respectively. In Tier 1, the off-site options were ranked (i.e., highest, middle, lowest) qualitatively based on the level of thermal destruction. Off-site options were not ranked relative to on-site options, because different assessment methods were used in the two tiers. It should not be assumed that the off-site options pose lower risk than the on-site options. In fact, some on-site options offer comparable or greater thermal destruction than off-site options.

In the Tier 2 assessment, three pathogenic microbes were evaluated to represent prions, bacterial spores, and bacterial cells (Section 6). For these microbes, all estimated exposure doses were below the available ID_{50} values. A significant unknown for this assessment, however, is the initial concentration likely in healthy livestock killed by a natural disaster. Therefore, the rankings in Table 7.3.3 are based on thermal destruction and containment provided by the options. These rankings assume prions could survive more management options than spores, and bacteria that do not form spores were most susceptible to thermal inactivation. The rankings

could be different if management options are not implemented according to guidelines. Uncertainties associated with the microbial assessment are discussed in Section 7.3.2.

Table 7.3.2. Tier 1 Ranking of Off-site Livestock Carcass Management Options for Microbes

Tier 1 Description	Rank[a]	Management Option	Principal Rationale
The qualitative Tier 1 assessment distinguishes the off-site options from the on-site options based on level of regulatory control. Among the off-site options, rankings are based qualitatively on the level of thermal destruction. Off-site options are not ranked relative to on-site options, although some will offer thermal destruction comparable to or greater than on-site options.	H	Off-site Incinerator	Thermal destruction of all microbes, ash is landfilled
	M	Off-site Rendering	Thermal inactivation of all microbes except prions, workers protected from prion exposure with the use of PPE
	L	Off-site Landfill	Containment, including liner, leachate collection, cover material, but no thermal destruction; when capacity is reached, landfill is closed and new ones built

Abbreviations: H = Highest rank; M = Middle rank; L = Lowest rank.

[a] Relative and absolute risks from microbial pathogens depends on initial concentrations in healthy cattle, which are unknown.

Table 7.3.3. Tier 2 Ranking of On-site Livestock Carcass Management Options for Microbes

Tier 2 Description	Rank[a,b]	Management Option	Principal Rationale
Rankings in the Tier 2 assessment are based on quantitative exposure dose estimates for a limited number of exposure pathways. For those pathways and the microbes assessed, all estimated exposure doses were below the available ID_{50} values for each representative microbe (<6, 3–4, and ~ 1 order of magnitude lower than the ID50 for *E. coli*, *B. anthracis*, and prions, respectively). Therefore, the rankings reflect the extent of thermal destruction.	1	Air-curtain	Thermal destruction of all microbes
	2	Open Pyre	Thermal destruction of all microbes except prions
	3	Compost: -Windrow -Soil application	Thermal inactivation of most microbes during windrow decomposition phase, incomplete inactivation of spore-forming microbes and prions with some decay/inactivation expected before the application of finished compost
	4	Burial	No thermal inactivation of any microbes, some decay expected

[a] Rank 1 poses the lowest relative risk and higher numbers indicate higher relative risk.

[b] Relative and absolute risks from microbial pathogens depends on initial concentrations in healthy cattle, which is unknown; qualitative ranking is based on thermal destruction and containment.

1.2.2. Uncertainties

The scenarios, modeling tools, and exposure estimation methods used in this assessment include numerous assumptions that might or might not be consistent with site-specific livestock carcass management applications. In addition, because limited data are available on the sources of chemicals and microbes released from carcass management activities, some aspects of the assessment use substitute data or simplifying assumptions that may over- or under-estimate the exposures. Important sources of uncertainty affecting the exposure assessment are discussed below. Where possible the effects of the uncertainties and limitations on over-or under-estimation are described.

- **Site Setting and Environment** – Aspects of the hypothetical site setting that contribute to uncertainty include the following:
  - **Site layout**, including the distances between carcass management units and exposure locations (e.g., the drinking water well), depth to groundwater, and lake size. Site layout assumptions can be considered reasonably conservative (i.e., leading to higher exposures). For example, the depth to groundwater and the distance to the drinking water well are based on the most conservative minimal values identified from state regulations. At most actual sites, adherence to state and federal guidelines could easily result in lower potential exposures than represented by the conservative assumptions used for the assessment.

    Although the site layout was designed to include all exposure pathways in the conceptual models, actual sites will not necessarily include all of the pathways. In this regard, the site setting is likely to overestimate actual exposures. For example, the assessment assumes that sources of groundwater contamination affect a nearby drinking water well. This scenario implies that drinking water is obtained from a shallow unconfined aquifer. However, as shallow wells are more susceptible to contamination than deeper wells, most actual sites would be expected to obtain drinking water from deeper wells less susceptible to contamination.
  - **Environmental characteristics –** Related to the site setting are assumptions about the characteristics of soil, surface water, and sediment used by the fate and transport models. In most cases, these assumptions are default values recommended in the USEPA (2005a)

documentation, which in turn are based on a number of elements, such as the best science available and professional judgement. As a national-level guidance, the HHRAP recommendations typically reflect national average conditions (USEPA 2005a). Environmental characteristics at particular sites could contribute to exposures that are either greater to or less than those estimated with the assumptions used for this assessment.

- **Meteorological conditions** -- Meteorology data were selected for a location in Iowa, because of the predominance and diversity of agricultural activities in the central Midwest, and because this region is not characterized by extreme weather conditions (e.g., aridity). These data affect air dispersion modeling and leaching from combustion ash for the combustion-based management options. The analysis uses estimated air concentrations of chemicals for the 48 hr period during the year when the weather would produce the greatest deposition to ground. Leaching from buried ash is a function of the total annual rainfall and the number of times it rains per year. Excluding factors other than weather, the exposure estimates could be greater or lower than would be expected at other sites (e.g., wetter or drier).

- **Carcass Management Options** – The assessment requires assumptions about the design and implementation of each of the carcass management options. Examples of these assumptions include

  - The sizes and dimensions or carcass management units
  - Method and duration of carcass storage before disposal
  - Types and amounts of combustion fuels
  - Combustion temperatures and durations
  - The use of tarps, erosion controls, PPE, and other mitigation
  - The use of finished compost

  These assumptions were based on typical practices described in the available literature or identified by experts (see Section 2.5). Although the assumptions about the carcass management options were chosen to represent typical practices, variations in actual practice are likely to result in exposures that may be higher or lower than estimated.

- **Fate and Transport Modeling** – The assessment uses various models to estimate concentrations of chemicals in air, soil, water, and foods. The models include existing computer models, e.g., AERMOD, MIRC, AQUAWEB), as well as modeling tools developed for this project based on HHRAP (USEPA 2005a) and ad hoc methods (e.g., for estimating leaching from combustion ash). Sources of uncertainty associated with fate and transport modeling for this assessment include the following:
  - **Input data** – Each model requires input such as initial chemical concentrations, emission factors, and chemical properties (e.g., vapor pressure, partition coefficients, biotransfer factors), as well as inputs discussed separately above (e.g., scenario assumptions, environmental characteristics). These data are subject to various limitations and uncertainties, discussed in Sections 3 and 4, which individually and collectively may cause exposures to be under- or over-estimated.
  - **Model precision and accuracy** – The models and modeling approaches used in the assessment have varying levels of sophistication. For example, AERMOD provides a more refined approach to estimating air dispersion and deposition of chemicals than the approach for estimating chemical movement to groundwater and subsequent well interception. On the other hand, natural variation in hydrological features underlying livestock rearing locations across the United States is substantial and no one setting is likely to be representative. In general, the less refined approaches are likely to over-estimate exposures that more refined models, because conservative assumptions are used to address data gaps and conservative approaches address uncertainties in model form. For example, the groundwater modeling approach assumes there is no dispersion or attenuation of the chemicals in groundwater as it flows along an unconfined aquifer for 30.5 m (100 ft) to the downgradient drinking water well.

  The uncertainties associated with fate and transport modeling data and methods can individually contribute to under-or over-estimation of exposures. In general, however, the assessment uses more conservative assumptions and approaches, which would most likely result in over-estimates of possible exposures.

Because multiple models are used and because modeling requirements differ by management option, the level of uncertainty attributable to fate and transport modeling varies among management options and among exposure pathways.

- **Potential Microbial Hazards** – The assessment requires assumptions about the pathogenic microbes that could be present in livestock categorized as "healthy." Livestock are assumed to be free from the signs or symptoms associated with infection with a given pathogen. The list of potential microbial hazards was developed by considering the specific types of microbes (e.g., viruses, bacteria, fungi) commonly present in livestock such as cattle, poultry, and swine. FADs were not considered; however, pathogens less frequently isolated from U.S. livestock with long incubation periods were included. Examples of these microbes include *B. anthracis* and prions that produce scrapie disease. Several of the potential microbial hazards, categorized as prions and spores of spore-forming bacteria that are identified in this assessment are resistant to high temperatures would not be inactivated by combustion-based management options or other thermal-based processes, such as composting. The ability of these microbes (i.e., prions and bacterial spores) to remain active despite the temperatures reached in open burning and in composting contributes to the less favorable ranking of those two management options. However, if the assumption that prions and spore-forming bacteria are present in livestock is *incorrect*, and these microbes are not present in managed livestock, then the on-site open burning and composting options would be ranked similarly to air-curtain burning for bacterial cells that cannot produce spores. The thermal processes associated with air-curtain burning, on-site open burning, and composting would inactivate all potential microbial hazards if prions and spore-forming bacteria were not present in managed livestock. Unlined burial would remain the least favorable management option, because the carcasses remain at ambient temperatures (i.e., no thermal inactivation), and there are no regulations that require containing or collecting leachate or gases.

- **Exposure Estimation** – Exposures are estimated using mean exposure factor values (e.g., body weight, daily food ingestion rates) for adults and children. Mean values are used to represent the general population and could under- or over-estimate exposure for some people, such as people who are extremely active or people who are sedentary, respectively.

The conceptual models and exposure estimation approach assume that farm residents consume a diet of home-grown foods including fruits, vegetables, meat and dairy products, as well as fish caught from the on-site lake. This scenario is not typical, and will overestimate food ingestion exposures, even using mean ingestion rates as described above.

The combined impact of these uncertainties has not been quantified, nor has the sensitivity of the exposure estimates to key uncertainties. However, based on the discussion above, the overall approach is expected to overestimate actual exposures for each exposure pathway.

Because so many site-specific variables affect chemical and microbial exposure from livestock carcass management, exposures at actual sites are likely to be less than, but might be greater than, estimated by this assessment. Based on the assessment, this Report contributes to understanding potential chemical and microbial exposure pathways and how design and implementation could modify exposures of humans, livestock, and wildlife. Table 7.3.4 describes how changing some of the key aspects of design or implementation of the carcass management options would change potential exposures.

Table 7.3.4. Effect of Scenario Design or Implementation on Potential Exposures

Management Options(s)	Aspect of Implementation	Effect of Change on Exposure
All on-site options	Scale of mortality	In general, larger mortalities result in greater potential releases and exposures. Large scale losses could make some management options technically infeasible or require the use of multiple options. Longer periods of temporary carcass storage might be required, which increases the potential for exposures.
All on-site options	Meteorology	Effect varies by parameter. For example, the strength and uniformity of winds determine the downwind distribution of airborne chemicals. The frequency, amount, and intensity of rainfall affects rates of erosion, surface runoff, and chemical leaching to soil.
All on-site options	Soil particle size and type	Natural soils vary in texture, mineral composition, and availability of pores or fractures of substantial size. Those factors in turn influence how quickly leachate and rainwater can flow through soils vertically and likely it is for chemicals and microbes to sorb to soil particles. Soils comprised of fine particles (e.g., clay) can hold more water, but also retard flow to groundwater and adsorb more chemicals and microbes than soils consisting of medium (e.g., loam) or larger particles (e.g., sand). This assessment uses recommended default soil properties from HHRAP (USEPA 2005a), which were chosen to reflect national average conditions.
All on-site options	Soil organic content	Higher organic content favors sorption of non-ionic organic chemicals (e.g., PAHs and dioxins/furans). It also favors sorption of microbes. In both cases, soils with higher organic content would filter out more contaminants than would soils with lower organic carbon content.

Management Options(s)	Aspect of Implementation	Effect of Change on Exposure
All on-site options	Surface slope	A slope of 5% was used. Lesser slopes could result in rainwater pooling during storms but virtually no runoff or erosion. Greater slopes would result in higher soil erosion and more rapid runoff during precipitation events. For temporary carcass storage piles on bare ground, greater slopes could allow faster and farther surface movement of leachate.
All on-site options	Lake size	In general, larger lakes provide more dilution of chemicals and microbes that reach them via surface runoff and erosion or by groundwater recharge (see Figure 5.4.1). Small lakes or ponds could respond to added carbon, nitrogen, phosphorus with noxious algal blooms. Small lakes also might respond to added BOD and COD from buried carcasses with fish kills from depleted oxygen.
All on-site options	Home-grown foods	This assessment assumes that farm residents eat home-grown fruits, vegetable, meat, dairy, and eggs, as well as fish caught in the on-site lake. Exposures will be lower for farm residents who also or exclusively consume commercial foods (e.g., from grocery stores).
All on-site options	Exposure assumptions	Exposures are estimated using assumptions about the body weight and ingestion rates (e.g., of drinking water, foods) of farm residents. The assumptions are based on mean values for the U.S. population (USEPA 2011). Higher or lower exposures could result at sites where actual exposure factors are different from those values.
All on-site options except compost application	Groundwater hydrology	For this assessment, groundwater carries chemicals and microbes that originated in carcasses and that migrated to groundwater to an on-site well and lake. In many locations, however, site-specific groundwater hydrology can preclude these pathways. For example, contamination of the well might be prevented by the speed or direction of groundwater flow, or the depth of the well relative to the source. For many lakes, the direction of water flow (recharge) is from the surface water to groundwater.
Open burning and Air-curtain burning	Source placement relative to receptor locations	Public objections to open burning in the past have primarily come from the smoke, soot, and sulfurous odors emanating from an open pyre. Air-curtain burning produces lower levels of all three nuisances than open pyre. The farther away from the farm residence, neighboring residences, towns and cities, the fewer people will be affected.
Open burning and Air-curtain burning	Ash disposal	For this assessment, ash is buried with clean soil on site, and leaching from the ash can carry chemicals and microbes to groundwater. In some cases, ash might be managed in other ways with more or less potential for exposure. For example, less exposure would be expected if the ash is sent to an off-site landfill. When ash is managed on site (e.g., buried, mixed sparingly in surface soils), the configuration and placement of the management area can affect environmental concentrations and potential exposure pathways.
Air-curtain burning	Fuel-to-carcass ratio	Fuels used in air-curtain burners include large quantities of wood and a relatively small amount of accelerant to start the fire. For this assessment, a 4:1 ratio of wood to carcasses is assumed. The literature suggests that higher quality wood (e.g., drier, excluding scrap material, reasonable diameter for combustion) would allow a 2:1 ratio, which would lower emissions of PAHs and possibly some inorganic particles.

Management Options(s)	Aspect of Implementation	Effect of Change on Exposure
Open burning	Type of coal added	Most U.S. citizens are not aware of differences among types of coal with respect to energy content and sulfur emissions. The two principal types of coal mined in the United States are bituminous and subbituminous. Bituminous coal has approximately two times the energy content per unit weight as subbituminous. It also contains more sulfur. Tradeoffs between odor and weight of coal added to the pyre can be a consideration for farms with nearby neighbors or towns.
Open burning	Potential microbial hazards	If prions are *not* present in healthy livestock prior to their death in a natural disaster, open burning could inactivate all pathogens in the carcasses. On-site open burning would be ranked more favorably if prions are not present in livestock carcasses.
Burial	Vertical distance to groundwater	The burial option requires at least 1 m (3 ft) between the bottom of a burial pit and the highest groundwater level expected over many decades (e.g., 50-year storm event). If groundwater reaches buried carcasses, its contamination is much more likely.
Composting	Type of bulking material	Carbon bulking materials commonly used in composting (e.g., silage, straw, corn stalks, woodchips) differ in their absorptive capacity and efficacy in preventing leachate from reaching subsurface soils. Woodchips are assumed in this assessment. Other materials might be more or less available and more or less effective.
Composting	Potential microbial hazards	If prions and spore-forming bacteria are *not* present in healthy livestock prior to their death in a natural disaster, carcass composting could inactivate all of the pathogens in the carcasses. In that case, compost could be land-applied in areas where there are other livestock and crops without the additional "wait time" required to allow for the complete inactivation of spore-forming bacteria and prions. Composting could be ranked more favorably if prions and spore-forming bacteria are not present in the livestock carcasses.

7.4. Summary of Findings, Mitigation Measures, and Research Needs

This assessment is meant to support selection of environmentally protective livestock carcass management methods in the event of a natural disaster. The findings presented in Section 7.2 shed new light on the potential for chemical and microbial exposures from the commonly-used, on-site carcass management options, and provide further insights into the relative contribution of the specific exposure pathways and carcass management activities. In addition, the assessment identifies some, but not necessarily all, of the chemicals and microbes that could be released from livestock carcass management and how chemical and microbial properties can affect their environmental fate and exposures.

The assessment finds that, when properly designed and implemented, the on-site carcass management options are not estimated to cause adverse health or environmental effects. Off-site

options, including incineration, landfilling, and rendering, are subject to air, water, and solid waste regulations designed for adequate health and environmental protection.

Because many site-specific factors contribute to the movement of chemicals and microbes in the environment, the exposure estimates presented in this report should not be interpreted as "actual" exposures associated with the management options. Site managers can use the findings of this report, in conjunction with site-specific factors, to make more informed decisions about available carcass management options. Section 7.3 discussed some ways in which different site-specific conditions could affect exposures relative to the scenarios evaluated.

The findings of this assessment also can support selection and priority setting for mitigation and best management practices to minimize exposures, and to set priorities for further research. Table 7.4.1 provides information to support these goals, including descriptions of the fate of chemical and microbes, mitigation measures to minimize exposures, and research needs for each option.

In addition to the mitigation measures recommended in Table 7.4.1, the following measures are recommended for all of the livestock carcass management options following a natural disaster:

- State and local agencies can develop plans for handling mass livestock mortalities that are appropriate at a county level given local hydrology, meteorology, and availability of off-site rendering, incineration, or landfill facilities.
- All persons involved should follow applicable regulations and available guidance for selecting a site, designing, and implementing carcass management units.
- Workers should wear PPE when engaged in carcass management activities.
- Individuals not participating in carcass management activities should have little or no direct contact with carcasses, active management processes, or residual materials (e.g., ash).

The conceptual models, environmental and exposure modeling approaches, and supporting data and assumptions developed for this exposure assessment constitute a significant resource for further technical and regulatory analysis. In the next phase of the current project, the assessment methods described in this Report will be adapted to evaluate livestock carcass management options in the event of a FAD outbreak. The methods also will be adapted to accidental or

intentional contamination of livestock with chemicals (e.g., pesticides) or radioactive materials. In other research, the assumptions for managing livestock carcasses following a natural disaster could be varied to evaluate the sensitivity of estimated exposures to those assumptions or to evaluate the benefits of various mitigation methods or standards. The exposure estimation methods or findings also could be used to build or refine decision support tools for site-specific planning or response actions.

Table 7.4.1. Summary of Livestock Carcass Management Options, Mitigation Measures, and Research Needs

Option or Activity	Exposure Summary	Potential Mitigations	Research Needs
On-site Combustion	▪ On-site combustion options generally are effective at inactivating all types of microbes (except prions) when there is an even burn at a sufficiently high temperature. ▪ Metal in fuels and associated with carcasses are not destroyed by combustion, and the combustion process generates new chemical agents of concern such as dioxins/furans and PAHs. Both on-site combustion options are assumed to include wood fuels, but open burning also includes coal which introduces additional PAHs and metals. Chemicals are either dispersed in combustion emissions (concentrations are highest within 1,000 meters) or retained in "bottom" ash. ▪ Because the ash contains potentially high concentrations of metals and persistent organic compounds and has a high pH, care should be taken to manage ash appropriately.	▪ When possible, install combustion units downwind from human, agricultural, and environmental receptors, including homes, businesses, farm buildings, crops, pastures, and surface waters. Otherwise, install combustion units more than 1,000 meters from these environmental receptors to reduce the potential for inhalation and deposition of contaminants in the air. ▪ Monitor burn piles to ensure combustion attains and maintains even heating for the appropriate duration of time, and provide an ample ratio of fuel to carcasses. ▪ Ash may have a high pH and contain persistent chemicals such as metals and PAHs. If the ash cannot be disposed of in a commercial landfill, it could be buried or encapsulated with clean soil. The ash should be isolated from the root zone of plants. ▪ Wet the ash prior to burial, and minimize other handling and processing to avoid resuspending contaminants in the air. Do not use the ash as a surface soil amendment.	▪ Measurement of the constituents in emissions for open burning and air curtain burning, including the effect of fuel selection and quantities on emissions characteristics. ▪ Measurement of the combustion temperatures within the pyre to better understand inactivation of resistant biological agents including prions. ▪ Fate and transport of prions in various media. ▪ Chemical (metals, organics, nutrients, and veterinary drugs) and microbial analysis of carcass ash. ▪ Data on leaching of chemicals from combustion ash. ▪ Monitoring well data (both chemical and microbial) at several distances from ash burial sites.
On-site Burial	▪ Burial does not thermally deactivate microbial contaminants. Most chemicals and microbes from the carcasses adhere to soil and are not highly mobile in an unsaturated burial site, but leachate may carry chemicals and survival-forms of microbes into groundwater supplies. ▪ Burial removes the land from other productive uses, and proper site selection for the burial trench ensures separation from the aquifer, downgradient wells, and water bodies.	▪ Do not place burial sites up-gradient of groundwater wells or surface water bodies; ensure compliance with required setback distances and other site restrictions. ▪ Comply with the minimum requirements for depth above the water table to minimize releases to groundwater. ▪ Properly lime the carcasses as required by the jurisdiction.	▪ Research to characterize microbial profile of leachate from buried carcasses. ▪ Research to characterize the release rates, minimal environmental conditions for survival, and fate and transport of microbes released from buried carcasses.

Option or Activity	Exposure Summary	Potential Mitigations	Research Needs
		▪ If feasible, include a liner of compacted clay in the burial trench. Ventilation shafts can be included to facilitate escaping gases and to maintain the integrity and effectiveness of the cover soil. ▪ Restrict access or minimize activity at the burial site to ensure the integrity of the cover soil. ▪ Monitor the burial site and replenish the soil cover as needed as carcasses decompose beneath the surface.	▪ Systematic study to determine survival of spore-forming microbes and viruses during the carcass decomposition process ▪ Monitoring data of chemical and microbial releases to air from burial sites. ▪ Monitoring of carcass burial sites to gain a better understanding of subsurface methane release and the potential for methane intrusion to structures.
On-site Composting	▪ Composting inactivates most microbes while minimally releasing chemicals and microbes from the windrow. With finished compost used as a soil amendment, this option enables beneficial recycling of nutrients and carbon. ▪ Finished compost may contain metals and persistent organic chemicals (e.g., veterinary drugs) that may remain in soil, be taken up by plants, or run off to surface water.	▪ Use best practices to ensure composting achieves recommended temperatures and time for pathogen control. ▪ Use appropriate carbon material in a quantity sufficient to provide adequate aeration and adsorption of liquids. ▪ Apply adequate cover material to the windrow to discourage potential scavengers and other pests. ▪ Test the soil under the windrow for acceptable levels of chemicals before growing crops or animal feed, or for pasturing livestock. ▪ Allow at buffer distance between the compost application area and the nearest surface water body ▪ Use runoff/erosion control best management practices to prevent areas where the compost has been applied to soils from reaching surface water bodies. ▪ Rapid revegetation with cover crops or native grasses can provide erosion control.	▪ Studies of prions populations, concentrations of metals, veterinary drugs, and other chemicals in finished compost. ▪ Field analysis of the fate and transport of prions and spore-forming microbes during composting and following application of compost to surface soil. ▪ Further study of the gaseous releases to air from the windrow, including chemical profile, release rates, concentrations at various distances, and changes in release rate as composting progresses.

Option or Activity	Exposure Summary	Potential Mitigations	Research Needs
Off-site Options	▪ For this assessment, release of chemicals and microbes from off-site carcass management facilities are assumed to be from regulated pollution control systems. These releases were not quantified and are assumed to be controlled to levels protective of human health and the environment.	▪ Do not allow the products of off-site carcass management options to enter the production stream for consumable products, such as bone meal, if the carcasses are suspected of containing prions. ▪ Ensure that appropriate disinfectants are used during off-site carcass transportation and handling.	▪ Monitoring data or studies to assess the releases from regulated, off-site management.
Carcass Handling	▪ Exposures to workers are not quantified in this assessment and are assumed to be effectively mitigated by the use of gloves, dust masks, and other personal protective equipment.	▪ Do not handle carcasses with bare hands, especially after there are visible signs of decomposition (e.g., bloating, leakage). ▪ Use appropriate personal protective equipment (see 29 CFR 1910.120, Appendix B) when handling carcasses, body fluids, litter, or other potentially contaminated materials.	▪ For a quantitative exposure assessment, data on exposure factors (e.g., frequency and duration of hand contact, area of skin exposed) for carcass handlers, and the effectiveness PPE or compliance with PPE use ▪ Concentrations of chemicals and microbes on contact surfaces. ▪ Data on the “typical” level of personnel protective equipment used during carcass management.
Temporary Carcass Storage	▪ For the carcass transportation and handling activities included in the exposure assessment, the temporary carcass storage pile is the most likely source of exposure. ▪ Estimated exposures from leachate reaching groundwater from the storage pile are low and comparable to exposures from leachate from the compost windrow. ▪ Potential exposures from the temporary storage pile are influenced by the duration of storage, the level of carcass decomposition and leakage, and management practices.	▪ Locate carcass storage piles on impervious surfaces or liners to prevent leaching to soil and leachate flowing to groundwater. Manage drainage to collect any leachate, leakages, or runoff. ▪ Cover the carcass storage pile to minimize releases of chemicals and microbes to air, control scavengers, insects, and other pests, and divert precipitation. ▪ Ensure adequate ventilation, particularly for storage indoors.	▪ Monitoring of emissions to air from the storage pile, including chemical profile, emission rates, concentrations at various distances, and changes in emissions as decomposition progresses.

Option or Activity	Exposure Summary	Potential Mitigations	Research Needs
Carcass Transportation	▪ Potential exposure pathways from carcass transportation begin with liquid leakage from the truck bed, emissions to air, and spillage in the event of an accident. ▪ Exposures from truck bed leakage and emissions to air are assumed to be negligible at locations along the transportation route, and are not estimated. ▪ The likelihood of truck accidents with spillage was estimated from highway traffic safety data. For eight truck trips of 100 km each, the risk of an accident with spillage is estimated to be 7.1E-05.	▪ Select leak-proof vehicles to transport carcasses. Because some leakage can be expected from vehicles designed to be leak-proof, use of plastic liners or absorbent material can minimize leakage. ▪ Use a tarp or similar covering for vehicles that are open on the top. ▪ Load vehicles to no more than 60% capacity by volume because carcasses may bloat and expand in volume as decomposition progresses. ▪ Transport carcasses as soon as possible.	▪ Further research to assess potential exposures associated with transporting carcasses to off-site facilities.

8. Quality Assurance

The development of this report was carried out in accordance with USEPA Quality Assurance Program. This project was approved by a designated quality assurance manager prior to the start of any work. This project addresses all elements listed in the "EPA Requirements for QA Project Plans, EPA QA/R-5."

An extensive review of the existing literature was an important component of this study. A literature review was conducted to identify and collect the available peer-reviewed journal articles, fact sheets, reports, guidance documents, and other pertinent information related to exposure assessment of livestock carcass management options. Various sources of information on carcass management, where mortality is due to natural disasters, were identified. The peer-reviewed articles were downloaded after libraries were searched across key databases and other web science searches. Technical reports released by various federal agencies and international organizations were identified and collected. Additional vendor-supplied data, newsletters, and fact sheets were obtained. Information included in the report was drawn primarily from peer-reviewed publications. Peer-reviewed publications contained the most reliable information, although some portions of the report may contain compilations of data from a variety of sources and non-peer-reviewed literature (workshop proceedings; graduate degree theses/dissertations; non-peer-reviewed reports and white papers from industry, associations, and non-governmental organizations) and unpublished data (online databases, personal communications, unpublished manuscripts, unpublished government data). Non-peer-reviewed and unpublished sources did not form the sole basis of any conclusions presented in the report of results. Generally, these sources were used to support results presented from peer-reviewed work, enhancing understanding based on peer-reviewed sources, identifying promising ideas for pathway analysis and exposure assessment, and provided discussion of tiered approach of ranking systems. The qualitative ranking has been performed based on the review of the literature search. Secondary data were used as per the U.S. EPA approved Quality Assurance document and review of published or unpublished data for identifying relevant information and exposure assessment of livestock carcasses. These secondary data included original research papers published in peer-reviewed journals and pertinent review articles that summarize original research, obtained from hard copies and computerized databases. However, no quality assurance (QA) (accuracy,

precision, representativeness, completeness, and comparability) of secondary data has been conducted. The data cited in this report were collected from published literature/fact sheets/web, and no attempt has been made to verify the quality or veracity of data collected from various sources.

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Appendices

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Appendix A. Data for Polycyclic Aromatic Hydrocarbons

The National Research Council (NRC) (1983) estimated 39% of annual U.S. emissions of polycyclic aromatic hydrocarbons (PAHs) from the early to mid-1970s originated from open burning (4,024 of the total of approximately 10,320 metric tons/yr) and 38% from residential wood stove heating (as cited by ATSDR 1995). Peters et al. (1981) estimated 36% from open burning, 35% from residential heating, and only 1% each from incineration and power generation. Open burning includes controlled burns of agricultural fields to clear remaining debris, to kill weed seeds in the surface soil, or to force new growth (e.g., berry bushes), and uncontrolled forest and grassland fires. Lobscheid and McKone (2004) estimated that the contribution of residential wood combustion to PAHs in air in the state of Minnesota to be on par with those released from gasoline-powered automobiles. By comparison, the contribution of carcass combustion to total PAH emissions to air across the United States is negligible (i.e., 0.124 metric tons total PAHs per 453 metric tons (50 U.S. tons) of cattle burned (main report, Table 3.3.2) compared with 10,320 metric tons PAHs released annually nationwide.

None of the materials included in the two on-site combustion scenarios, open pyre burning and air-curtain combustion, contain PAHs initially. Combustion of carcasses and various fuels, however, does produce PAHs in various quantities. PAHs as released in flames are primarily in the vapor phase; however, upon cooling in ambient air, mid-to higher molecular weight PAHs are found almost entirely in particulate material (USEPA 1998 citing Schure and Natusch 1982). Apparently, PAHs adsorb to particle surfaces (primarily through hydrogen bonding) and might condense to aerosol particles. In general, the highest concentrations of PAHs in air emissions are found on the smaller diameter aerosol particles because the smaller particles have higher surface-to-mass ratios than do larger particles (USEPA 1998 citing Natusch and Tomkins 1978).

The fuels used to burn carcasses differ for open pyre and air-curtain burning as do the average temperatures of the burn. Several fuels generally are included to ensure a relatively complete open pyre burn (e.g., wooden railway ties and kindling, bales of hay or straw, diesel, coal; see main report, Section 3.2.1, Table 3.2.1), whereas only wood is needed for an air-curtain burner (diesel exhausts from the fans used to create the air curtain are not included here). Open pyre

burning also occurs at lower temperatures (e.g., 550°C, Table 3.2.1) than air-curtain burning (e.g., 850°C, Table 3.3.1, Section 3.3.1). To estimate emissions of PAH compounds to air, three important assumptions were made:

1. As described in the main report, and based on literature reviewed for the exposure assessment, PAH production and emission profiles (i.e., relative emission rates for individual PAH compounds compared with total PAHs) from different categories of livestock are assumed to not differ substantially.
2. As described in Section A.2.1, the relative PAH emissions in vapor and particulate phases are assumed to be compound-specific and could be influenced by burn temperature.
3. PAH production and emission profiles, including releases to air in particulate versus vapor phases, partitioning of PAHs to fly ash compared with bottom ash, and total PAH and ash production, are assumed to vary by fuel type. Therefore, emissions factors (EFs) are estimated for PAHs by compound and by fuel type in Sections A.2.2 (wood – kindling and railway ties combined), Section A.2.3 (coal), and Section A.2.4 (hay or straw).

To compare emissions to human health-based or other environmental-based benchmarks, the relative potency factor (RPF) approach was used with benzo[a]pyrene (BaP) as the index chemical (USEPA 2010a; WHO 1998). All chronic oral exposures for humans are combined into a single benzo[a]pyrene-equivalent exposure as described in Section 5.3.2 of the main report. Section A.3 lists compound-specific RPF values that were multiplied by the total ingestion exposure to each PAH. The resulting BaP-equivalent oral exposures then could be added across all of the PAHs (for which data were adequate) and compared with BaP carcinogenic potency.

A.1. PAH Emissions by Carcasses from Different Livestock Species

Data on emission of PAHs as measured by Chen et al. (2003) for hogs and other livestock from lower and higher temperature incinerators are compared to data from U.S. Environmental Protection Agency (USEPA) for game birds incinerated in an air-curtain burner (USEPA 2013). This comparison suggests that the PAHs emitted in the highest quantities relative to total PAHs

are sufficiently similar across the studies to apply the same set of emission factors (EFs) across different types of livestock (e.g., hogs, cattle, poultry).

Chen et al. (2003) studied emissions of PAHs from different types of incinerators, including a hog farm waste incinerator (HOWI), which burned at 255°C to 595°C with unrefined methane gas as the auxiliary fuel, and a livestock disease control incinerator (LIWI), which burned at a somewhat higher temperature (755°C to 891°C) fueled by diesel. Results from the HOWI, which Chen et al. (2003) presented as bar graphs in Figure 1 of their report, are presented in Table A.1, with values approximated from the graphs.

Table A.1. PAH Concentrations in Emissions from Hog Incinerator and Air-curtain Incinerator.

PAH (number of aromatic rings)	Hogs in Animal Waste Incinerator[a] (µg/m^3)				Poultry in Air curtain Burner [b] (Total ppb)	
	Gaseous µg/m^3	Particle µg/m^3	Total µg/m^3	Percent of Total	1 bird/10 min	1 bird/4 min
Naphthalene (3)	277.0	7.86	284.8	46.5%	268	786
Acenaphthylene (3)	27.7	0.34	28.04	4.6%	42.1	198
Acenaphthene (3)	6.34	0.77	7.10	1.2%	nd	J 9.7
Fluorene (3)	16.32	0.90	17.22	2.8%	J 14.7	63.3
Phenanthrene (3)	34.24	17.25	51.49	8.4%	52.3	151.1
Anthracene (3)	8.43	4.33	12.77	2.1%	J 5.16	J 33.32
Fluoranthene (4)	11.97	46.41	58.33	9.5%	27.4	71.8
Pyrene (4)	12.04	58.37	70.41	11.5%	22.7	58.0
Benzo[a]anthracene (4)	1.53	3.91	5.44	0.89%	J 4.34	J 14.21
Chrysene (4)	1.55	3.06	4.61	0.75%	J 4.31	J 13.45
Cyclopenta[c,d]pyrene (5)	0.44	0.58	1.02	0.17%	na	na
Benzo[k]fluoranthene (5)	0.65	0.19	0.84	0.14%	J 2.16	J 5.38
Benzo[b]fluoranthene (5)	1.49	1.71	3.20	0.52%	J 5.31	J 14.76
Benzo[e]pyrene (5)	2.70	3.59	6.28	01.0%	J 2.48	J 6.11
Benzo[a]pyrene (5)	1.83	0.83	2.67	0.44%	J 3.39	J 10.42
Perylene (5)	0.84	0.59	1.42	0.23%	nd	nd
Indeno[1,2,3,-cd]pyrene (6)	10.05	8.11	18.16	3.0%	J 2.44	J 5.52
Dibenzo[a,h]anthrance (6)	2.95	1.79	4.74	0.77%	nd	nd
Benzo[b]chrycene (6)	1.78	0.77	2.55	0.42%	na	na
Benzo[ghi]perylene (6)	2,94	3.47	6.41	01.0%	J 3.21	J 6.03
Coronene (7)	2.79	1.72	4.51	0.74%	na	na
Total PAHs	425	173	613.1	100%	nc	nc

Abbreviations: na = not analyzed, nc = not calculated because of uncertainty in measurements below the quantitation limit; nd = not detected; PAH = polycyclic aromatic hydrocarbon.

Note: Shaded cells represent the PAHs released in the highest proportions; which are similar for hogs and poultry.

[a] Data provided by Shui-Jen Chen, first author of Chen et al. (2003), instead of being estimated from mean values as presented in bar graphs in Figure 1 from Chen et al. (2003), for hogs in incinerator fueled by methane from waste-treatment facility.

[b] USEPA (2013). Poultry incinerated in pilot-scale air-curtain burner (refractory box) with clean wood as auxiliary fuel.

Chen et al. (2003) found that the highest proportion of PAHs released were low molecular weight (MW) compounds with three to four aromatic rings. As expected from physical/chemical characteristics, releases of the smaller, low MW PAHs were primarily in vapor phase whereas releases of the high MW PAHs were primarily in particulate phase.

In a test of a pilot-scale air-curtain burner, USEPA compared PAH emissions for Cornish game hens (nominally 2–3 pounds per bird) loaded with two different quantities of clean wood. The wood was added to the burner at a constant rate of 25 pounds per hour (in 1.5 x 1.5 x 12 inch boards); the game hens were added at different rates from 1 bird per 10 minutes (or 25 lbs wood per 6 birds) to 1 bird per 4 minutes (or 25 lbs of wood per 15 birds). Kansas State University recommends wood to carcass ratios of 2:1 to 1:1 (USEPA 2013). The results for those two conditions also are in Table A.1. Many of the measurements, however, were below the quantitation limit (marked with a J) for the compound.

The pattern of individual PAHs recovered from the air as emitted from the birds combusted in the air-curtain burner is similar to the pattern from the HOWI (Table A.1). The cells highlighted in light blue in Table A.1 identify those PAHs that account for more than 2% of the total mass of PAHs. Close to half (47%) of the mass of PAH emissions from the HOWI was emitted as naphthalene ("moth balls," which sublimates from a solid to vapor phase at ambient temperatures). Another 35% of the total PAH mass from the HOWI came from only five other PAHs with 3 or 4 rings. For the HOWI, over 97% of the naphthalene was released in gaseous form. Similarly, the other 3-ringed PAHs were primarily emitted as gases rather than in particulate form. The 4-ringed PAHs were emitted primarily in particulate form. One PAH not conforming to the pattern for the HOWI is indeno[1,2,3-cd]pyrene, which has six rings. Its release was approximately 3% of the total PAH mass, and a little over 50% of the chemical measured was in vapor phase despite its high molecular weight.

To examine differences in emissions of the HOWI and the LIWI, Chen et al. (2003) grouped PAHs according to molecular weight, with low MW containing two-to three-ringed PAHs, middle MW containing four-ringed PAHs, and high MW containing five-, six-, and seven-ringed PAHs. They found the gaseous concentrations of the stack flue gas to be comparable for the two

carcass incinerators (LIWI = 478 µg/m^3 and HOWI = 426 µg/m^3). As shown in Table A.2, emissions from the lower burning temperature HOWI were higher than from the higher temperature LIWI, even though the HOWI included a waste effluent scrubber.

Table A.2. Emission Quantities and Emission Factors of the Stack Flue Gas for PAHs (Chen et al. 2003).

PAH Group	Emission Amount (g/day)		Emission Amount (percent)		Emission Factor (µg/kg waste)		Emission Factor (percent)	
	HOWI	LIWI	HOWI	LIWI	HOWI	LIWI	HOWI	LIWI
Low MW PAHs	29.4	11.0	78%	85%	235,000	2,435	82%	85%
Medium MW PAHs	5.66	1.05	15%	8%	34,700	234	12%	8%
High MW PAHs	2.65	0.888	7%	7%	15,600	198	5%	7%
Total PAHs	37.7	12.9	100%	100%	285,000	2,867	100%	100%

Abbreviations: HOWI = hog farm waste incinerator; LIWI = livestock disease control incinerator; MW = molecular weight; PAH = polycyclic aromatic hydrocarbon.

A.2. Air Emission Factors for PAHs by Combusted Material

Emission profiles for PAH congeners can differ among substances combusted, combustion temperatures, and combustion conditions (ATSDR 1995). To allow alternative assumptions on auxiliary fuel use in response to comments, this section reports methods and original data for calculating PAH emissions in g/s separately for carcasses (Section A.2.1), wood (Section A.2.2), coal (Section A.2.3), and straw/hay (Section A.2.4).

A.2.1. Carcasses

All of the PAHs collected by Chen et al. (2003) are assumed to be derived from the carcasses per se. The burn temperatures of 255°C to 595°C were close to the assumed open pyre burn temperature of 550°C (Section 3.2). Both methane (used as the auxiliary fuel in the HOWI) and diesel (used as the auxiliary fuel in the LIWI) should produce minimal PAHs when combusted compared with PAHs generated due to combustion of the carcasses. Table A.1 (in Section A.1 above) presents the data from Chen et al. (2003) from Figure 1 of their original report, with 613 µg/m^3 total PAHs in both vapor and particulate phases combined. The first two data columns in Table A.3, present the same data as the fraction of the total PAHs in particulate and vapor phases separately. The total PAH concentration from the particulate phase and in the vapor phase sum to 100%.

We calculated the emission factors for each congener, in µg/kg carcasses (third and fourth data columns of Table A.3), from the fractions in Table A.3 assuming 285,000 µg[total PAHs]/kg[carcasses] emitted to air (Table A.2 for HOWI). Except during wet deposition, vapor-phase chemicals disperse farther from the source than particle-phase chemicals, which deposit closer to the source, with distance from the source decreasing with increasing particle size. Multiplying the fractions by 45,359 kg (i.e., 50 tons) of carcasses and dividing by 172,800 seconds (i.e., 48 hours), emission factors were estimated in g/s in particulate and vapor phases separately (final two data columns in Table A.3). We use those values to represent the open-pyre emissions from only carcasses.

Table A.3. PAH Emission Factors for Carcasses Combusted at Lower Temperature Incinerators for Use in Modeling of Open Pyre Burning.

PAH (number of aromatic rings) [acronym/acronyms]	Fraction of Total PAHs from Hog Carcasses		Emission Factors (µg/kg carcasses)		Emission Factors (g/s)	
	Particle	Vapor	Particle	Vapor	Particle	Vapor
Naphthalene (3) [Nap]	1.32E-02	4.66E-01	3.77E+03	1.33E+05	9.90E-04	3.49E-02
Acenaphthylene (3) [Acy/ANL]	5.72E-04	4.58E-02	1.63E+02	1.30E+04	4.28E-05	3.42E-03
Phenanthrene (3) [Phe/PA]	2.90E-02	5.76E-02	8.27E+03	1.64E+04	2.17E-03	4.31E-03
Fluorene (3) [Flu]	1.51E-03	2.75E-02	4.32E+02	7.83E+03	1.13E-04	2.05E-03
Acenaphthene (3) [Ace/Acp/AN]	1.30E-03	1.07E-02	3.69E+02	3.04E+03	9.69E-05	7.98E-04
Anthracene (3) [Ant/AC]	7.29E-03	1.42E-02	2.08E+03	4.04E+03	5.45E-04	1.06E-03
Pyrene (4) [Pyr]	9.82E-02	2.03E-02	2.80E+04	5.77E+03	7.35E-03	1.52E-03
Chrysene (4) [Chr/CHR]	5.15E-03	2.61E-03	1.47E+03	7.43E+02	3.85E-04	1.95E-04
Fluoranthene (4) [Flt/FL]	7.81E-02	2.01E-02	2.23E+04	5.74E+03	5.84E-03	1.51E-03
Benzo[a]anthracene (4) [BaA]	6.58E-03	2.58E-03	1.88E+03	7.34E+02	4.92E-04	1.93E-04
Benzo[a]pyrene (5) [BaP]	1.40E-03	3.08E-03	3.98E+02	8.78E+02	1.05E-04	2.30E-04
Benzo[e]pyrene (5) [BeP]	6.04E-03	4.54E-03	1.72E+03	1.30E+03	4.52E-04	3.40E-04
Benzo[k]fluoranthene (5) [BkF]	2.88E-03	2.51E-03	8.20E+02	7.15E+02	2.15E-04	1.88E-04
Benzo[b]fluoranthene (5) [BbF]	2.88E-03	2.51E-03	8.20E+02	7.15E+02	2.15E-04	1.88E-04
Cyclopenta[c,d]pyrene (5) [CYC]	9.76E-04	7.41E-04	2.78E+02	2.11E+02	7.30E-05	5.54E-05
Perylene (5) [PER/Pery]	9.93E-04	1.41E-03	2.83E+02	4.03E+02	7.43E-05	1.06E-04
Dibenzo[a,h]anthrance (6) [DBA]	3.32E-03	4.97E-03	9.45E+02	1.41E+03	2.48E-04	3.71E-04
Indeno[1,2,3,-cd]pyrene (6) [IND]	1.37E-02	1.69E-02	3.89E+03	4.82E+03	1.02E-03	1.27E-03
Benzo[ghi]perylene (6) [BghiP]	5.84E-03	4.95E-03	1.66E+03	1.41E+03	4.37E-04	3.70E-04
Benzo[b]chrysene (6) [BbC]	1.30E-03	3.00E-03	3.69E+02	8.54E+02	9.69E-05	2.24E-04
Coronene (7) [COR/CO]	2.89E-03	4.70E-03	8.25E+02	1.34E+03	2.17E-04	3.51E-04
Total PAHs [a]	**0.283**	**0.717**	8.07E+04	2.04E+05	2.12E-02	3.49E-02

Abbreviations: PAH = polycyclic aromatic hydrocarbon; s = second.

Source: Chen et al. (2003), Hog Incinerator or HOWI, Figure 1.

[a] Sum of proportion vapor and proportion particulate for total PAHs (bold) = 100% or 1.0.

The first two data columns in Table A.4 present the fraction of the total PAHs in particulate and vapor phases separately for the higher burn-temperature LIWI (from Figure 2 in Chen et al. 2003). The fractions of the total PAH in the particulate phase and in the vapor phase sum to 100%.

Table A.4. PAH Emission Factors for Carcasses Combusted at Higher Temperatures for Use in Modeling of Air-Curtain Burning.

PAH (number of aromatic rings) [acronym/acronyms]	Fraction of Total from Hog Carcasses		Emission Factors (µg/kg carcasses)		Emission Factors (g/s)	
	Particle	Vapor	Particle	Vapor	Particle	Vapor
Naphthalene (2)	6.11E-02	5.92E-01	1.75E+02	1.70E+03	4.60E-05	4.46E-04
Acenaphthylene (3)	1.91E-03	8.41E-02	5.48E+00	2.41E+02	1.44E-06	6.33E-05
Phenanthrene (3)	3.82E-03	9.55E-02	1.10E+01	2.74E+02	2.88E-06	7.19E-05
Fluorene (3)	3.82E-03	2.10E-02	1.10E+01	6.03E+01	2.88E-06	1.58E-05
Acenaphthene (3)	3.82E-03	7.64E-03	1.10E+01	2.19E+01	2.88E-06	5.75E-06
Anthracene (3)	9.55E-04	1.91E-03	2.74E+00	5.48E+00	7.19E-07	1.44E-06
Pyrene (4)	3.82E-03	1.91E-02	1.10E+01	5.48E+01	2.88E-06	1.44E-05
Chrysene (4)	1.91E-03	7.64E-03	5.48E+00	2.19E+01	1.44E-06	5.75E-06
Fluoranthene (4)	3.82E-03	2.10E-02	1.10E+01	6.03E+01	2.88E-06	1.58E-05
Benzo[a]anthracene (4)	5.73E-04	2.87E-03	1.64E+00	8.22E+00	4.31E-07	2.16E-06
Benzo[a]pyrene (5)	9.55E-04	1.91E-03	2.74E+00	5.48E+00	7.19E-07	1.44E-06
Benzo[e]pyrene (5)	9.55E-04	2.87E-03	2.74E+00	8.22E+00	7.19E-07	2.16E-06
Benzo[k]fluoranthene (5)	9.55E-04	3.82E-03	2.74E+00	1.10E+01	7.19E-07	2.88E-06
Benzo[b]fluoranthene (5)	9.55E-04	3.82E-03	2.74E+00	1.10E+01	7.19E-07	2.88E-06
Cyclopenta[c,d]pyrene (5)	1.91E-04	6.69E-03	5.48E-01	1.92E+01	1.44E-07	5.03E-06
Perylene (5)	1.91E-03	5.73E-03	5.48E+00	1.64E+01	1.44E-06	4.31E-06
Dibenzo[a,h]anthrance (6)	9.55E-04	1.91E-03	2.74E+00	5.48E+00	7.19E-07	1.44E-06
Indeno[1,2,3,-cd]pyrene (6)	9.55E-04	3.82E-03	2.74E+00	1.10E+01	7.19E-07	2.88E-06
Benzo[g,h,i]perylene (6)	1.91E-03	3.82E-03	5.48E+00	1.10E+01	1.44E-06	2.88E-06
Benzo[b]chrysene (6)	1.91E-03	7.64E-03	5.48E+00	2.19E+01	1.44E-06	5.75E-06
Coronene (7)	1.91E-03	5.73E-03	5.48E+00	1.64E+01	1.44E-06	4.31E-06
Total PAHs [a]	**0.099**	**0.901**	2.84E+02	2.58E+03	7.46E-05	6.78E-04

Abbreviations: PAH = polycyclic aromatic hydrocarbon; s = second.

Source: Chen et al. (2003), Livestock Waste Incinerator or LIWI, Figure 2.

[a] Sum of proportion vapor and proportion particulate for total PAHs (bold) = 100% or 1.0

From those fractions and assuming 2,867 µg[total PAHs]/kg[carcasses] emitted to air (Table A.2 for HIWI), the emission factors were calculated in µg/kg carcasses (third and fourth data

columns of Table A.4). Multiplying those values by 45,349 kg (i.e., 50 tons) of carcasses and dividing by 172,800 seconds (i.e., 48 hours), emission factors were estimated in g/s in particle and vapor phase separately (final two data columns in Table A.4). Those values were input to the AERMOD simulation of air-curtain burner (ACB) emissions from carcasses only.

A.2.2. Wood (Open Pyre and ACB, Timbers and Kindling)

Air EFs are estimated for PAHs released from wood from open pyres (railroad ties and wood kindling combined) from multiple sources. PAHs released to air in particulate phase and vapor phase from burning wood, or that reported vapor-phase emissions, are not distinguished in the literature reviewed. Many reports evaluated the content of wood ash for use in soil amendments (e.g., recycling in forests, Bundt et al. 2001; Sarenbo 2009; Enell et al. 2008). Studies included different subsets of the 21 PAHs included in this appendix.

We used data from Hays et al. (2003) to estimate EFs for open-pyre burning of wood. Data included PAH content of fine particles ($PM_{2.5}$) released from residential wood combustion (woodstove burning Douglas fir with low moisture content – 13% = WSDL[woodstove burning Douglas fir]), and compounds containing 4 rings or more and for anthracene. Their experimental design did not capture vapor-phase PAHs, and they did not analyze emissions for naphthalene, acenapthylene, phenanthrene, or fluorene. Those data were supplemented with data from Lamberg et al. (2011) who measured PAH EFs for particles of 1 µm or less (PM_1) (Table A.5). We assume the PM_1 includes condensed aerosols of the 2- and 3-ringed PAHs. Neither study measured naphthalene releases.

Samples from the stack were diluted with air and flowed through an insulated line externally heated to 150°C (i.e., 302°F) (Lamberg et al. 2011). The fourth data column in Table A.5 presents the average of the three units in ng/mg, with the next column presenting results in µg[PAH]/kg[PM1]. To allow extrapolation of the 3-ring PAH data from the Lamberg et al. (2011) study to the 3-ring PAHs not sampled by Hays et al. (2003), we calculated an average concentration of each 3-ring PAH to the concentration of benzo[a]pyrene (Table A.5, final column).This approach assumes similar emission profiles across the two studies, which is

reasonable considering the similar fuel types and burn temperatures. Omitting the 3-ring PAHs because they were not analyzed by Hays et al. (2003) would be misleading.

Data from Hays et al. (2003) are presented in the first four data columns of Table A.6. The ratios of the 3-ring PAHs to BaP from Lamberg et al. (2011), presented in the last column of Table A.5, were multiplied by the BaP emission rate from Hays et al. (2003), in the fourth column of Table A.6, to estimate the EFs in g/s for 3-ring PAHs that might have been released (final data column Table A.6). For anthracene, measured by both groups, the estimated EFs are different by about one half-order of magnitude. The values listed in bold in Table A.6 were used to estimate EFs to air from all wood (i.e., 36,000 kg) used to burn 50 tons of cattle in an open pyre.

Table A.5. PAH Air Emission Factors for Wood/Kindling Added to Open Pyre.

PAH (number of aromatic rings)	ng[PAH]/mg[PM1] particles				Avg of 3 CBs (µg/kg)	Ratio Avg 3 CB/Avg BaP
	CB1	CB2	CB3	Avg of 3 CB		
Acenaphthylene (3)	51.1	129.3	11.9	64.1	0.064	**0.0402**
Phenanthrene (3)	2317	5370	1061	2916	2.916	**1.83**
Fluorene (3)	90	334	34.6	152.9	0.153	**0.0970**
Acenaphthene (3)	1.6	3.5	1.4	2.17	0.002	**0.00136**
Anthracene (3)	483.7	955.7	227	555.5	0.555	**0.349**
Pyrene (4)	2742	3200	2578	2840	2.840	nr
Chrysene (4)	907	1201	909	1006	1.006	nr
Fluoranthene (4)	2835	3476	2187	2833	2.833	nr
Benzo[a]anthracene (4)	1004	1397	1052	1151	1.151	nr
Benzo[a]pyrene (5) [a]	1149	2002	1628	1593	1.593	nr
Benzo[e]pyrene (5)	525	801	600	642	0.642	nr
Benzo[k]fluoranthene (5)	783	1208	860	950.3	0.950	nr
Benzo[b]fluoranthene (5)	1120	868	657	881.7	0.882	nr
Cyclopenta[c,d]pyrene (5)	2150	1991	1954	2032	2.032	nr
Perylene (5)	153	255	217	208.3	0.208	nr
Dibenzo[a,h]anthrance (6)	49.5	156.3	122	109.3	0.109	nr
Indeno[1,2,3,-cd]pyrene (6)	507	924	704	711.7	0.712	nr
Benzo[ghi]perylene (6)	669	1051	925	881.7	0.882	nr
Benzo[b]chrysene (6)	na	na	na	na	na	na
Coronene (7)	421.8	419	245	361.9	0.362	nr

Abbreviations: CB = combustion burner; na = not analyzed; nr = not relevant – not calculated or used; PAH = polycyclic aromatic hydrocarbon; PM1 = particles of 1 µm or less.

Source: Lamberg et al. (2011).

[a] Benzo[a]pyrene value, shaded in light blue, used as divisor to calculate ratios in final data column.

Table A.6. PAH Air Particulate Emission Factors for Wood and Kindling Added to Cattle Open-Pyres.

PAH (number of aromatic rings)	Dry Weight Wood Burned (mg/kg)	Total PAHs released (mg)	EFs (mg/s) (Hays et al. 2003)	EFs (g/s) (Hays et al. 2003)	Estimated EFs (g/s) [a]
Naphthalene (2)	na	na	na	na	na
Acenaphthylene (3)	na	na	na	na	1.21E-06
Phenanthrene (3)	na	na	na	na	5.52E-05
Fluorene (3)	na	na	na	na	2.90E-06
Acenaphthene (3)	na	na	na	na	4.11E-08
Anthracene (3)	0.0107	341	1.975E-03	1.98E-06	1.05E-05
Pyrene (4)	0.0469	1496	8.658E-03	8.66E-06	nr
Chrysene (4)	0.0973	3103	1.796E-02	1.80E-05	nr
Fluoranthene (4)	0.0501	1598	9.248E-03	9.25E-06	nr
Benzo[a]anthracene (4)	0.1046	3336	1.931E-02	1.93E-05	nr
Benzo[a]pyrene (5)	0.1635	5215	3.018E-02	3.02E-05	nr
Benzo[e]pyrene (5)	0.1027	3276	1.896E-02	1.90E-05	nr
Benzo[k]fluoranthene (5)	0.0909	2899	1.678E-02	1.68E-05	nr
Benzo[b]fluoranthene (5)	0.0909	2899	1.678E-02	1.68E-05	nr
Cyclopenta[c,d]pyrene (5)	na	na	na	na	na
Perylene (5)	0.0238	759	4.393E-03	4.39E-06	nr
Dibenzo[a,h]anthrance (6)	0.0082	261	1.514E-03	1.51E-06	nr
Indeno[1,2,3,-cd]pyrene (6)	0.0895	2854	1.652E-02	1.65E-05	nr
Benzo[ghi]perylene (6)	0.0457	1457	8.436E-03	8.44E-06	nr
Benzo[b]chrysene (6)	0.0057	181	1.052E-03	1.05E-06	nr
Coronene (7)	0.0202	644	3.729E-03	3.73E-06	nr

Abbreviations: EF = emission factor; na = not analyzed; nr = not relevant – not calculated or not used (use Hays et al. 2003 value); PAH = polycyclic aromatic hydrocarbon; PM1 = particles of 1 µm or less; s = seconds.

Source: Hays et al. (2003) Table 3, WSDL, which means woodstove burning Douglas fir, 13% moisture content.

[a] Estimated EFs based on Hays et al. (2003) value for BaP and ratios of chemical to BaP from Lamberg et al. (2011).

In the absence of data distinguishing vapor-phase from particle-phase PAHs for wood burning, we assume that all of the PAHs released from wood burning in an open pyre would be in particulate phase and, therefore, could deposit closer to the source than would vapor-phase PAHs. We also assumed $PM_{2.5}$ instead of PM_{10}, because PAH concentrations on smaller ash particles are higher than PAH concentrations on larger particles (higher surface to mass ratio) and because $PM_{2.5}$ penetrate deeper into the lungs than PM_{10}.

We used Sarenbo's (2009) measurements of PAHs released from industrial boilers in Sweden powered by burning wood (Table 4 in Sarenbo 2009) to estimate PAH emissions from burning wood in an air-curtain pit at higher temperatures than in open pyres. Wood used as fuel was first

pulverized, burned once, and then the ash was reburned, which reduced the organic carbon content from 40% to 5%.

To estimate emissions of fly ash per kg of wood burned, we converted the wood added (4:1 ratio of wood to carcass biomass) into the total weight of fly ash released to air. For 45,359 kg of carcasses, we estimate 181,437 kg of wood required. Assuming the wood to be 12% water (typical value for woods used in stoves, boilers), 88% of the original mass of wood added (i.e., 159,664 kg) is burnable. According to Lamberg et al. (2011), 0.4% of the dry weight of birch logs is ash, with moisture ranging from 10 to 13%. For the air curtain burner (ACB) burn, we assume that the relatively high temperature of the burn eliminated the moisture and combusted almost all of the remaining materials to total (fly and bottom) ash.

To apportion the ash between fly and bottom ash, we used data from Narodoslawsky and Obernberger (1996). To evaluate heavy metal content of wood ash produced by wood-burning facilities in Austria, they estimated the proportion of ash emitted to air and caught on filters and the proportion remaining as bottom ash. Using a multi-cyclone filter and a filter fly-ash precipitator, they captured 15–25% of the initial weight of wood chips burned as cyclone fly ash and 1–4% as filter fly ash, with the remainder 75–85% of the initial biomass retained in the bottom ash. The bottom ash fell through the bottom grate at initial temperatures of 500–1000°C; the cyclone filter was installed after the heat exchanger and therefore operated at approximately 140–200°C. Based on the ranges of cyclone and filter fly ash from wood chips reported by Narodoslawsky and Obernberger (1966), we assume 78% of wood added to the ACB pit remains as bottom ash while 22% is emitted to air as fly ash. That means that 650 kg of bottom ash remains and 140 kg of ash is emitted to air for an ACB combustion of 50 tons of cattle. Table A.7Table A.7 lists the average concentration of PAHs in the fly ash emitted from the first burn as measured each week for 9 weeks (i.e., 9 samples from the same boiler).

Table A.7. PAH Air Emissions for Wood added to Air-Curtain Burning (ACB) of Carcasses (based on Sarenbo 2009), Particule-Phase Only.

PAH (number of aromatic rings)	Concentrations in Wood Fly Ash (mg/kg)				Total PAH (mg)	EF (g/s) Particles
	Average	SD	Min	Max		
Naphthalene (2)	69	23	44	120	9.69E+03	5.61E-05
Acenaphthylene (3)	28	11	17	55	3.93E+03	2.28E-05
Phenanthrene (3)	20	7.8	10	38	2.81E+03	1.63E-05
Fluorene (3)	0.23	nd	0.23	0.23	3.23E+01	1.87E-07
Acenaphthene (3)	nd	nd	nd	nd	0	0
Anthracene (3)	1.9	1	0.66	4.3	2.67E+02	1.54E-06
Pyrene (4)	14	5.7	7.9	28	1.97E+03	1.14E-05
Chrysene (4)	1.0	0.66	0.38	2.7	1.41E+02	8.13E-07
Fluoranthene (4)	12	5.0	6.5	24	1.69E+03	9.76E-06
Benzo[a]anthracene (4)	0.82	0.55	0.27	2.2	1.15E+02	6.67E-07
Benzo[a]pyrene (5) [a]	1.5	0.97	0.54	3.9	2.11E+02	1.22E-06
Benzo[e]pyrene (5)	0.605 [a]	na	na	na	8.49E+01	4.92E-07
Benzo[k]fluoranthene (5)	0.96	0.65	0.33	2.6	1.69E+02	9.76E-07
Benzo[b]fluoranthene (5)	1.2	0.59	0.5	2.6	1.35E+02	7.81E-07
Cyclopenta[c,d]pyrene (5)	na	na	na	na	na	na
Perylene (5)	2.10 [a]	na	na	na	2.95E+02	1.71E-06
Dibenzo[a,h]anthrance (6)	1.1	0.7	0.37	2.8	1.55E+02	8.94E-07
Indeno[1,2,3,-c,d]pyrene (6)	3.2	1.9	1.3	7.7	4.50E+02	2.60E-06
Benzo[g,h,i]perylene (6)	0.083	0.036	0.05	0.13	1.17E+01	6.75E-08
Benzo[b]chrysene (6)	na	na	na	na	na	na
Coronene (7)	2.0 [a]	na	na	na	2.83E+02	1.64E-06

Abbreviations: EF = emission factor; na = not analyzed; nd = not detected; PAH = polycyclic aromatic hydrocarbon; PM1 = particles of 1 µm or less; s = seconds; SD = standard deviation.

Source: Values based on Sarenbo (2009).

[a] Value based on ratios to BaP released as estimated from Lamberg et al. (2011), although higher burn temperature might result in different ratios.

Presumably, additional quantities of naphthalene and the 3-ringed PAHs were released that remained in vapor phase. We did not attempt to correct the emissions in Table A.7 to account for vapor-phase PAHs, which would disperse quickly away from the burn location. However, estimates of benzo[e]pyrene (BeP), perylene, and coronene that might have been released in particulate phase (toxic and likely to deposit locally) are based on the ratios of those chemicals released from wood as reported by Lamberg et al. (2011).

To estimate emissions of fly ash per kg of wood burned, we converted the wood added (4:1 ratio of wood to carcass biomass) into the total weight of fly ash released to air. For 45,359 kg of carcasses, we estimate 181,437 kg of wood required. Assuming the wood to be 12% water

(typical value for woods used in stoves, boilers), 88% of the original mass of wood added (i.e., 159,664 kg) is burnable. According to Lamberg et al. (2011), 0.4% of the dry weight of birch logs is ash, with moisture ranging from 10 to 13%. For the ACB burn, we assume that the relatively high temperature of the burn eliminated the moisture and combusted almost all of the remaining materials to total (fly and bottom) ash.

To apportion the ash between fly and bottom ash, we used data from Narodoslawsky and Obernberger (1996). To evaluate heavy metal content of wood ash produced by wood-burning facilities in Austria, they estimated the proportion of ash emitted to air and caught on filters and the proportion remaining as bottom ash. Using a multi-cyclone filter and a filter fly-ash precipitator, they captured 15–25% of the initial weight of wood chips burned as cyclone fly ash and 1–4% as filter fly ash, with the remainder 75–85% of the initial biomass retained in the bottom ash. The bottom ash fell through the bottom grate at initial temperatures of 500–1000°C; the cyclone filter was installed after the heat exchanger and therefore operated at approximately 140–200°C. Based on the ranges of cyclone and filter fly ash from wood chips reported by Narodoslawsky and Obernberger (1966), we assume 78% of wood added to the ACB pit remains as bottom ash while 22% is emitted to air as fly ash. That means that 650 kg of bottom ash remains and 140 kg of ash is emitted to air for an ACB combustion of 50 tons of cattle.

To estimate the total PAH quantities (mg) released to air during ACB combustion of cattle carcasses (Table A.7, Total PAH column), the concentrations of PAHs in the wood fly ash (first data column in Table A.7) were multiplied by the total of 140 kg of ash released to air. Dividing the totals released by 172,800 seconds (i.e., 48 hours), and converting units to grams, the final EFs were estimated for particle-phase PAHs in g/s (final data column of Table A.7).

A.2.3. Coal

In the United States, coal from eastern states (e.g., Ohio, Pennsylvania, and parts of West Virginia) has higher sulfur content, accounting for 3–10% of the coal's weight (i.e., bituminous and anthracite coal). Coal from western states (e.g., Wyoming, Montana, Utah, Colorado,

Alaska) can have sulfur contents that make up less than 1 percent of its weight (e.g., low sulfur subbituminous coal).[19]

Most of the coal mined in the United States is subbituminous and bituminous. Bituminous coal has a carbon content of 45–80% and provides approximately twice the energy per unit weight than subbituminous coal. Subbituminous coal, with a carbon content of 35–45%, is younger in age, contains more moisture and volatile chemicals, and is more alkaline than bituminous coal. Bituminous coal is generally used to generate electricity or converted to coke for use in the steel industry at facilities with pollution controls that can reduce sulfur emissions as well as reduce particulate emissions. Without post-combustion emission controls, it generates a yellowish foul-smelling smoke, with relatively larger particle size distributions. Because of the relatively high sulfur content of bituminous coal, many power plants are switching to low-sulfur subbituminous coal from the western states, even though twice as much is required and transportation costs can be higher. Less than 10% of the coal mined in the United States is anthracite, and that is found only in Pennsylvania. U.S. anthracite coal has a high sulfur content, in contrast to Chinese anthracite coal which has a low sulfur content.

USDA guidance does not specify what type of coal should be added to carcasses for open pyre burning (i.e., "coal used as fuel should be of good quality," USDA 2005, page 12). Coal quality rankings generally correspond to the energy content per unit weight, with the top grade of coal being anthracite (> 90% carbon), then bituminous (45–80% carbon), then subbituminous (35–45%), and finally lignite (< 40% carbon). Higher energy content correlates with higher non-volatile carbon content and lower moisture content. Lower sulfur content also is desirable to minimize odors and yellowish smoke. The concentration of sulfates is higher in salt water than in fresh water; therefore coal with high-sulfur content is formed from compression of organic matter predominantly from brackish and salt-water wetlands, whereas low-sulfur coal originates from freshwater bogs (NRC 1993). Thus, sulfur content can vary independently of carbon content in coal.

[19] http://www.sourcewatch.org/index.php/Sulfur_dioxide_and_coal#cite_note-18

Many investigators have studied low sulfur anthracite and bituminous coal emissions to air from residential coal stoves in China, where coal is a popular residential fuel (Chen et al. 2004, 2005; Liu et al. 2009, 2012; Zhi et al. 2008); few have examined coal emissions from residential stoves in the United States, where use of coal in homes is rare. We calculated emissions of PAHs from the burning of coal added as an auxiliary fuel to the open pyre combustion scenario from measured emissions for Chinese residential combustion of honeycomb coal briquettes (Chen et al. 2004). That study was selected because temperatures for residential coal burning are lower than for coal-fired power plants (for which USEPA data are available), and therefore more appropriate and similar to open pyre coal burning. In addition, Chen et al. (2004) used a series of filters to measure particle sizes associated with the emitted PAHs after dilution and cooling in ambient air. Initially, all PAHs released from a burn at 125°C (257°F, residential fire box) are in vapor phase (Chen et al. 2004). After dilution with ambient air and cooling, a higher proportion of the lighter molecular weight PAHs remain in the gas phase, while the heavier PAH compounds condense more into aerosols and onto fine particles.

Chen et al. (2004) sampled and analyzed PAHs in emissions in a high efficiency stove with the air-control valve fully opened (i.e., highest burn temperature possible for the stove). They captured initial emissions using a large hood and large mixing chambers to simulate dilution with ambient air. From those chambers, a long narrow curved pipe submerged in water cooled the emissions to approximately 23–25°C. Those emissions were segregated by particle size using a multi-filter sample. The first filter, with a mesh size of 7.2 µm, captured larger particles. A series of filters with smaller mesh pores (i.e., 3.0, 1.5, 0.95, and 0.49 µm) captured smaller particles. The proportion of total PAHs removed by the pre-filter was less than 2%, with the exception of phenanthrene for which 7.44% was retained on the pre-filter. Only 7–10% of fluorene and phenanthrene were in the 3.0–7.2 µm particle range. Approximately 57–76% of the total mass of PAHs remained in vapor phase or sorbed to particles less than 0.49 µm (the final filter). The mass mean aerodynamic diameter (MMAD) ranged from 0.39 to 0.44 µm (Table 6 in Chen et al. 2004). Based on those findings, we assume all particle-phase PAHs are associated with fine particles (i.e., $PM_{2.5}$ or smaller).

Larger particles (e.g., > $PM_{2.5}$) could deposit closer to the source. They would, however, have a lower content of sorbed PAH than smaller particles, because of the lower surface to mass ratio for larger particles. Given that we are not assessing carcinogenic risks from PAH exposure via inhalation (48 hour exposure is negligible comparable with a 70-year lifetime for which cancer potency factors are calculated), our assumption is that the bulk of PAH deposition to ground, and possible chronic exposures that might result from subsequent ingestion of soils and crops, is associated with $PM_{2.5}$ or smaller.

Table A.8 lists the reported emission factors for residential anthracite coal combustion in µg[PAH]/kg[coal] for vapor-phase, particulate, and total PAH (µg/kg) from Chen et al. (2004).

Table A.8. PAH Air Emission Factors from Residential Coal Combustion Used in Open-Pyre Model.

PAH (number of aromatic rings)	Emissions Coal Combustion[a] (µg PAH/kg coal)				Coal Emission Factors (g PAH/sec) for 5 Tons Coal/48 Hours		
	Particles	Vapor	Total	% Vapor	Particles	Vapor	Total
Naphthalene (2)	na	na	na	na	na	na	na
Acenaphthylene (3)	0.003	0.748	0.75	99.7	7.87E-11	1.96E-08	1.97E-08
Phenanthrene (3)	0.064	82.086	82.15	99.9	1.68E-09	2.15E-06	2.16E-06
Fluorene (3)	0.069	4.622	4.691	98.5	1.81E-09	1.21E-07	1.23E-07
Acenaphthene (3)	nd	0.534	0.534	100	0	1.40E-08	1.40E-08
Anthracene (3)	0.002	2.031	2.034	99.9	5.25E-11	5.33E-08	5.34E-08
Pyrene (4)	0.075	4.34	4.415	98.3	1.97E-09	1.14E-07	1.16E-07
Chrysene (4)	0.696	1.441	2.138	67.4	1.83E-08	3.78E-08	5.61E-08
Fluoranthene (4)	0.004	8.215	8.219	100	1.05E-10	2.16E-07	2.16E-07
Benzo[a]anthracene (4)	0.073	0.144	0.2178	66.3	1.92E-09	3.78E-09	5.70E-09
Benzo[a]pyrene (5)	0.171	nd	0.171	nd	4.49E-09	0	4.49E-09
Benzo[e]pyrene (5)	1.71	0.145	1.857	7.8	4.49E-08	3.81E-09	4.87E-08
Benzo[k]fluoranthene (5)	1.02	0.178	2.2	7.4	2.68E-08	4.67E-09	3.14E-08
Benzo[b]fluoranthene (5)	1.02	0.178	2.2	7.4	2.68E-08	4.67E-09	3.14E-08
Cyclopenta[c,d]pyrene (5)	na	na	na	na	na	na	na
Perylene (5)	na	na	na	na	na	na	na
Dibenzo[a,h]anthrance (6)	0.591	nd	0.591	nd	1.55E-08	0	1.55E-08
Indeno[1,2,3,-cd]pyrene (6)	0.829	nd	0.829	nd	2.18E-08	0	2.18E-08
Benzo[g,h,i]perylene (6)	1.097	nd	1.097	nd	2.88E-08	0	2.88E-08
Benzo[b]chrysene (6)	na	na	na	na	na	na	na
Coronene (7)	1.119	nd	1.119	nd	2.94E-08	0	2.94E-08
Total PAHs	8.543	105	119	nr	nr	nr	2.97E-06

Abbreviations: na = not analyzed; nd = not detected; nr = not reported; PAH = polycyclic aromatic hydrocarbon; PM1 = particles of 1 µm or less; s = seconds; SD = standard deviation.

Source for first four data columns, Chen et al (2004); source for last three columns, data from first four columns converted to g/s assuming a 48-hr burn and 5 tons of coal.

To convert those EFs to units of g[PAH]/second (g/s) of combustion for input into AERMOD particulate dispersion modeling, the initial emissions data were multiplied by 5 tons of coal (i.e., 4,536 kg coal), divided by 48 hours (i.e., 172,800 s), divided by 1,000,000 (µg/g). Naphthalene was not analyzed because it remains almost entirely in vapor phase even after mixing with ambient temperature air and because its toxicity is low. Emission factors in g/s for particle-phase and for vapor-phase PAHs are inputs for AERMOD's simulation of open pyre burning of 50 tons of cattle with the auxiliary fuels specified in Section 3.1.1 of the main report.

Data from Chen et al. (2004) for anthracite coal reflect full open flue burning, with an abundance of oxygen. We assume that condition is representative of an open pyre burn, with oxygen intake from all sides. Most studies of residential heaters are based on "as operated" at lower temperatures (resulting in less complete combustion) to allow longer burns at moderate temperatures.

A limitation of using data from Chen et al. (2004) is that overall emissions from different types of coal (e.g., anthracite, bituminous) can differ substantially. Total PAH emissions from anthracite coal (0.117 mg/kg) in the high-efficiency stove fueled studied by Chen et al. (2004) produced substantially lower emissions than reported for other sources. Specifically, Chen and colleagues reported higher PAH emissions from coal briquettes (101 mg/kg), lignite (436 mg/kg), subbituminous (2,137 mg/kg) and bituminous coal (3,848 mg/kg) as burned in residential stoves with air intake regulated at lower levels to reduce burn temperature (Table 5 in Chen et al. 2004). Power plants burning bituminous coal at much higher temperatures emit PAHs at lower levels (e.g., approximately 0.55–0.57 mg/kg for bituminous coal; Table 5 in Chen et al. 2004). The authors do not specify presence or absence of pollution control equipment. Presumably, open burning of subbituminous coal yields lower emissions of PAHs than bituminous coal, with total PAHs of between 0.6 mg[PAHs]/kg coal (bituminous coal burned at higher temperature in power plant] and 2,200 mg[PAHs]/kg coal (subbituminous coal burned at lower temperatures in residential stoves).

We assume that open pyre burning of anthracite coal at somewhat higher temperatures and with ample oxygen supply might have similar PAH emissions as those reported by Chen et al. (2004).

However, investigating other sources suggested that we had underestimated PAH emissions from coal in open pyres. Using USEPA estimates of emissions from anthracite coal used in residential space heaters (AP-42, Table 1.2-5, 1996 update[20]) would result in higher PAH emissions to air by one or two orders of magnitude depending on the congener. For uncontrolled residential coal boilers and furnaces combusting bituminous or subbituminous coal, USEPA (AP-42 1998 update[2], Table 4.1-6) estimated EFs (in µg/kg coal) approximately three orders of magnitude higher than the values listed in Table A.8. Comparison is hampered, however, because USEPA (AP-42, 1998 update[2]) provided estimates to a single significant digit and grouped several PAH congeners together (e.g., benzopyrenes with perylene, anthracene with phenanthrene, all benzofluoranthenes together). Yang et al. (2016) found that total PAH emission factors (in mg/kg) from coal and wood combustion in industrial boilers correlate well with benzo[a]pyrene EFs (correlation coefficient r^2 of 0.9991; four types of fuel compared). USEPA (AP-42, 1998 update[2]) did not report benzo[a]pyrene emissions alone, however, so BaP comparisons could not be made.

We conclude that PAH emissions from 5 tons of coal might be 100 to 1000 times higher than the emission factors calculated by Chen et al. (2004) for anthracite coal. Multiplying the PAHs from coal by 1000, and then dividing by a 70-yr lifetime for carcinogenic effects of PAHs, the underestimate is a factor of 14 for the relative risk analyses in Section 7 of the main report.

A.2.4. Straw or Hay

To estimate EFs for bales of hay added to open pyres, we used data from similar materials, including various types of "straw" left over in or from agriculture (e.g., rice, wheat, other grain crops, corn stover). EPA's *Emissions of Organic Air Toxics from Open Burning* (USEPA 2002a) provided estimates of total PAH emissions from burning of straw; however, USEPA did not distinguish particle- from vapor-phase chemicals as needed in AERMOD. Therefore, we used data from Zhang et al. (2011) to estimate the distribution of PAHs among particle- and vapor-phase releases.

[20] Technology Transfer Network Clearinghouse for Inventories & Emissions Factors: *Emissions Factors & AP 42, Compilation of Air Pollutant Emission Factors*. Retrieved 6/25/2016 from https://www3.epa.gov/ttnchie1/ap42/

Zhang et al. (2011) estimated EFs for PAHs released from combustion of corn, rice, and wheat straw, measuring both particle and vapor phases along with particle size distributions (Table A.9). The total PAH EFs for rice, corn, and wheat were 5.26, 1.74, and 1.37 mg/kg, respectively. Particle size distributions peaked at 0.10, 0.15, and 0.15 µm, respectively. Graphs of the size distribution of particles from fresh smoke and steady-state releases indicated that all particles were smaller than 1 µm (i.e., PM_1). The purpose of their study was to estimate total agricultural crop field burning to ambient air PAH concentrations in China; therefore, they did not analyze air samples for several of the 21 PAHs covered in this appendix, and several PAHs included as analytes could not be detected given their sampling techniques (see Table A.9). In addition, some proportion of the PAHs detected appear to have been omitted from the PAH totals (Zhang et al. 2011, Table 1, last row).

Total PAHs emitted for three types of straw and for corn stover, as reported by USEPA (USEPA 2002a, Table 3-2), are listed in the first four data columns of Table A.10. An average EF was calculated across all four types of agricultural residues (fifth data column Table A.10). We estimated EFs separately for vapor and particulate emissions to use with AERMOD to simulate open-pyre burning by multiplying the vapor fraction estimated from Zhang et al. (2011) (final column in Table A.9) by the average EF in Table A.10 (USEPA 2002a). For analytes that were not detected in the vapor phase or were not analyzed by Zhang et al. (2011), we assume that the total PAH concentration reported by USEPA (2002a) is in the particle phase for AERMOD simulation of deposition particle-phase chemicals will deposit to surface water and soil closer to the source and in greater concentrations than vapor-phase chemical.

To estimate EFs in g/s from 6,000 kg of straw added to the pyre to burn 45,359 kg (i.e., 50 tons) of cattle, the EFs for vapor and particulate PAHs (mg[PAH]/kg[straw]), the final two columns of Table A.10, were multiplied by 6,000 kg to estimate the total released (first two data columns in Table A.11). Those values divided by 172,800 seconds (i.e., 48 hours) provided EFs for open pyre burning in g/s. The EFs used to simulate PAH releases from straw added to open pyres are listed in the final two columns of Table A.11. The higher emissions of PAHs to air from straw despite the lower quantity of straw burned overall compared with wood might result from

Table A.9. PAH Air Emission Factors from Straw Burning (mg/kg burned, USEPA 2002a) Converted to EFs (mg/kg) for Vapor-phase and Particle-Phase Chemicals Separately.

PAH (number of aromatic rings)	Total Vapor and Particles (mg/kg)					Calculated (mg/kg)	
	Barley	Corn	Rice	Wheat	Average	V	P
Naphthalene (2)	80.3	4.48	8.39	196.19	72.34	71.62	0.7234
Acenaphthylene (3)	11.75	0.40	1.06	1.50	3.678	3.368	0.310
Phenanthrene (3)	17.35	1.61	1.54	4.09	6.148	2.664	3.484
Fluorene (3)	2.70	0.12	0.36	0.32	0.875	0.553	0.322
Acenaphthene (3)	9.31	0.66	0.31	0.17	2.613	1.375	1.238
Anthracene (3)	3.00	0.19	0.27	1.07	1.133	0.496	0.636
Pyrene (4)	3.58	0.77	0.35	2.47	1.793	0.299	1.494
Chrysene (4)	1.43	0.27	0.17	1.37	0.810	0.198	0.612
Fluoranthene (4)	2.30	0.80	0.45	3.93	1.870	0.321	1.549
Benzo[a]anthracene (4)	1.13	0.19	0.15	1.30	0.693	0.1910	0.5015
Benzo[a]pyrene (5)	0.78	9.56	0.08	0.41	2.708	0.7736	1.934
Benzo[e]pyrene (5)	1.01	11.26	0.11	0.59	3.243	0	3.243
Benzo[k]fluoranthene (5)	2.40	4.66	0.15	1.14	2.088	0	2.088
Benzo[b]fluoranthene (5)	0.60	2.85	0.10	0.48	1.008	0.2290	0.779
Cyclopenta[c,d]pyrene (5)	na	na	na	na	na	na	na
Perylene (5)	0.23	2.08	0.02	0.44	0.693	0	0.6925
Dibenzo[a,h]anthrance (6)	0.01	0.57	nd/na	nd/na	0.290	0	0.29
Indeno[1,2,3,-cd]pyrene (6)	0.59	9.67	0.06	0.67	2.748	0	2.748
Benzo[ghi]perylene (6)	0.52	0.57	0.04	1.05	0.545	0.2543	0.2907
Benzo[b]chrysene (6)	na	na	na	na	na	na	na
Coronene (7)	na	na	na	na	na	na	na

Abbreviations: na = not analyzed; nd = not detected; P = particle-phase; PAH = polycyclic aromatic hydrocarbon; V = vapor-phase.

virtually all of the emissions from straw being released to air in submicron sized particles and vapor, with essentially none remaining in bottom ash. As reported by Zhang et al. (2011), particles released to air from burning of dry straw are essentially all less than 1 µm in diameter.

Straw is not added to air-curtain burning units; so we do not calculate EFs for higher temperature burning of straw.

A.3. Relative Potency Factors

The exposure assessment used RPFs for PAH compounds to evaluate exposures to PAHs as a group (WHO/IPCS 1998; USEPA 1993, 2002a, 2002b, 2010a; USEPA SAB 2011). The RPFs express the carcinogenic potency of each compound relative to the potency of the index PAH, BaP, given their similarities in mode of action. Several PAH compounds are now considered unlikely to be carcinogenic. Those are represented in Table A.11 by low RPFs (i.e., 0.001).

Table A.10. Estimated PAH Air Emission Factors from Burning 6,000 kg Straw in Open Pyre.

PAH (number of aromatic rings)	Total Releases from 6,000 kg Straw		Emission Factors	
	vapors (g/pyre)	particles (g/pyre)	vapors (g/s)	particles (g/s)
Naphthalene (2)	429.7	4.34	2.49E-03	2.51E-05
Acenaphthylene (3)	20.2	1.86	1.17E-04	1.08E-05
Phenanthrene (3)	15.984	20.90	9.25E-05	1.21E-04
Fluorene (3)	3.316	1.93	1.92E-05	1.12E-05
Acenaphthene (3)	8.250	7.43	4.77E-05	4.30E-05
Anthracene (3)	2.977	3.82	1.72E-05	2.21E-05
Pyrene (4)	1.793	8.96	1.04E-05	5.19E-05
Chrysene (4)	1.190	3.67	6.89E-06	2.12E-05
Fluoranthene (4)	1.923	9.30	1.11E-05	5.38E-05
Benzo[a]anthracene (4)	1.146	3.01	6.63E-06	1.74E-05
Benzo[a]pyrene (5)	4.641	11.60	2.69E-05	6.72E-05
Benzo[e]pyrene (5)	0	19.46	0	1.13E-04
Benzo[k]fluoranthene (5)	0	12.53	0	7.25E-05
Benzo[b]fluoranthene (5)	1.374	4.67	7.95E-06	2.70E-05
Perylene (5)	0	4.16	0	2.40E-05
Dibenzo[a,h]anthrance (6)	0	1.74	0	1.01E-05
Indeno[1,2,3,-cd]pyrene (6)	0	16.49	0	9.54E-05
Benzo[ghi]perylene (6)	1.526	1.74	8.83E-06	1.01E-05

Abbreviations: PAH = polycyclic aromatic hydrocarbons; s = second.

As of June 2016, USEPA is reevaluating several PAH mixtures for its Integrated Risk Information System (IRIS) based on workshop recommendations (USEPA 2002b).[21] USEPA might also reevaluate the cancer slope factor for BaP, currently 7.3 per mg/kg-day, given its Science Advisory Board's recommendations (USEPA SAB 2011). The RPF approach is similar to the toxic equivalency approach (TEQ) for non-cancer effects of dioxins (USESPA 2010b). Table A.11 lists the RPFs for PAHs used in the assessment of livestock carcass management options and their sources.

[21] https://cfpub.epa.gov/ncea/iris2/chemicalLanding.cfm?substance_nmbr=1033

Table A.11. Relative Potency Factors for PAHs.

PAH (number of aromatic rings)	RPF	Source of RPF
Naphthalene (2)	NR	Not relevant, as a vapor, disperses and does not settle out
Acenapthylene (3)	0.001	Nisbet and LaGoy (1992) and Malcolmn and Dobson (1994) from USEPA (2010a draft for SAB Review)
Phenanthrene (3)	0.001	Nisbet and LaGoy (1992) and Malcolmn and Dobson (1994) from USEPA (2010a draft for SAB Review)
Fluorene (3)	0.001	Nisbet and LaGoy (1992) and Malcolmn and Dobson (1994) from USEPA (2010a draft for SAB Review)
Acenaphthene (3)	0.001	Nisbet and LaGoy (1992) and Malcolmn and Dobson (1994) from USEPA (2010a draft for SAB Review)
Anthracene (3)	0.3	Clement (1988, 1990); Muller et al. (1997); Larsen & Larsen (1998) from USEPA (2010a draft for SAB Review)
Pyrene (4)	0.001	Nisbet and LaGoy (1992) and Malcolmn and Dobson (1994) from USEPA (2010a draft for SAB Review)
Chrysene (4)	0.03	Larsen and Larsen (1998); Muller et al. (1997) from USEPA (2010a draft for SAB Review)
Fluoranthene (4)	0.05	Larsen and Larsen (1998) from USEPA (2010a draft for SAB Review) [more conservative than others]
Benzo[a]anthracene (4)	0.1	USEPA 1993 in USEPA 2010a
Benzo[a]pyrene (5)	1	By definition of index chemical
Benzo[e]pyrene (5)	0.007	Clement (1990), most conservative value in USEPA 2010a
Benzo[b)]fluoranthene (5)	0.1	USEPA 1993 in USEPA 2010a
Benzo[k]fluoranthene (5)	0.1	USEPA 1993 in USEPA 2010a
Cyclopenta[c,d]pyrene (5)	0.02	Larsen and Larsen (1998) in USEPA (2010a) middle of the road
Perylene (5)	0.001	Malcolmn and Dobson (1994) from USEPA (2010a draft for SAB Review)
Dibenz[a,h]anthracene (6)	0.1	Malcolmn and Dobson (1994) from USEPA (2010a draft for SAB Review)
Indeno[1,2,3-cd] pyrene (6)	0.1	USEPA 1993 in USEPA 2010a
Benzo[g,h,i]perylene (6)	0.02	Larsen and Larsen (1998), Clement (1988, 1990); some others higher some others lower by 10%
Benzo[b]chrysene (6)		Not available
Coronene (7)	0.001	Malcolmn and Dobson (1994) from USEPA (2010a draft for SAB Review)

Abbreviations: NR = not reported; PAH = polycyclic aromatic hydrocarbon; RPF = relative potency factor.

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Appendix B. Data for Dioxins and Furans

The materials used in open pyre burning and air-curtain combustion may or may not initially contain dioxins and furans. The process of combusting carcasses and various fuels, however, might produce dioxins and furans.

Measurement of dioxins/furans released from on-site burning is complicated by their ubiquitous presence in the environment (usually at low concentrations), including in top soils. In addition, on-site burning operations typically do not have a conventional stack that allows accurate measurement of emissions per unit volume. Heated soils under an open pyre or around an air-curtain pit can release a fraction of the initially soil-bound dioxin/furan compounds to air during combustion (Black et al. 2012a,b). Thus, unless investigators attempt to distinguish dioxin/furan releases from the materials burned from releases of vapor-phase dioxins/furans from heated soils, the relative contribution of each source is unknowable. Therefore, we ascribe the measured dioxin/furan releases from materials burned on the ground to the putative material burned (e.g., straw, wood) (Section B.1), and not the carcasses themselves or their placement on the ground.

To compare dioxin emissions to human health-based or other environmental-based benchmarks, the toxic equivalency approach (TEF) approach (USEPA 2010) combined data for all congeners relative to 2,3,7,8-tetrachlorodibenzo-p-dioxin (2,3,7,8-TCDD), the index chemical (Section B.2).

B.1. Fuel-specific Emissions Data for Dioxins and Furans

The fuels used to burn carcasses differ for open pyre and air-curtain burning as does the average temperature of the burn. Several fuels generally are included to ensure an open pyre burn (e.g., wooden railway ties and kindling, bales of hay or straw, diesel, or coal), whereas only wood is needed for an air-curtain burner (diesel exhausts from the fans used to create an air curtain are not included here). Open pyre burning also occurs at lower temperatures than air-curtain burning. In this assessment, we use 550°C and 850°C for each, respectively.

Dioxin/furan emissions generated from livestock carcasses are not reported, therefore, we assume dioxin/furan congeners are not released from the carcasses. The fraction of dry matter in

the carcasses (e.g., 30–35%; Hanna 2010; Lohman 1971; Malone et al. 1987, cited in CAST 2008) is substantially less than the fraction dry matter in the auxiliary fuel particularly wood. Omission of emissions from carcasses should not affect estimates of exposures to dioxins/furans or the ranking of carcass management options.

The 17 different toxic dioxin/furan congeners with chlorine substitutions at the 2,3,7, and 8 positions emitted from combustion partition to varying degrees between vapor- and particle-phases in ambient air. Therefore we sought congener-specific emission data for each type of auxiliary fuel used for on-site burning. We assume that the total for released dioxins/furans came from the fuels, and did not attempt to factor in releases that might result from heated soils. We assume that the relative emissions in vapor and particle phase could be compound-specific and influenced by burn temperature.

If dioxin emissions were reported only on the basis of total toxicity equivalency factors (i.e., TEFs or TEQs) instead of by congener, we did not apportion the emissions to individual congeners. Some investigators reported the results only as total TEFs using congener-specific values from WHO/IPCS (1998) that differ slightly from those currently recommended by USEPA (2010).

B.1.1. Open Pyre Wood Burning

We estimated emissions factors (EFs) in g/s for dioxins/furans from the addition of wood to open pyres by using the congener-specific measurements reported by Wunderli et al. (2000) for combustion of native wood as used for residential heating in wood stoves (not waste wood from demolition). They plotted the distribution of measured concentrations (ng/kg) in fly ash particles in Figure 2 of their report (n = 6 samples). Our estimate of the median values from the Figure 2 histograms are listed in Table B.1 (first data column in ng/kg[ash]). Mean values would have been prefereable (Section 5.2.3 of main report), but Figure 2 plotted only the minimum and maximum measurements along with the 10^{th}, 50^{th}, and 90^{th} percentiles. Owing to the similarity in the names of the polychlorinated dibenzo-p-dioxins (CDDs) and polychlorinated dibenzofurans (CDFs), with different locations of chlorine atoms, we include the CAS Registry Number in Table B.1.

Table B.1. Dioxin/Furan Concentrations in Wood Fly Ash from Open Burning, 2,3,7,8-TCDD-Toxic Equivalency Factors, and Air Emission Factors (g/s).

Compound	CAS Reg. Number	ng/kg [ash]	TEF (EPA)	ng[TEF]/ kg[Ash]	% Total TEQ	Particle (g/s)	% [a] Part icles	Vapor (g/s)
OctaCDD, 1,2,3,4,6,7,8,9-	3268-87-9	19.00	0.0003	5.7E-03	0.251	2.8E-11	95	1.5E-12
OctaCDF, 1,2,3,4,6,7,8,9-	39001-02-0	5.50	0.0003	1.6E-03	0.07	8.2E-12	96	3.4E-13
HeptaCDD, 1,2,3,4,6,7,8-	35822-46-9	8.00	0.01	8.0E-02	3.53	1.2E-11	84	2.3E-12
HeptaCDF, 1,2,3,4,6,7,8-	67562-39-4	1.70	0.01	1.7E-02	0.75	2.5E-12	84	4.8E-13
HeptaCDF, 1,2,3,4,7,8,9-	55673-89-7	0.35	0.01	3.5E-03	0.15	5.2E-13	84	9.9E-14
HexaCDD, 1,2,3,4,7,8-	39227-28-6	0.70	0.1	7.0E-02	3.09	1.0E-12	63	6.1E-13
HexaCDF, 1,2,3,4,7,8-	70648-26-9	0.50	0.1	5.0E-02	2.20	7.4E-13	59	5.2E-13
HexaCDD, 1,2,3,6,7,8-	57653-85-7	0.80	0.1	8.0E-02	3.53	1.2E-12	63	7.0E-13
HexaCDF, 1,2,3,6,7,8-	57117-44-9	0.23	0.1	2.3E-02	1.01	3.4E-13	59	2.4E-13
HexaCDD, 1,2,3,7,8,9-	19408-74-3	1.00	0.1	1.0E-01	4.41	1.5E-12	63	8.7E-13
HexaCDF, 1,2,3,7,8,9-	72918-21-9	0.45	0.1	4.5E-02	1.98	6.7E-13	59	4.7E-13
PentaCDD, 1,2,3,7,8-	40321-76-4	0.70	1	7.0E-01	30.9	1.0E-12	27	2.8E-12
PentaCDF, 1,2,3,7,8-	57117-41-6	1.10	0.03	3.3E-02	1.45	1.6E-12	32	3.5E-12
HexaCDF, 2,3,4,6,7,8-	60851-34-5	0.70	0.1	7.0E-02	3.09	1.0E-12	59	7.2E-13
PentaCDF, 2,3,4,7,8-	57117-31-4	1.20	0.3	3.6E-01	15.9	1.8E-12	32	3.8E-12
TetraCDD, 2,3,7,8-	1746-01-6	0.55	1	5.5E-01	24.2	8.2E-13	16	4.3E-12
TetraCDF, 2,3,7,8-	51207-31-9	0.80	0.1	8.0E-02	3.53	1.2E-12	24	3.8E-12
Total TEF	nr	2.2[b]	nr	2.3[c]	100%	nr	nr	nr

Abbreviations: s = second; TEF = toxic equivalency factors; TEQ = toxic equivalents; nr = not summed, not relevant.

[a] Proportion (i.e., percent) 2,3,7,8-substituted dioxins and furans in particle phase (USEPA 2003, Table 3-4, p 3-65) from air monitoring data published by Eitzer and Hites (1989) and Eitzer (1989). The proportion released in vapor phase in hot flue is higher than after cooling and mixing with ambient air.

[b] Total TEF in ng[TEQ]/kg[fly ash] as reported by Wunderli et al. (2000, Figure 2) for native wood.

[c] Total TEF as the sum of values in the same column (ng[TEF]/kg[fly ash]). Values in column are calculated from values in the first data column (ng[chemical]/kg[fly ash]) multiplied by TEFs (USEPA 2010) in second data column.

Wunderli et al. (2000) included the median value (50th percentile) total TEF estimate (i.e., 2.2 ng/kg) based on WHO/IPCS (1998) TEQ values in their Figure 2. To confirm the reading of Figure 2 and that the researchers used the current recommended USEPA (2010) TEF values instead of older WHO recommendations, the concentration of each congener in ash reported by the Wunderli group (Table B.1, first data column) was multiplied by USEPA's (2010) TEFs (Table B.1, second data column) to estimate ng[TEF]/kg[fly ash] (Table B.1, third data column). The sum of the estimates of median TEF concentrations (i.e., 2.3 ng/kg, Table B.1) were similar

to the median total (i.e., 2.2 ng/kg) in Figure 2 plotted by Wunderli et al. (2000), even though median (not mean) values were summed. The percent was calculated of the total fly ash TEQ of 2.3 ng/kg represented by each congener (Table B.1, fourth data column) and confirmed they summed to 100%. The calculations of the distribution of dioxins/furans in the fly ash appear consistent with the data.

To estimate emission rates in g/sec, we assume 36,000 kg of wood (railroad ties plus kindling) were burned. With an initial moisture content of 12%, the mass of dry wood burned would be 31,900 kg. Based on a report by NAEI (2003), Watkiss and Smith (2001) assumed emission factors for PM_{10} from combustion of wood sleepers and wood kindling in an open pyre to be 7.9 g/kg. Assuming that all of the fly ash captured by Wunderli et al. (2000) was 10 µm or less in diameter, a fly ash release rate was estimated of 8 g[fly ash]/kg[wood]. That value is consistent with the assumptions for open pyre burning: the proportion of the dry weight of native wood comprised of ash was 0.02; the proportion of ash remaining as bottom ash was 0.645; and the proportion emitted as fly ash was 0.355. Thus, an estimated total of 257 kg of fly ash was released from wood in the open pyre.

The emission rate in g/s for particle-bound dioxins/furans (Table B.1, fifth data column) equals the total fly ash (257 kg) multiplied by the concentration of each congener in fly ash (Table B.1, first data column) divided by 172,800 seconds for a 48-hour burn (including unit conversion of 1.0E-09 ng/kg).

The estimated vapor-phase dioxins/furans released from open pyre burning of wood is based on USEPA's draft summary of the proportion of each dioxin and furan found in particle phase across six different monitoring studies (USEPA 2003). The data were summarized by the number of chlorine substitutions and whether the compound was a dioxin or furan. Those values are listed in Table B.1 (second to last data column). Using those estimates of particle- and vapor-phase partitioning, we calculated EF values for vapor-phase congeners released from open burning of wood after cooling and mixing with air (Table B.1, final data column).

B.1.2. Air-Curtain Burning (ACB) Wood Burning

To estimate congener-specific emissions of dioxins and furans to air from wood burning in an air-curtain burner (ACB) pit we used data from USEPA's National Center for Environmental

Assessment (NCEA) *Database of Sources of Environmental Releases of Dioxin-like Compounds in the United States (Version 3.0) Reference Years 1987 and 1995* (USEPA 2012).[22] Industrial wood-fired furnaces were used to be consistent with the higher temperatures reached in an ACB pit than in an open pyre (USEPA did not present EFs for dioxins/furans for residential wood combustion). The data, from 1987 and 1995, are prior to the requirements for dioxin-emissions reduction that followed the 1998 World Health Organization and USEPA's assessment of human health risks from dioxins. We assumed, therefore, that the emission rates, reported in ng/kg[wood fuel] represent high-temperature combustion without post-combustion emission controls for dioxins. We assume the sampled emissions were in particle-phase and calculated additional EFs for vapor-phase dioxins using the same procedure as for Table B.1 (open pyre).

Combustion of 50 tons (45,359 kg) of cattle would require four times (4x) the quantity of fresh wood (181,437 kg) added. Assuming 12% moisture, that quantity would equal 160,000 kg dry wood. Because the original data are in units of ng chemical released per kg wood fuel, it is not necessary to estimate the total fly ash produced to calculate EFs. The final EFs in g/s for particulate and vapor-phase dioxins/furans input to AERMOD to simulate ACB combustion of 50 tons of cattle carcasses are in the final columns of Table B.2.

The congener-specific EFs in g/s for particulate and vapor-phase emissions for the ACB burn (Table B.2) are higher than those estimated for the open pyre burn (Table B.1) by 1.5 to 2.5 orders of magnitude in large part because of the higher quantity of wood assumed to be added to the ACB than to the open pyre. The 4:1 ratio of wood to carcasses assumed here is based on Table 3.2.1 of the main report, Section 3.2.1 and is based on communications from the *5th International Symposium on Animal Mortality Management* held October 1, 2015, in Lancaster, Pennsylvania.

[22] Average emission factor in ng/kg wood processed, with non-detects set to zero (data also presented for non-detects = ½ level of detection but not used here). The difference in releases using zero and using ½ the LOD for non-detects is considered negligible, resulting in 0.5952 ng TEQ/kg wood and 0.6157 ng TEQ/kg wood, respectively.

Table B.2. Dioxin/Furan Emission Factors from Industrial Wood Burning, 1987 and 1995 (ng/kg wood) (USEPA 2012), and Emission Factors (g/s) for ACB Combustion of 50 tons of Carcasses.

Compound	CAS Reg. Number	EF ng/kg [wood] [a]	EF total ng /burn	Particle (g/s)	Percent Particle [b]	Vapor (g/s) [c]
OctaCDD, 1,2,3,4,6,7,8,9-	3268-87-9	3.33E+00	6.04E+05	3.50E-09	95	1.84E-10
OctaCDF, 1,2,3,4,6,7,8,9-	39001-02-0	6.74E-01	1.22E+05	7.08E-10	96	2.95E-11
HeptaCDD, 1,2,3,4,6,7,8-	35822-46-9	7.45E-01	1.35E+05	7.83E-10	84	1.49E-10
HeptaCDF, 1,2,3,4,6,7,8-	67562-39-4	1.06E+00	1.93E+05	1.11E-09	84	2.12E-10
HeptaCDF, 1,2,3,4,7,8,9-	55673-89-7	1.13E-01	2.06E+04	1.19E-10	84	2.27E-11
HexaCDD, 1,2,3,4,7,8-	39227-28-6	1.15E-01	2.09E+04	1.21E-10	63	7.12E-11
HexaCDF, 1,2,3,4,7,8-	70648-26-9	3.75E-01	6.80E+04	3.94E-10	59	2.74E-10
HexaCDD, 1,2,3,6,7,8-	57653-85-7	1.38E-01	2.51E+04	1.45E-10	63	8.52E-11
HexaCDF, 1,2,3,6,7,8-	57117-44-9	4.18E-01	7.58E+04	4.39E-10	59	3.05E-10
HexaCDD, 1,2,3,7,8,9-	19408-74-3	3.21E-01	5.82E+04	3.37E-10	63	1.98E-10
HexaCDF, 1,2,3,7,8,9-	72918-21-9	1.78E-01	3.24E+04	1.87E-10	59	1.30E-10
PentaCDD, 1,2,3,7,8-	40321-76-4	7.90E-02	1.43E+04	8.29E-11	27	2.24E-10
PentaCDF, 1,2,3,7,8-	57117-41-6	4.06E-01	7.37E+04	4.27E-10	32	9.07E-10
HexaCDF, 2,3,4,6,7,8-	60851-34-5	1.92E-01	3.49E+04	2.02E-10	59	1.40E-10
PentaCDF, 2,3,4,7,8-	57117-31-4	3.89E-01	7.06E+04	4.08E-10	32	8.68E-10
TetraCDD, 2,3,7,8-	1746-01-6	3.97E-02	7.20E+03	4.17E-11	16	2.19E-10
TetraCDF, 2,3,7,8-	51207-31-9	6.84E-01	1.24E+05	7.18E-10	24	2.27E-09
Total	nr	5.59E-01	1.01E+05	5.87E-10	100	6.29E-09

Abbreviations: ACB = air-curtain burner; EF = emission factors; s = second; nr = not relevant.

[a] Data from 1987 and 1995 as reported in EPA/NCEA Dioxin Database (USEPA 2012) in ng/kg wood processed; assumed releases quantified were in particle-phase.

[b] Proportion (i.e., percent) dioxins and furans in particle phase (USEPA 2003).

[c] Vapor-phase EFs calculated from previous two data columns.

B.1.3. Open Pyre Coal Burning

There are no reports on dioxin/furan emissions from burning coal in an open pyre identified in the available literature, which likely reflects the lack of information on the type of coal most likely burned and the relatively small quantity of coal in comparison with wood and carcasses.

B.1.4. Open Pyre Straw Burning

For open-pyre burning of straw-like materials, we identified one secondary source that reported emissions in units of mg[TEQ]/kg[straw burned] (USEPA 2002 citing Gullett and Touati 2002). For rice straw and wheat straw, USEPA (2002) reported EFs of 5.37E-07 and 4.52E-07

mg[TEQ]/kg, respectively apparently by using the WHO/IPCS 1998 TEQs to calculate combined dioxin/furan emissions. We assume all of those emissions were in the particulate phase to allow more deposition closer to the source than would occur if some of the congeners were emitted in part in vapor phase.

For open-pyre burning of 50 tons of cattle, we assume 6,000 kg of straw/hay bales are added, with the burn lasting 48 hours (172,800 seconds). Including a unit conversion from mg to g, the rice and wheat straw emission factors would equal 1.86E-11 and 1.57E-11 g[WHO98TEQ]/s. The average of those two values is 1.72E-11 g[WHO98TEQ]/s. In the absence of congener-specific data, to estimate dispersion and deposition using AERMOD, we assume all emissions are particulate phase 2,3,7,8-TCDD.

B.2. Toxicity Equivalency Factors (TEFs) for Dioxins and Furans

The exposure assessment used TEFs for dioxin and furan congeners to estimate total exposure to these chemicals as a group. The TEFs express the toxic potency of each congener relative to the index chemical 2,3,7,8-TCDD. We list the TEFs for each of the 17 toxic congeners in Table B.1 in Section B.1 and in Table B.3. Some agencies and investigators use the acronym TEQ (e.g., World Health Organization) instead of TEF to refer to Toxicity Equivalency factors.

The TEF for the index chemical is by definition equal to 1.0. The resulting 2,3,7,8-TCDD-equivalent oral exposures can then be added across the dioxin/furan congeners and compared with the reference dose for 2,3,7,8-TCDD.

Table B.3. Toxicity Equivalency Factors for Dioxins/Furans.

Compound	CAS Reg. Number	TEF (USEPA)
OctaCDD, 1,2,3,4,6,7,8,9-	3268-87-9	0.0003
OctaCDF, 1,2,3,4,6,7,8,9-	39001-02-0	0.0003
HeptaCDD, 1,2,3,4,6,7,8-	35822-46-9	0.01
HeptaCDF, 1,2,3,4,6,7,8-	67562-39-4	0.01
HeptaCDF, 1,2,3,4,7,8,9-	55673-89-7	0.01
HexaCDD, 1,2,3,4,7,8-	39227-28-6	0.1
HexaCDF, 1,2,3,4,7,8-	70648-26-9	0.1
HexaCDD, 1,2,3,6,7,8-	57653-85-7	0.1
HexaCDF, 1,2,3,6,7,8-	57117-44-9	0.1
HexaCDD, 1,2,3,7,8,9-	19408-74-3	0.1
HexaCDF, 1,2,3,7,8,9-	72918-21-9	0.1
PentaCDD, 1,2,3,7,8-	40321-76-4	1
PentaCDF, 1,2,3,7,8-	57117-41-6	0.03
HexaCDF, 2,3,4,6,7,8-	60851-34-5	0.1
PentaCDF, 2,3,4,7,8-	57117-31-4	0.3
TetraCDD, 2,3,7,8-	1746-01-6	1
TetraCDF, 2,3,7,8-	51207-31-9	0.1

Abbreviations: CAS = Chemical Abstracts Service; TEF = toxic equivalency factor; CDD = chlorinated dibenzodioxins; CDF = chlorinated dibenzofurans.
Source: USEPA (2010).

B.3. References

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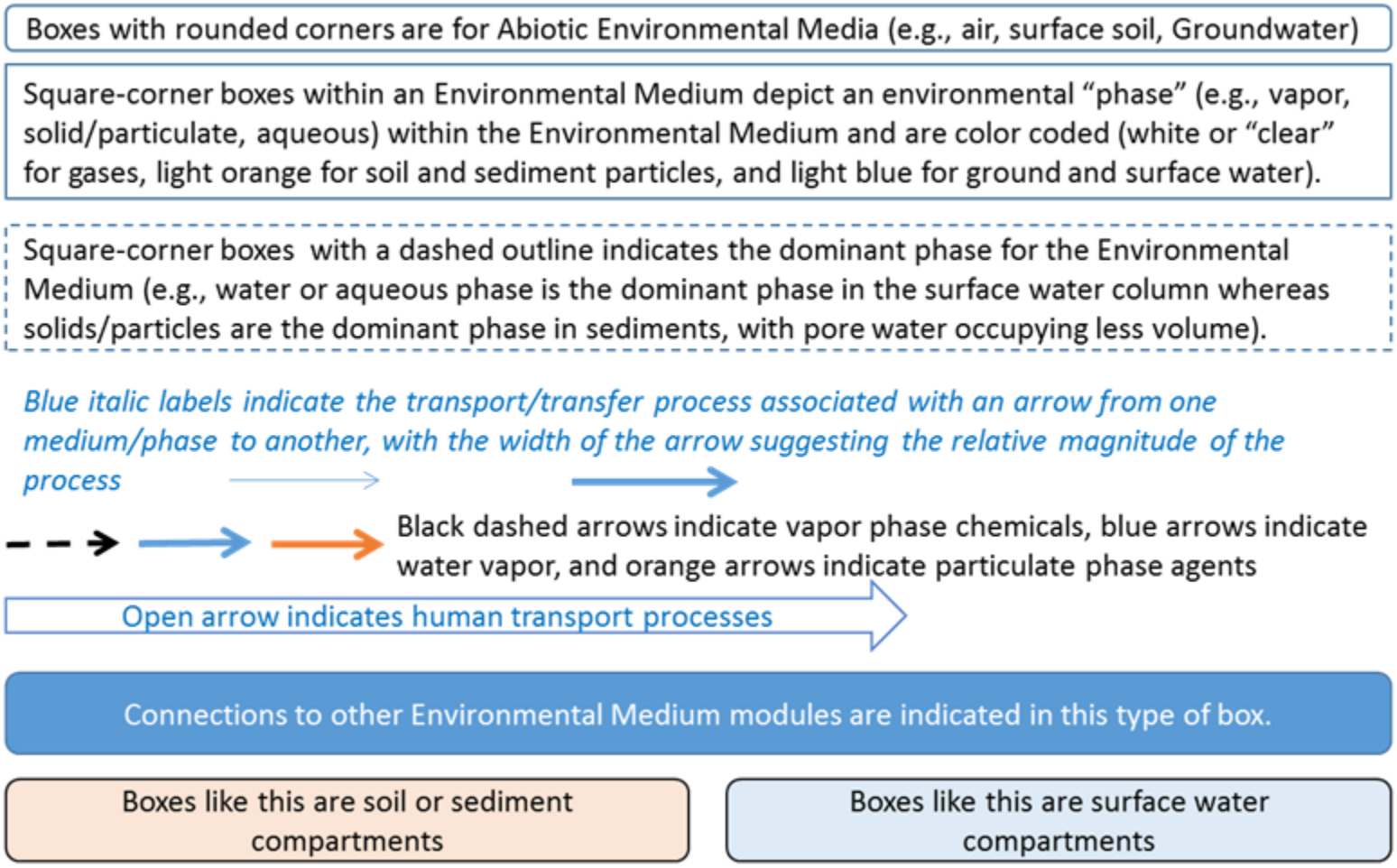
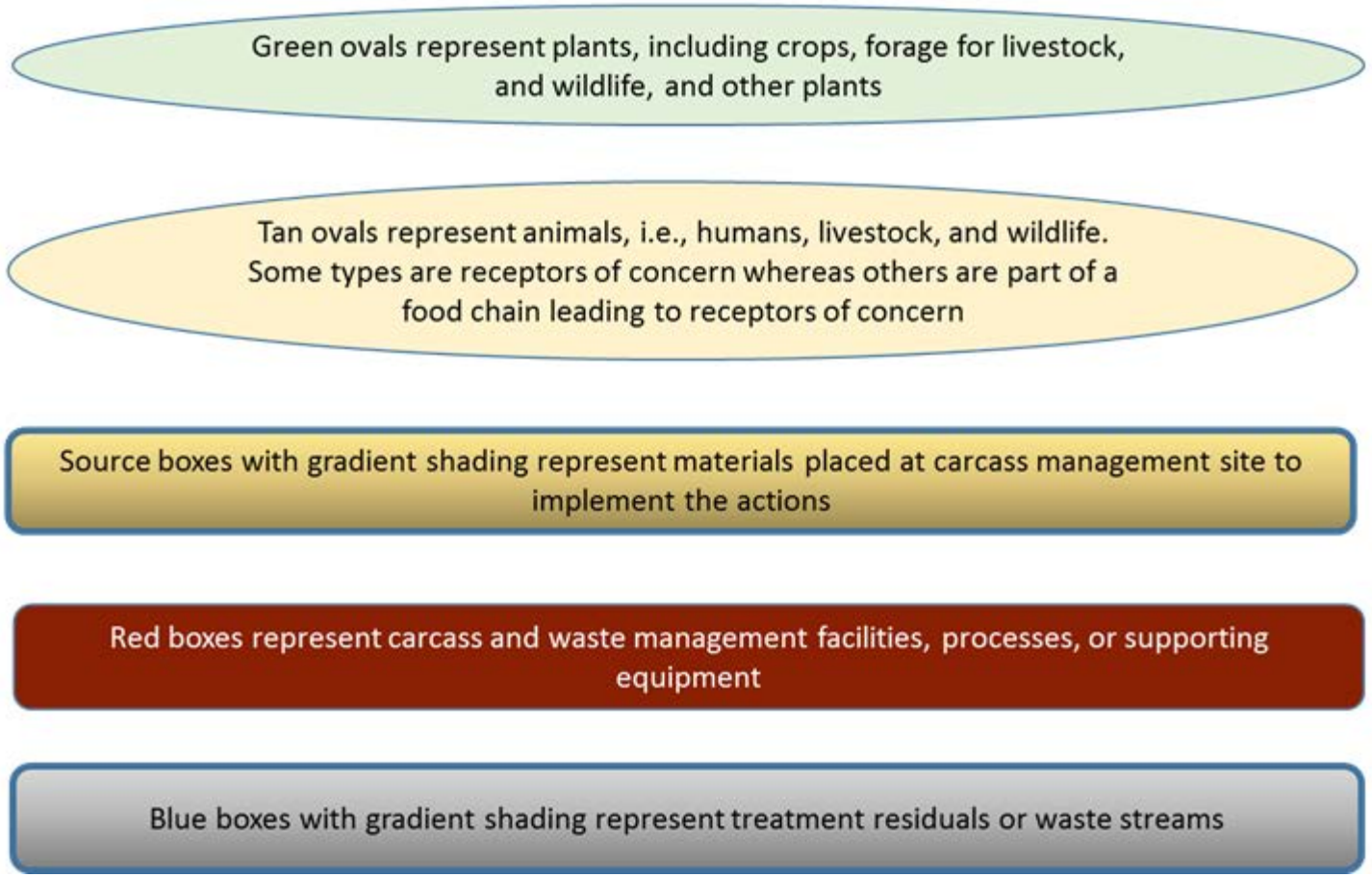
Appendix C. Conceptual Models

Conceptual Models Outline

1. Legend to Module Diagrams
2. Conceptual Model Overviews
3. Detailed Source and Compartment Modules
    a. Source Modules
    b. Abiotic Environmental Compartment Modules
    c. Biotic Environmental Compartment Modules

C.1. Legend to Module Diagrams




Green ovals represent plants, including crops, forage for livestock, and wildlife, and other plants
Tan ovals represent animals, i.e., humans, livestock, and wildlife. Some types are receptors of concern whereas others are part of a food chain leading to receptors of concern
Source boxes with gradient shading represent materials placed at carcass management site to implement the actions
Red boxes represent carcass and waste management facilities, processes, or supporting equipment
Blue boxes with gradient shading represent treatment residuals or waste streams

C.2. Conceptual Model Overviews

Livestock Carcass Management Option	Figure
On-site Open Burning (pyre)	C.1
On-site Air-curtain Burning	C.2
Off-site Fixed-facility Incineration	C.3
On-site Unlined Burial	C.4
On-site Composting	C.5
Off-site Lined Landfill	C.6
Rendering	C.7
Temporary Carcass Storage	C.8
Carcass Handling	C.9
Carcass Transportation	C.10

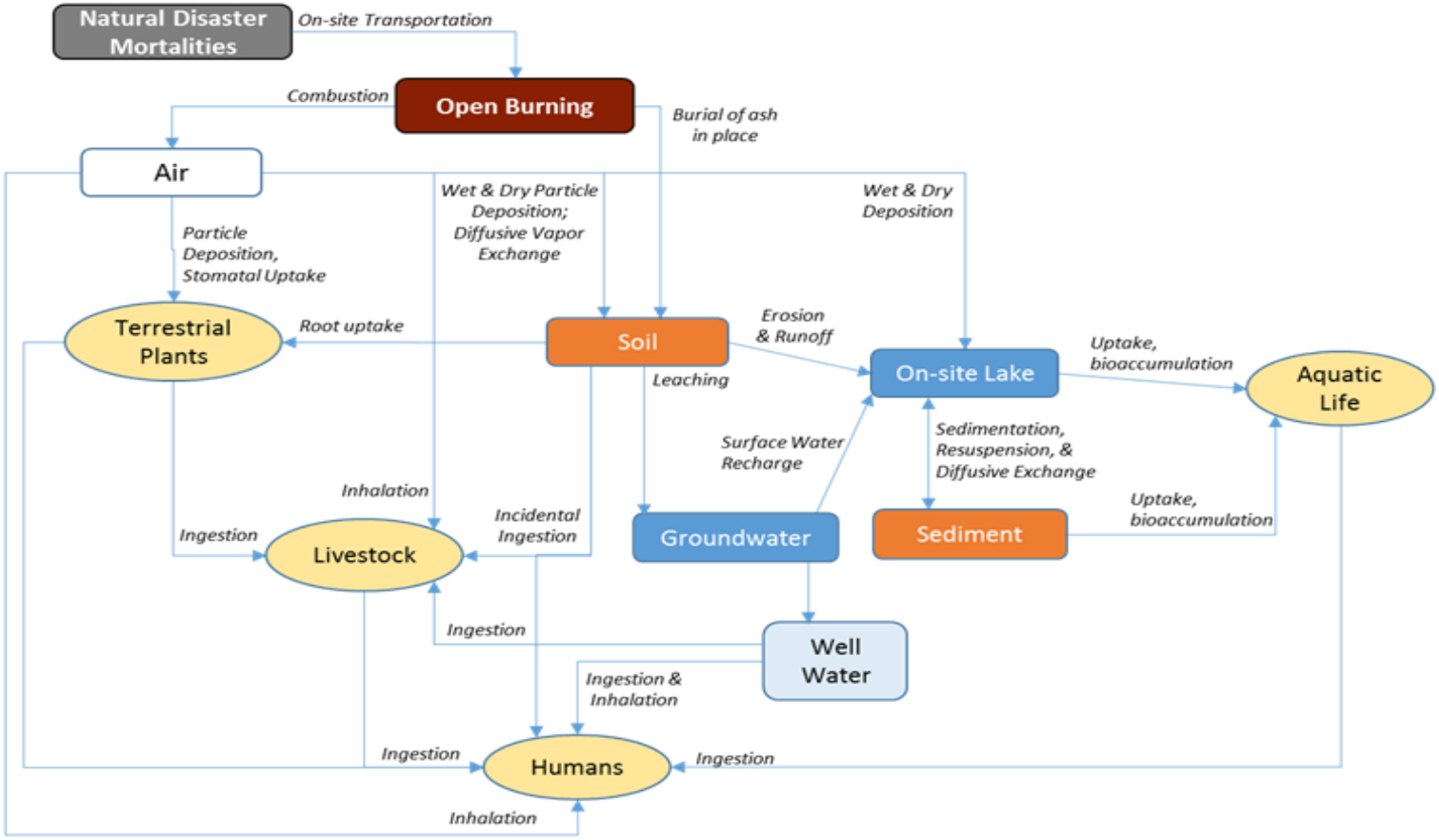


Figure C.1. On-site Open Burning

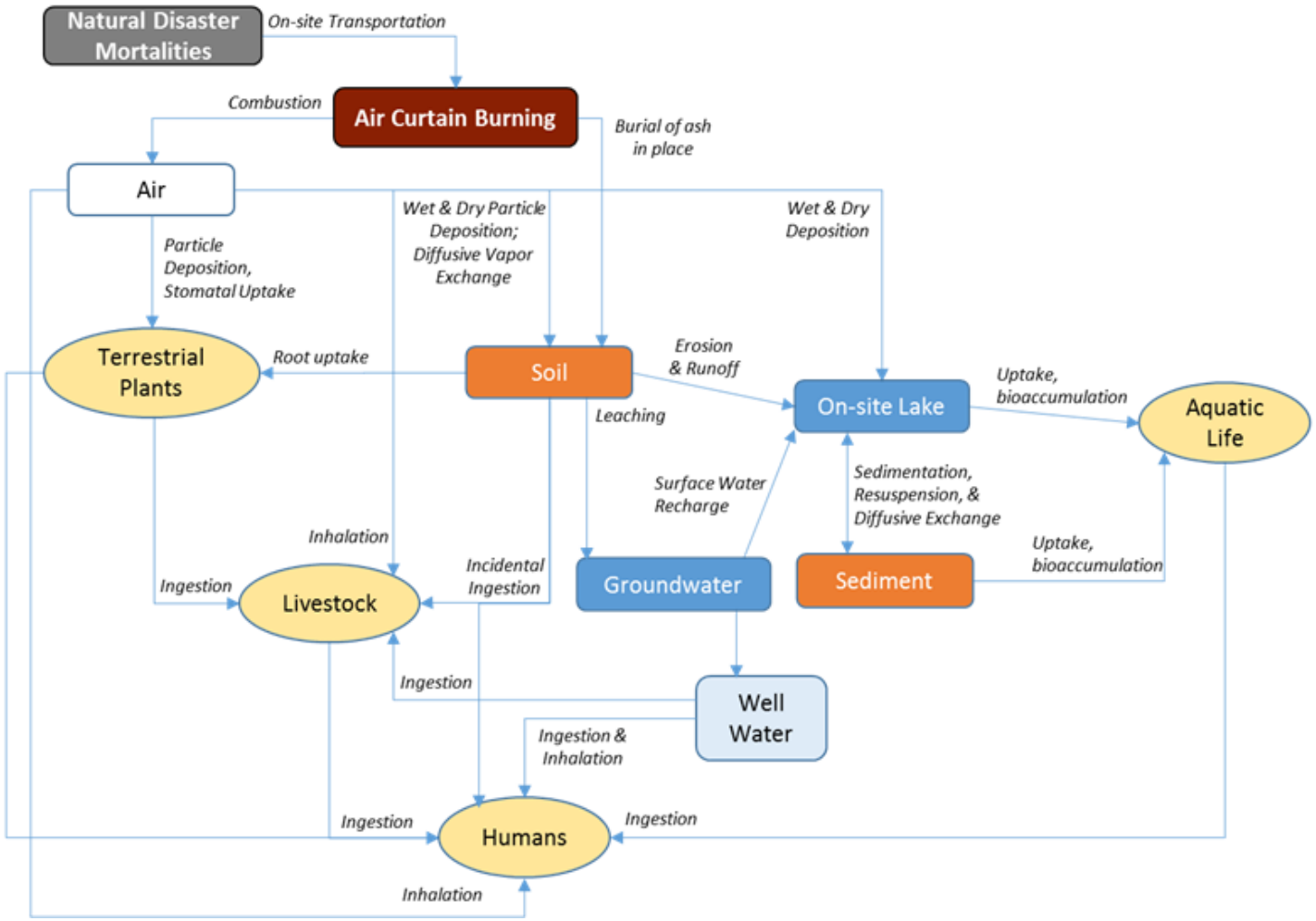


Figure C.2. On-site Air-curtain Burning

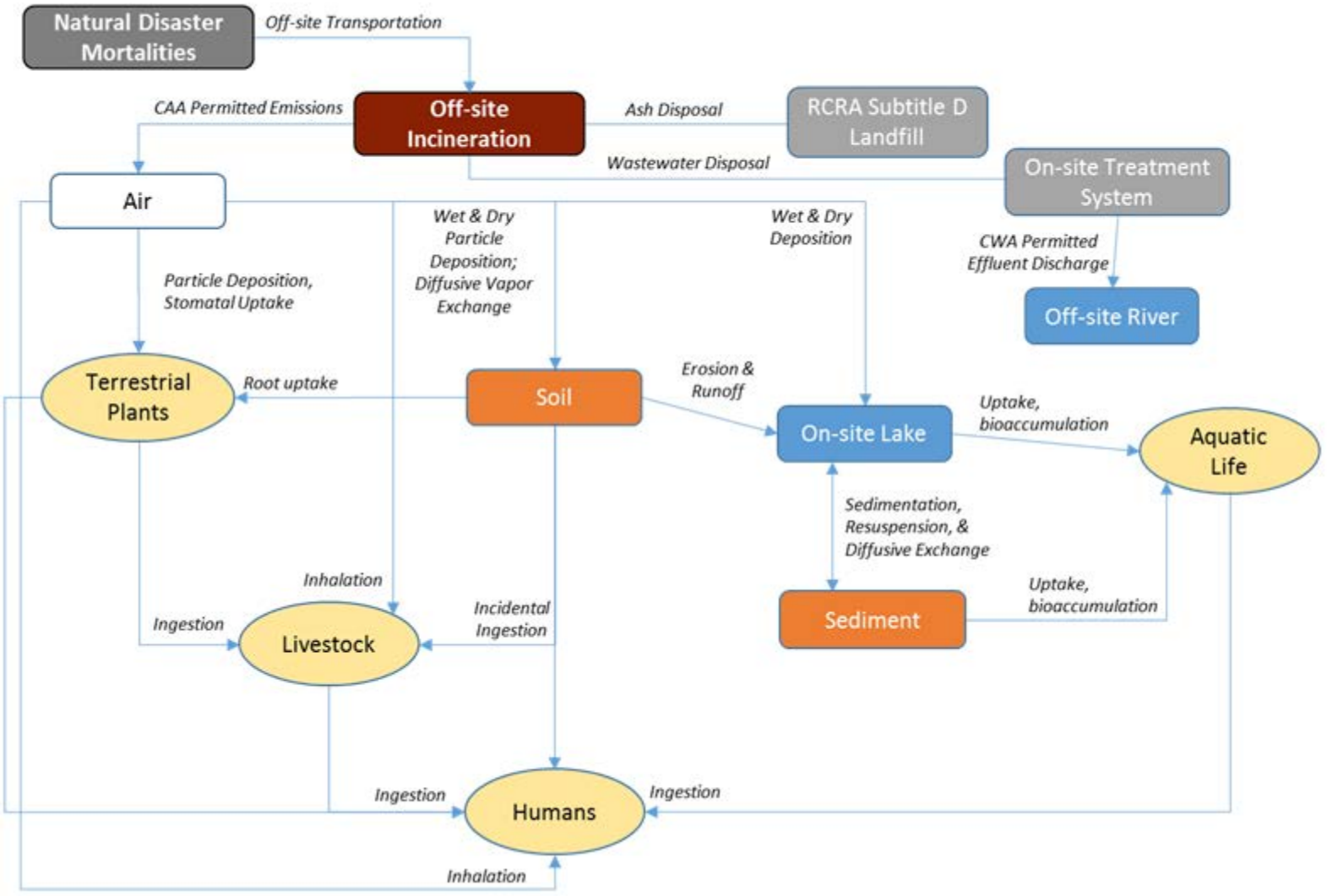


Figure C.3. Off-site Incineration

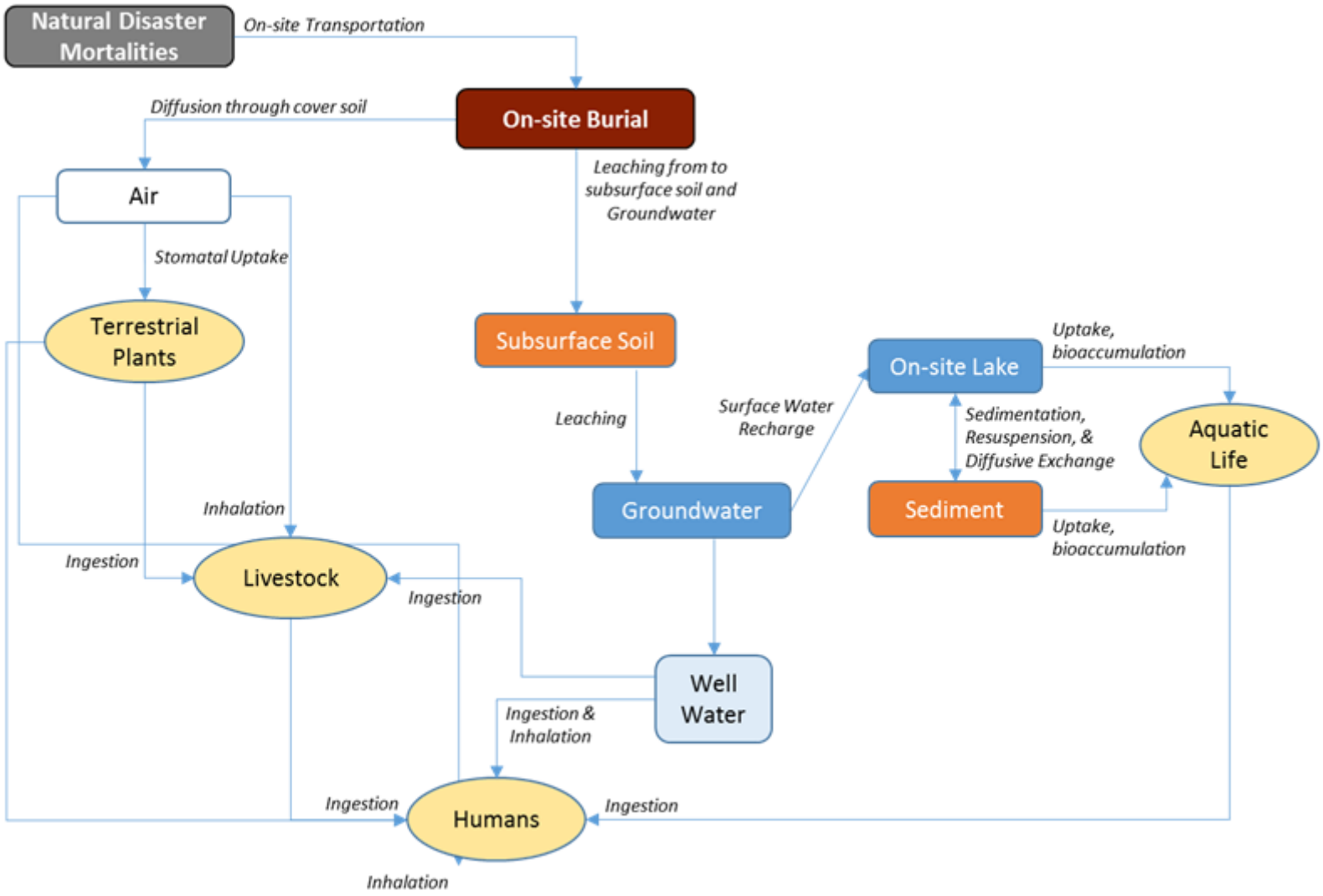


Figure C.4. On-site Unlined Burial

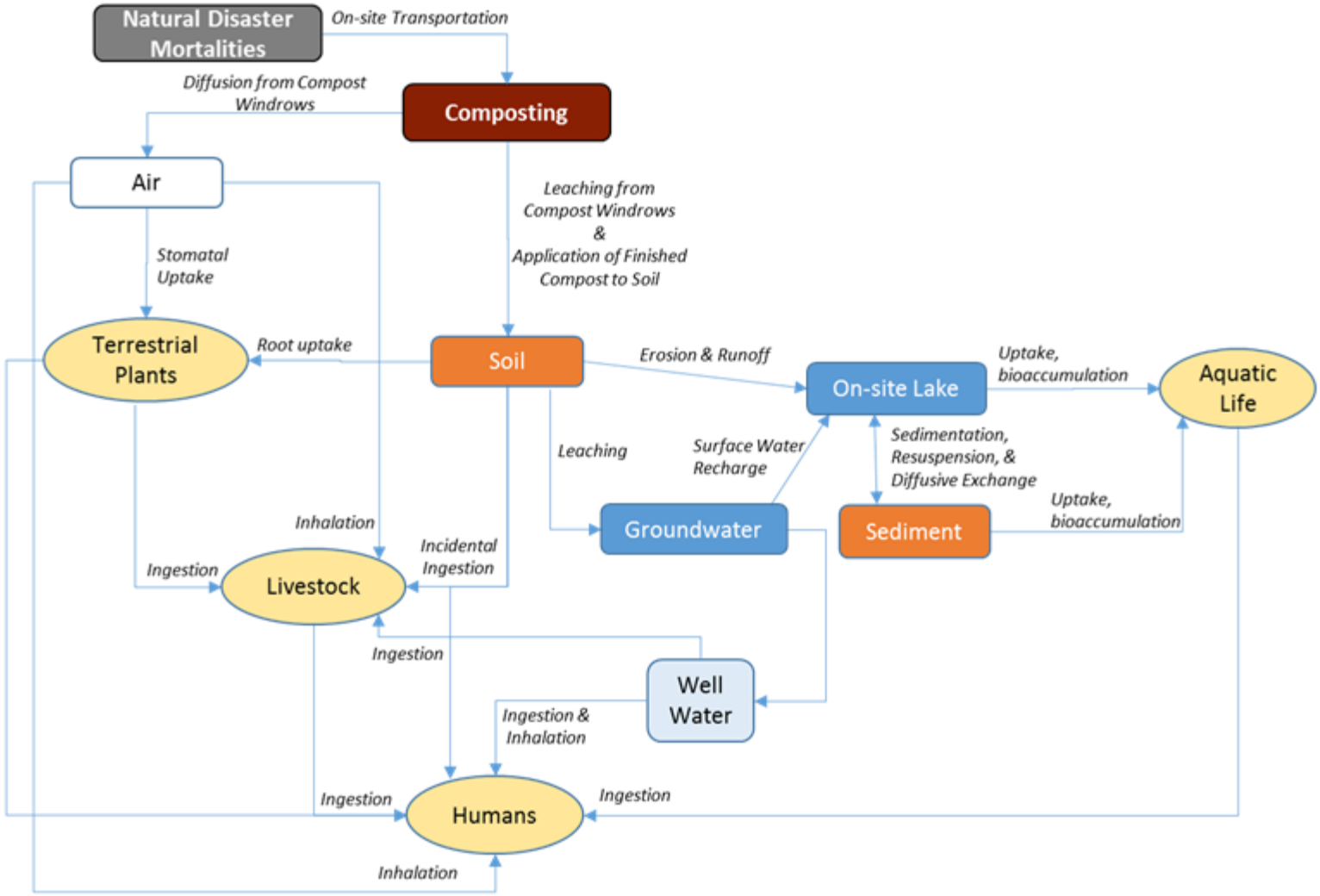


Figure C.5. On-site Composting

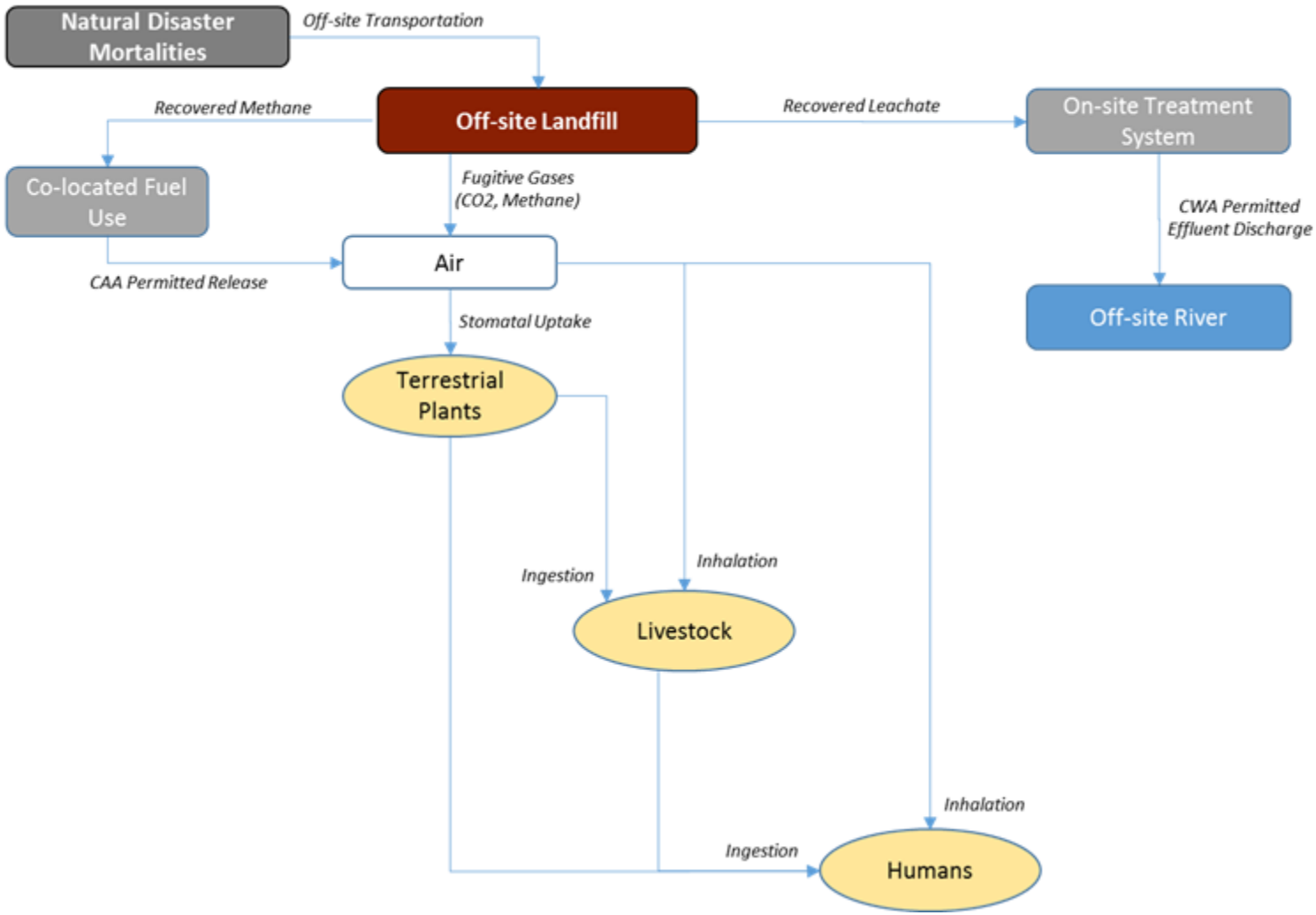


Figure C.6. Off-site Landfilling

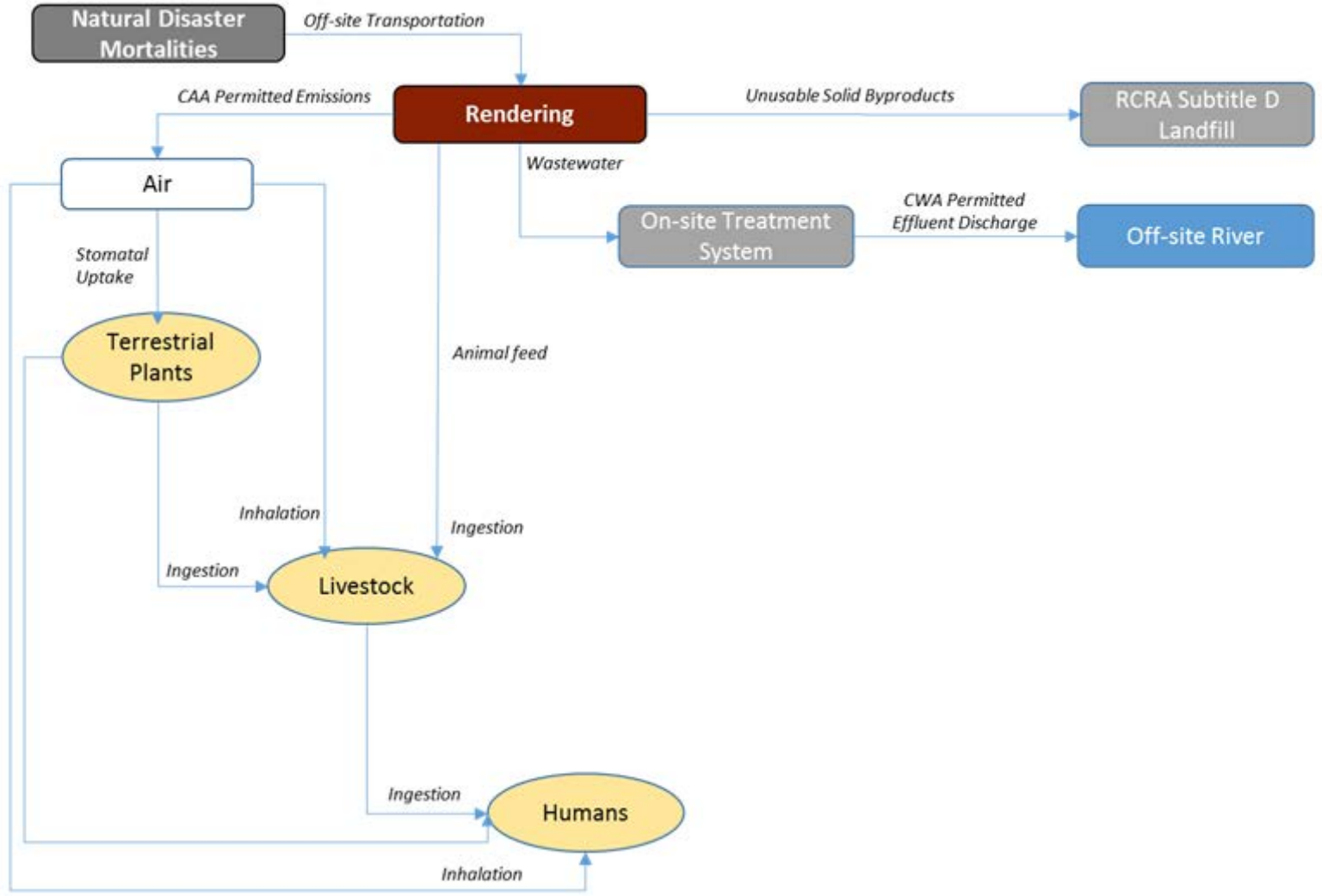


Figure C.7. Rendering

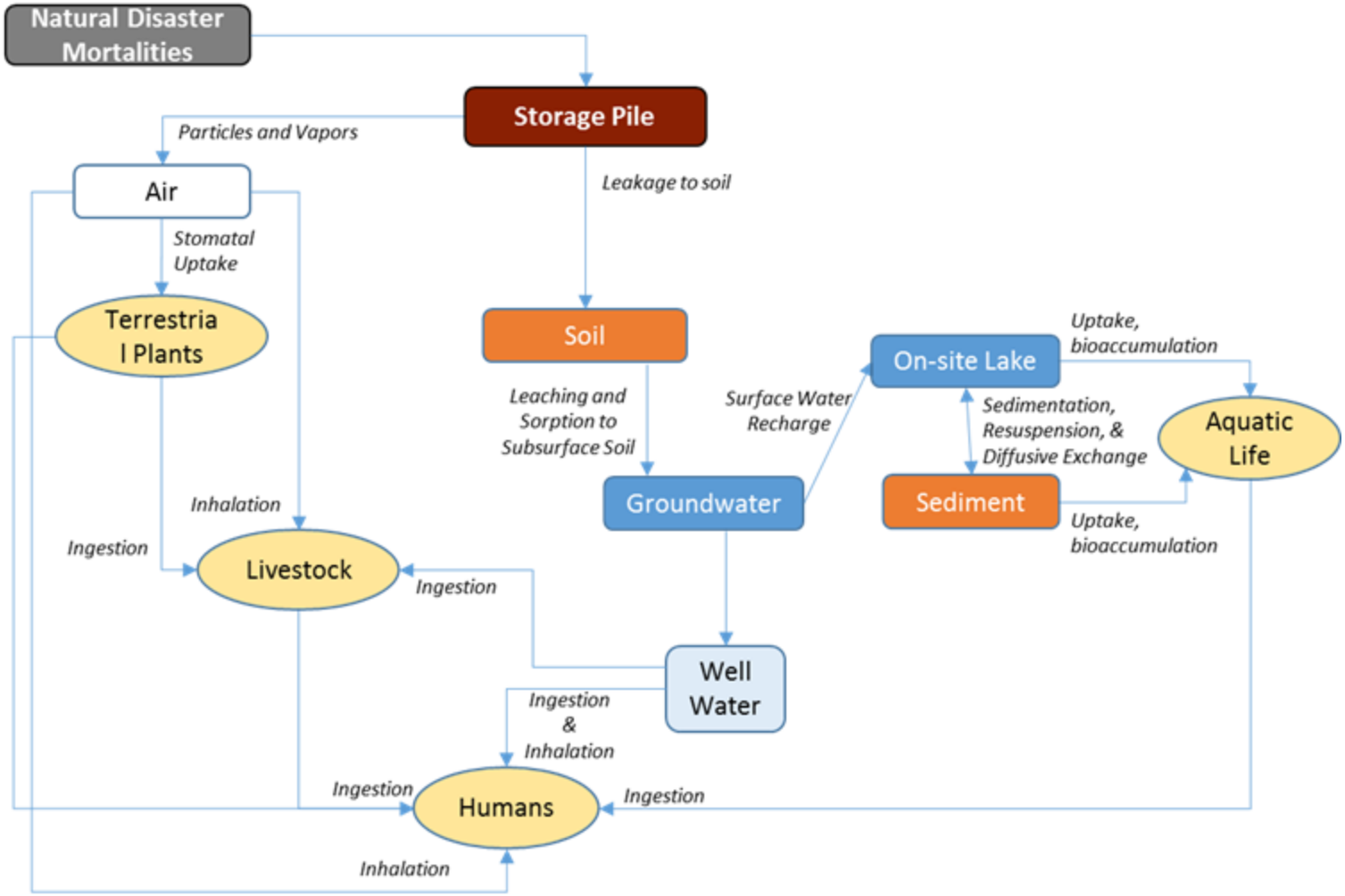


Figure C.8. Temporary Carcass Storage Pile

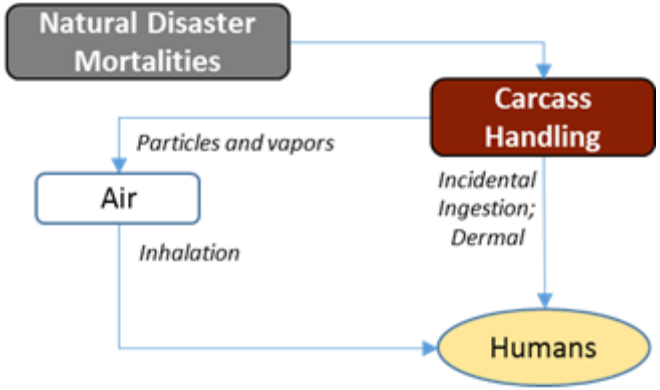


Figure C.9. Carcass Handling

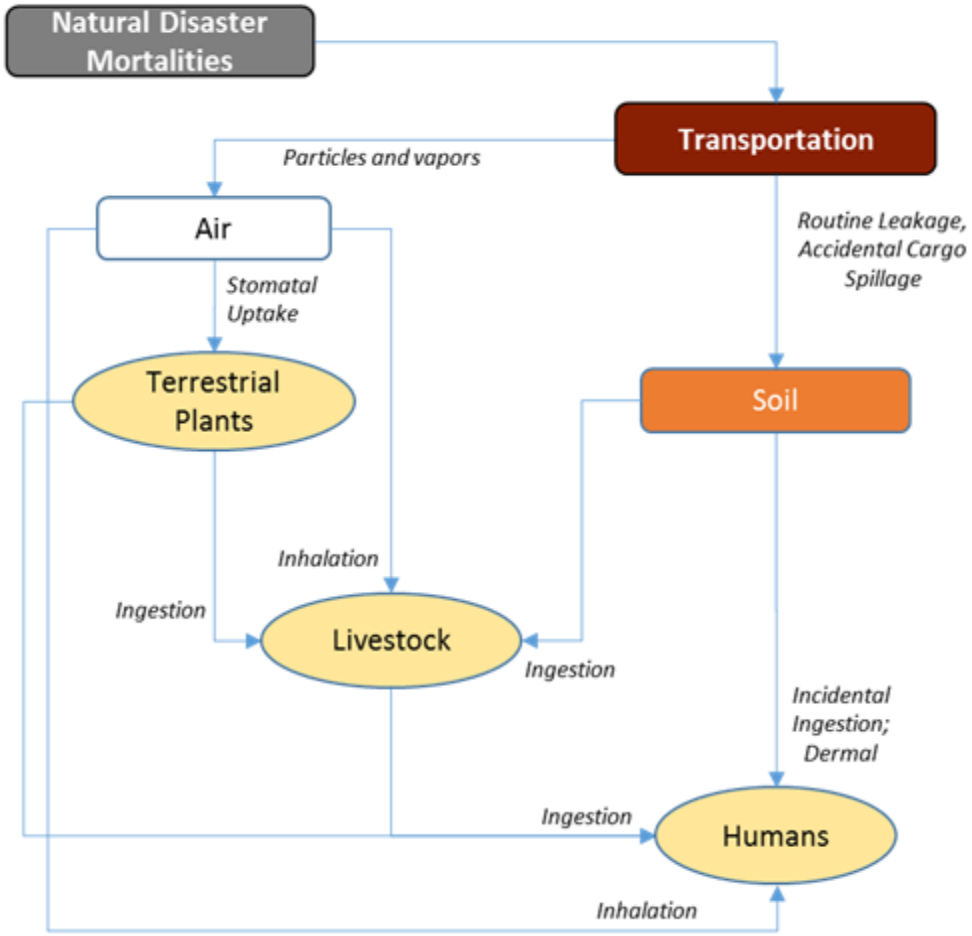


Figure C.10. Carcass Transportation

C.3. Carcass Management Source Modules

Livestock Carcass Management Option	Figure
On-site Open Burning (pyre)	C.11
On-site Air-curtain Burning	C.12
Off-site Fixed-facility Incineration	C.13
On-site Unlined Burial	C.14
On-site Composting	C.15
Off-site Lined Landfill	C.16
Rendering	C.17

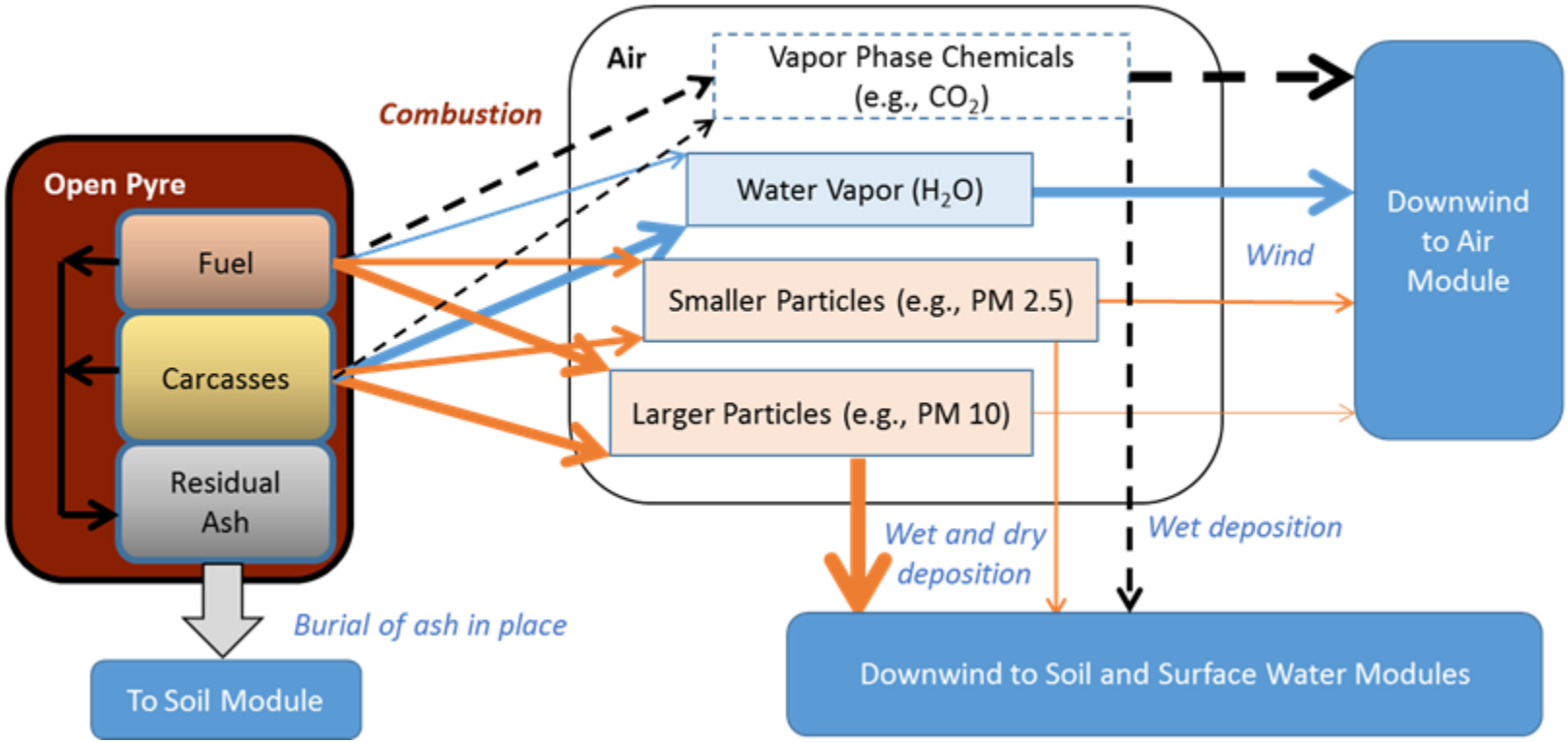


Figure C.11. Combustion-based Management: On-site Open Burning Module

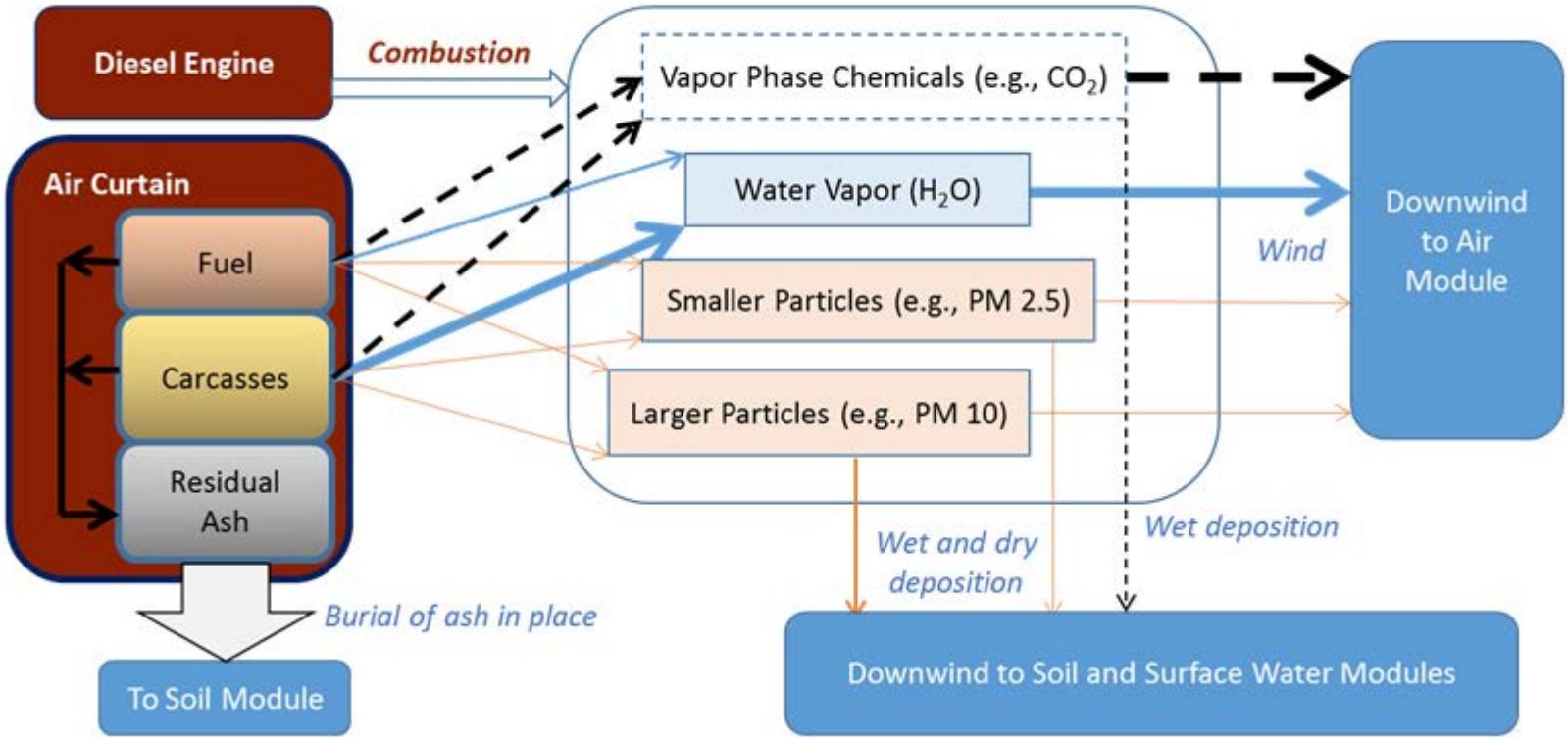


Figure C.12. Combustion-based Management: Air-curtain Burning Module

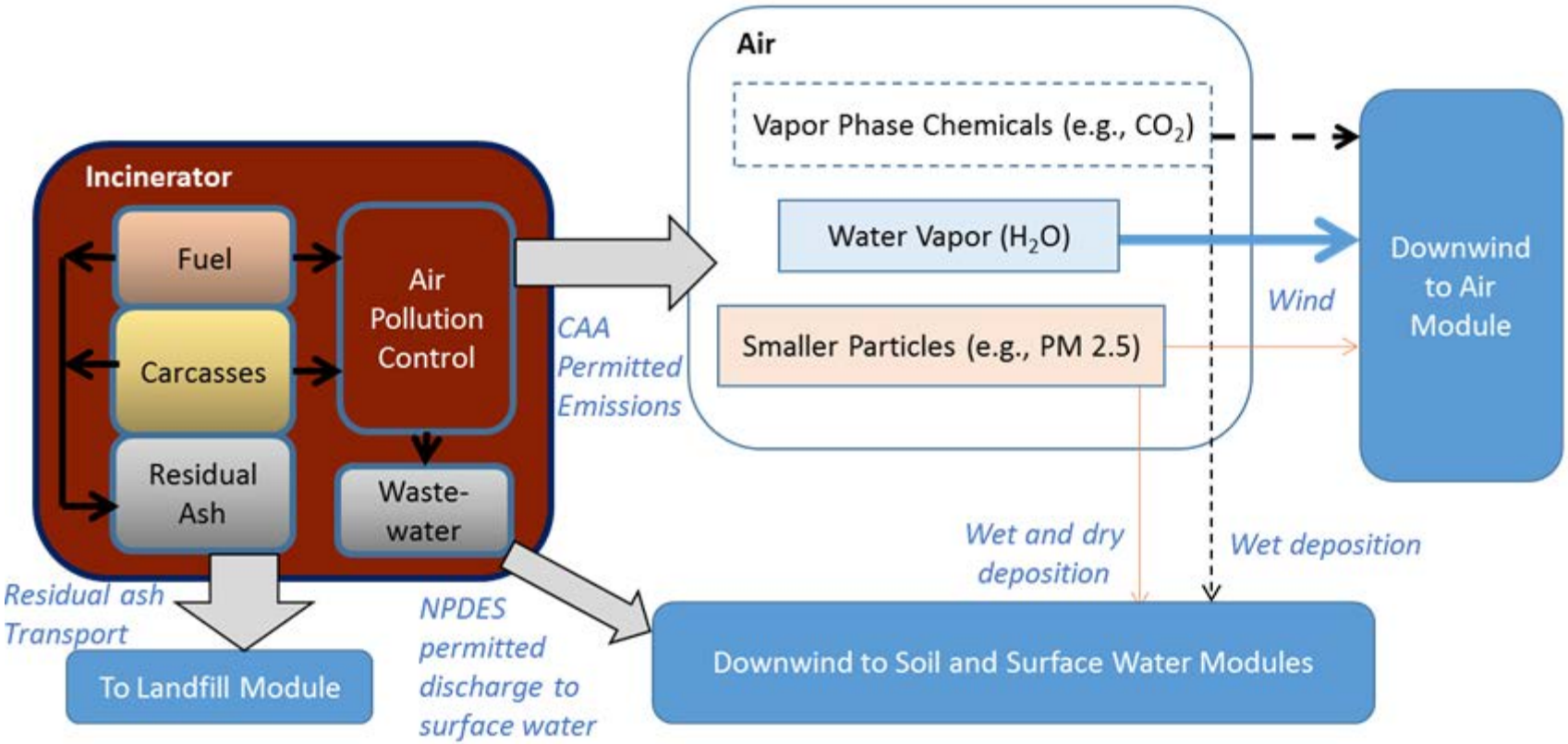


Figure C.13. Combustion-based Management: Fixed-facility Incineration Module

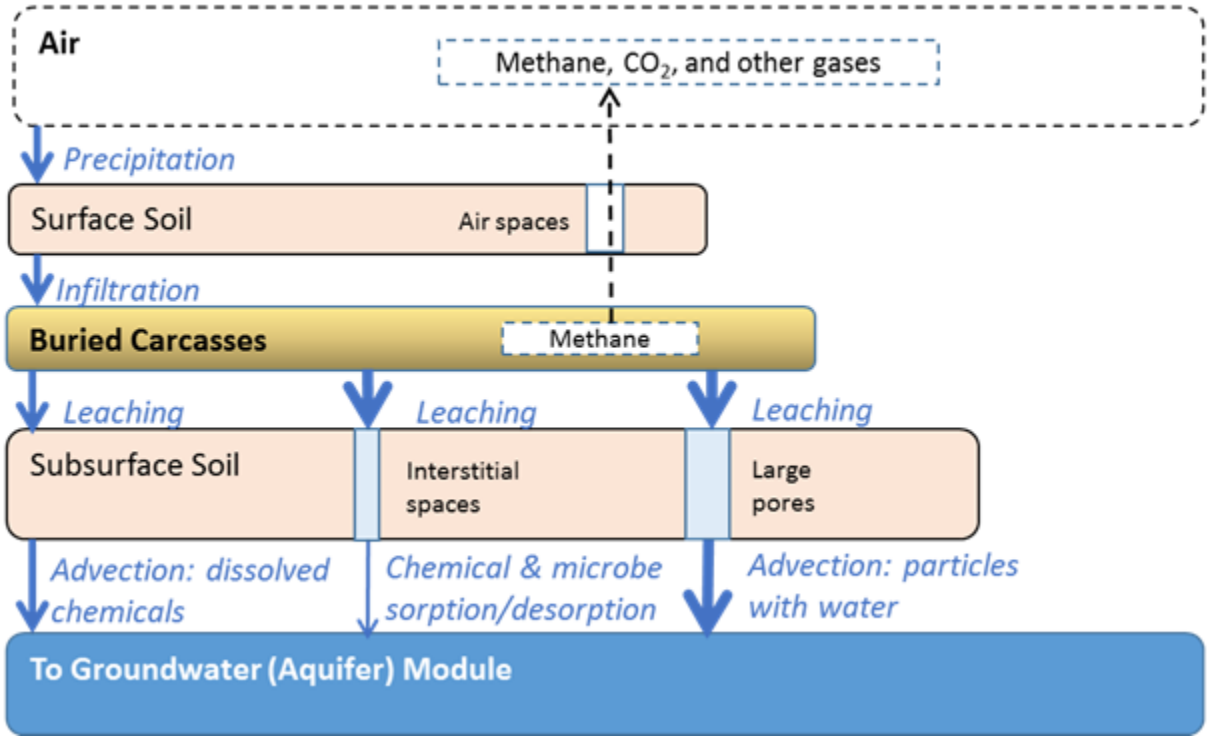


Figure C.14. Land-based Management: On-site Burial Module

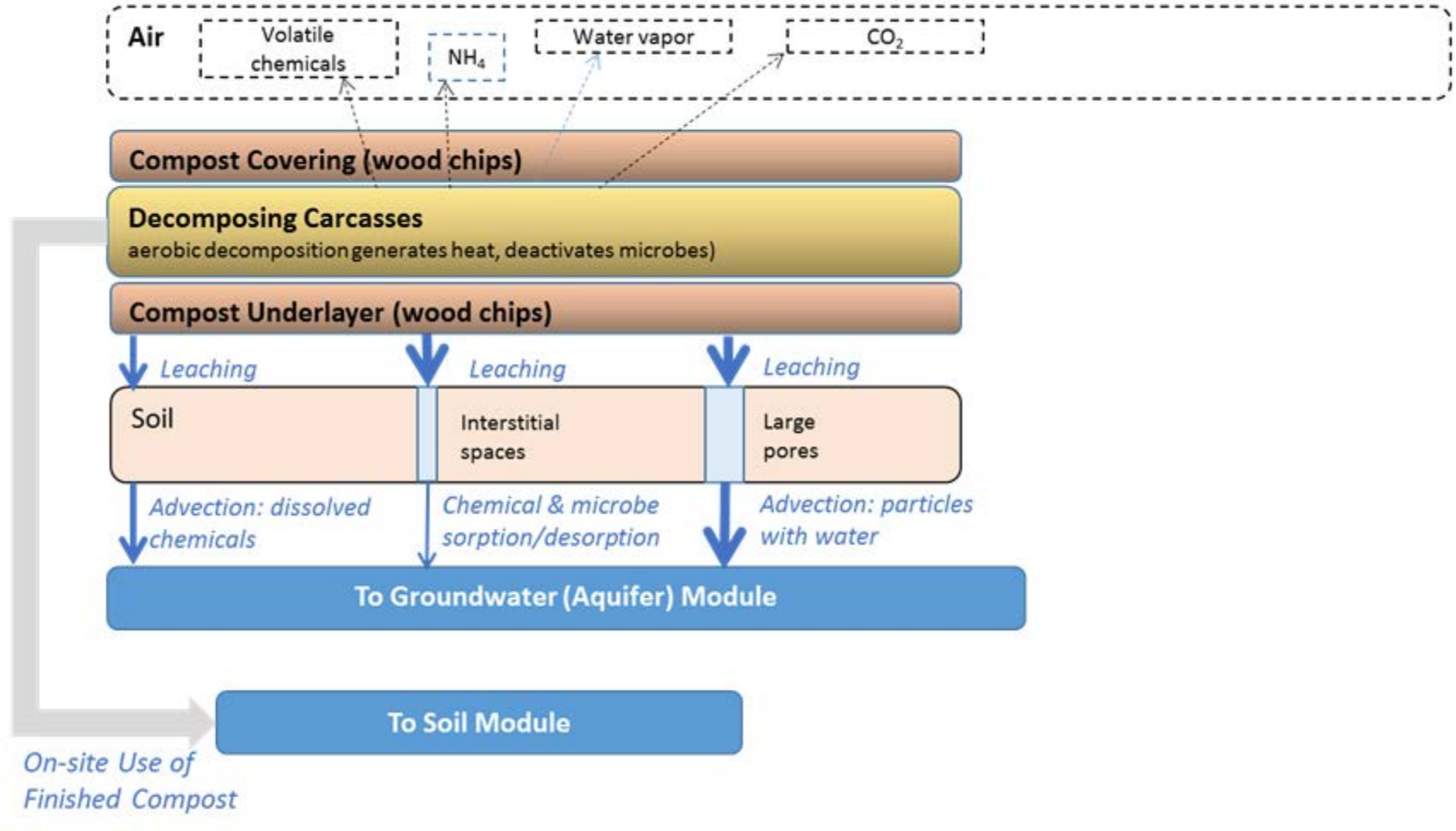


Figure C.15. Land-based Management: Composting Module

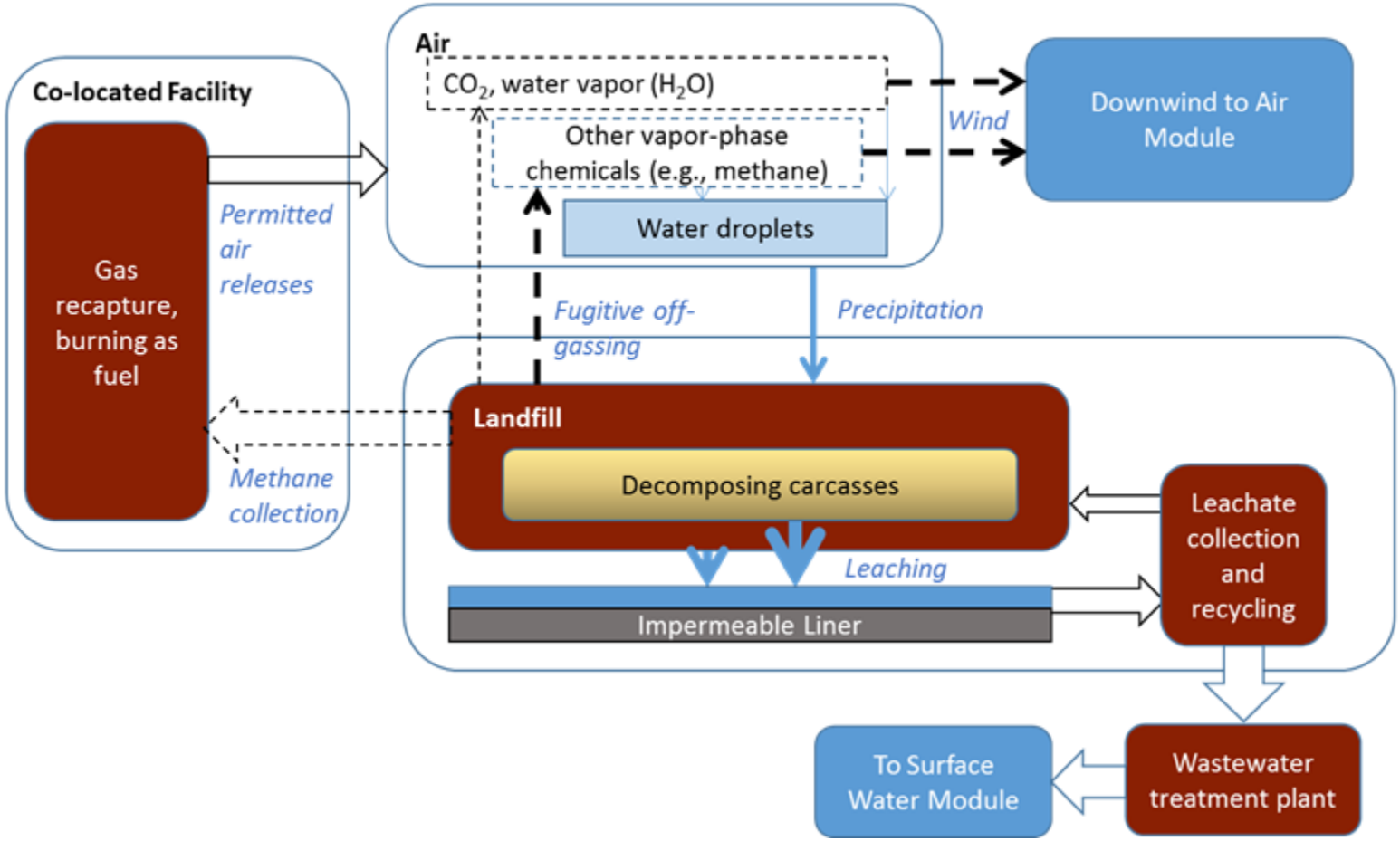
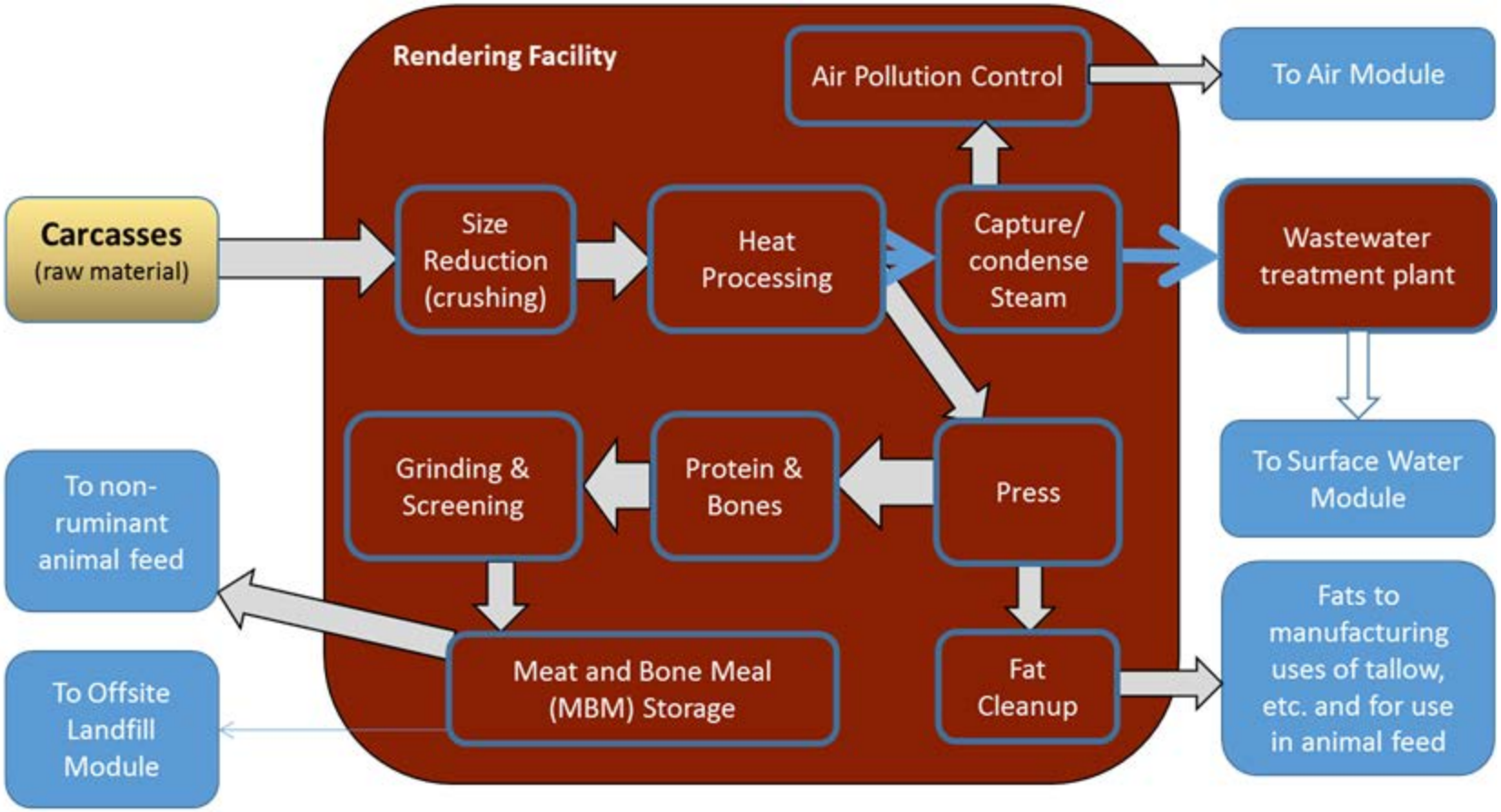


Figure C.16. Land-based Management: Off-site Landfill Module



(a) Adapted from Meeker & Hamilton 2006 and from Bisplinghoff 2006

Figure C.17. Rendering Module[a]

C.3.1. Abiotic Compartment Modules

Livestock Carcass Management Option	Figure
Air	C.18
Soil	C.19
Surface Water and Sediment	C.20
Groundwater	C.21

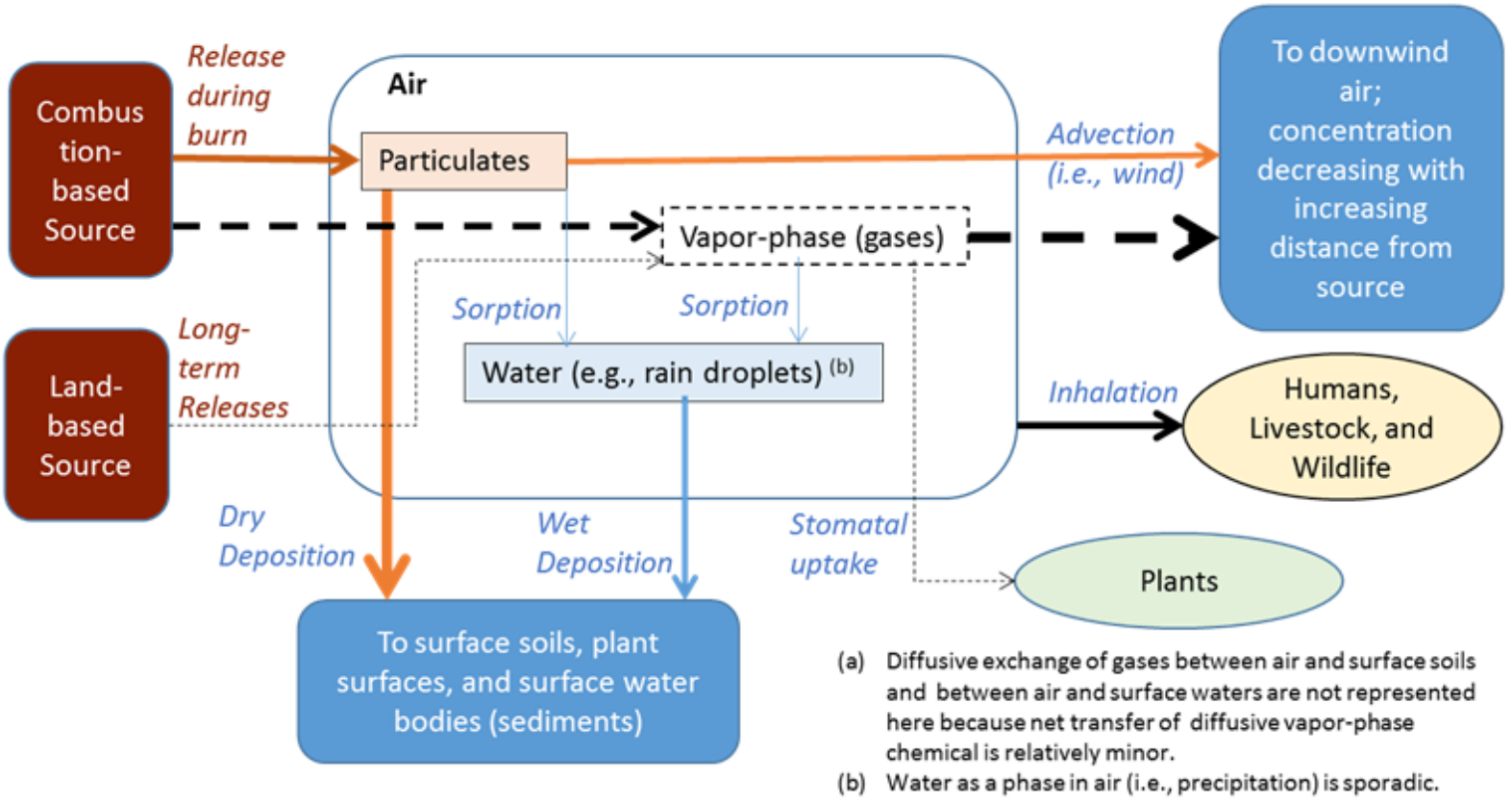


Figure C.18. Air Module[a]

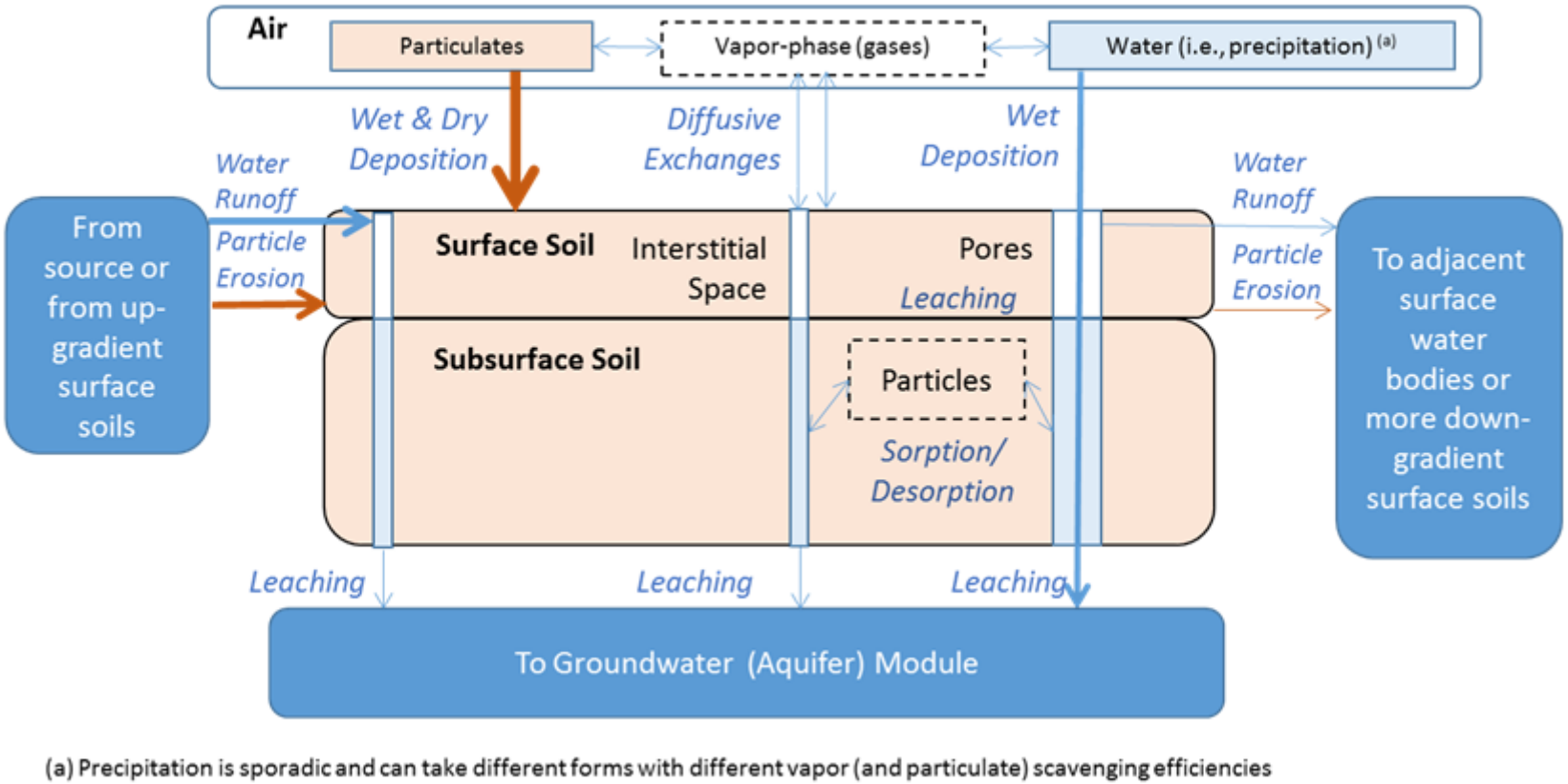


Figure C.19. Soil Module[a]

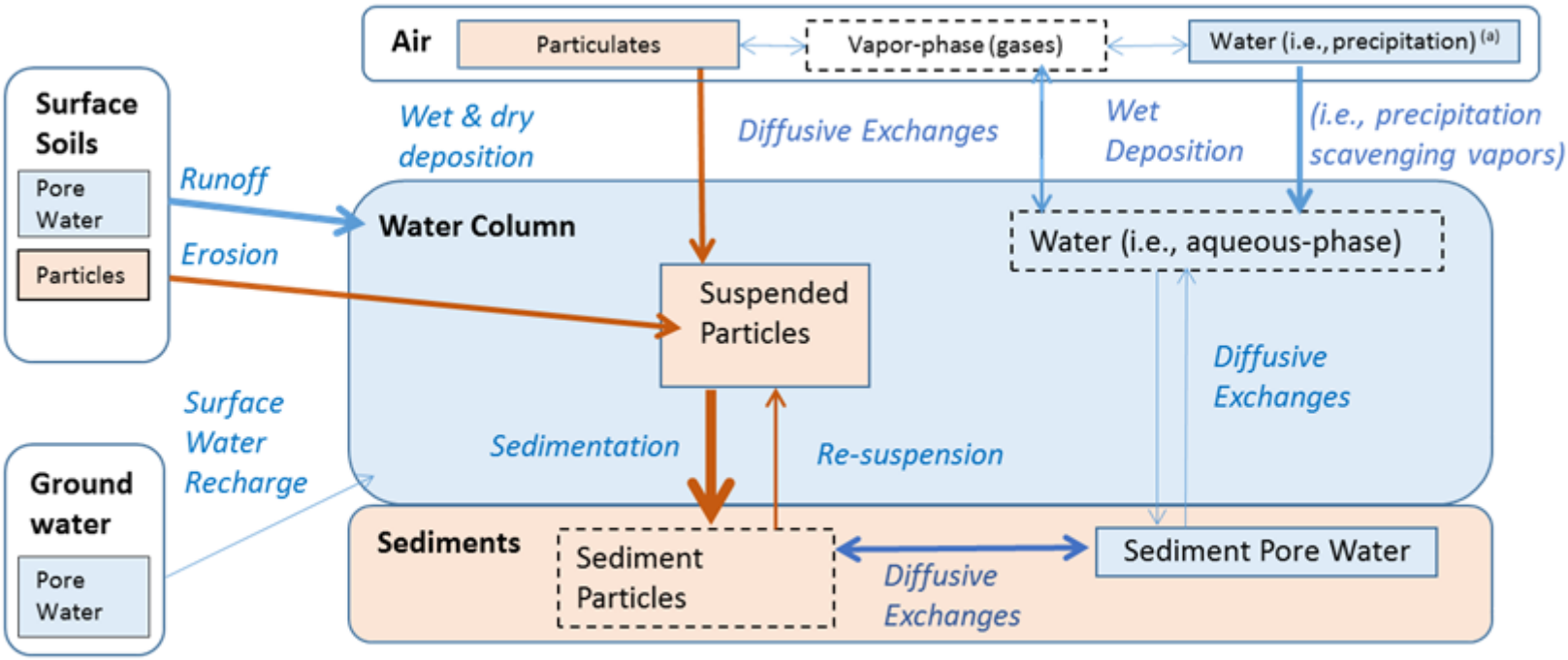


Figure C.20. Surface Water Module[a]

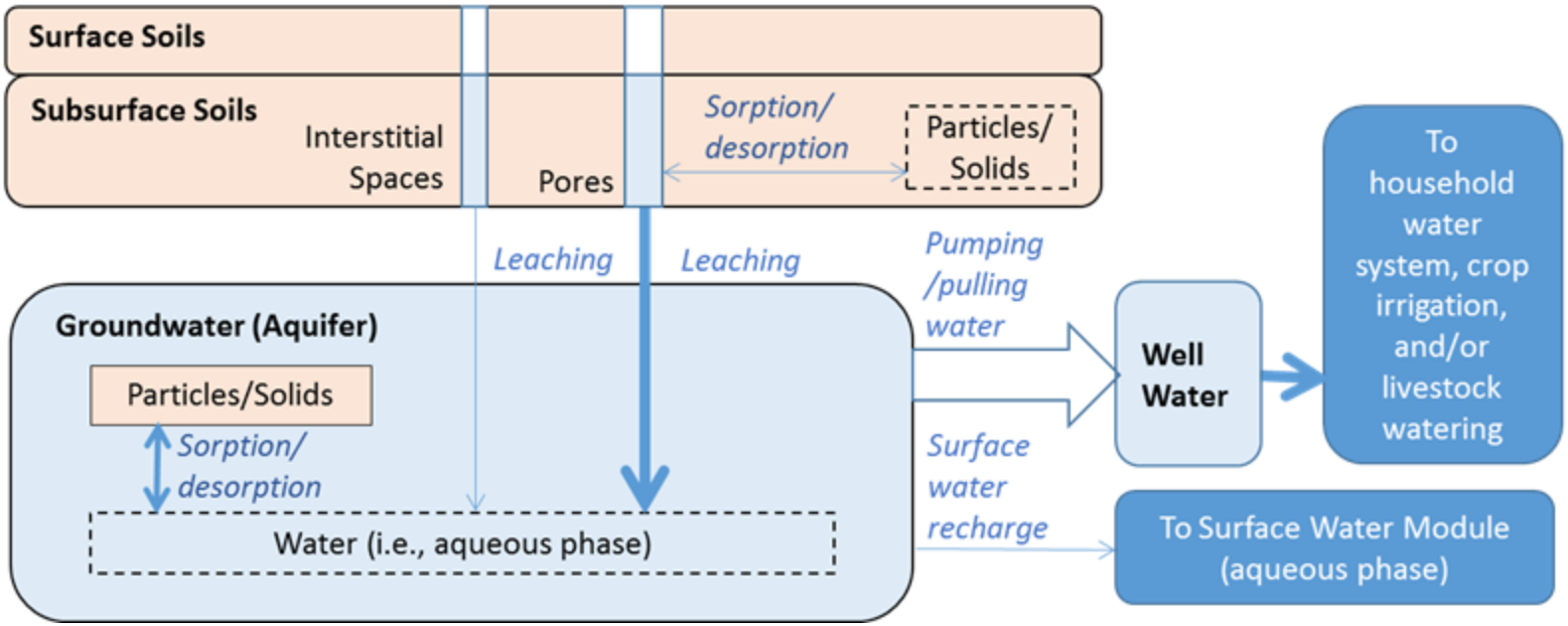


Figure C.21. Groundwater (Aquifer) Module

C.3.2. Biotic Compartment Modules

Livestock Carcass Management Option	Figure
Aquatic Ecosystem	C.22
Terrestrial Plants	C.23
Livestock	C.24
Terrestrial Wildlife	C.24
Human Receptors	C.26

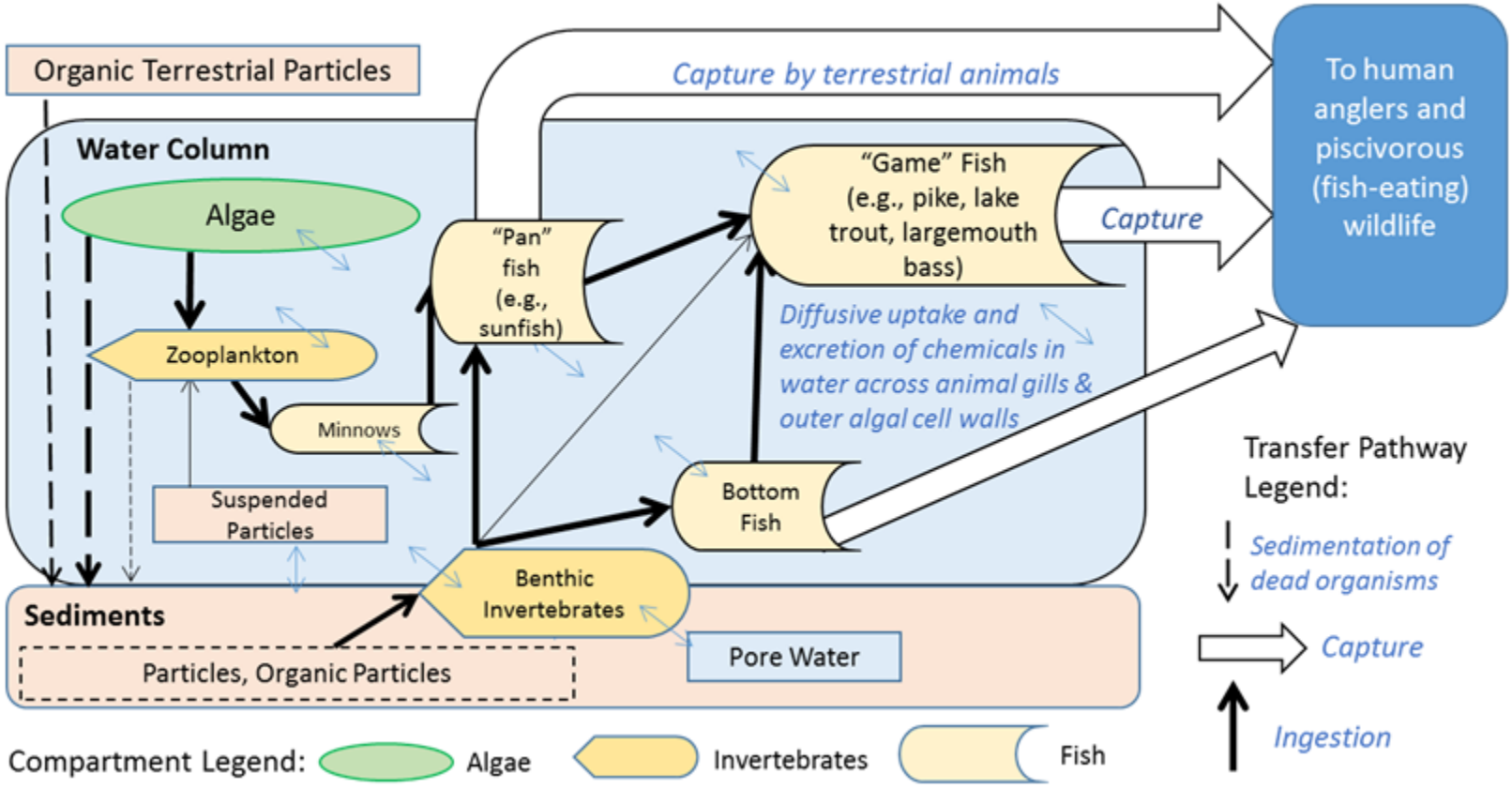


Figure C.22. Aquatic Ecosystem Biotic Module

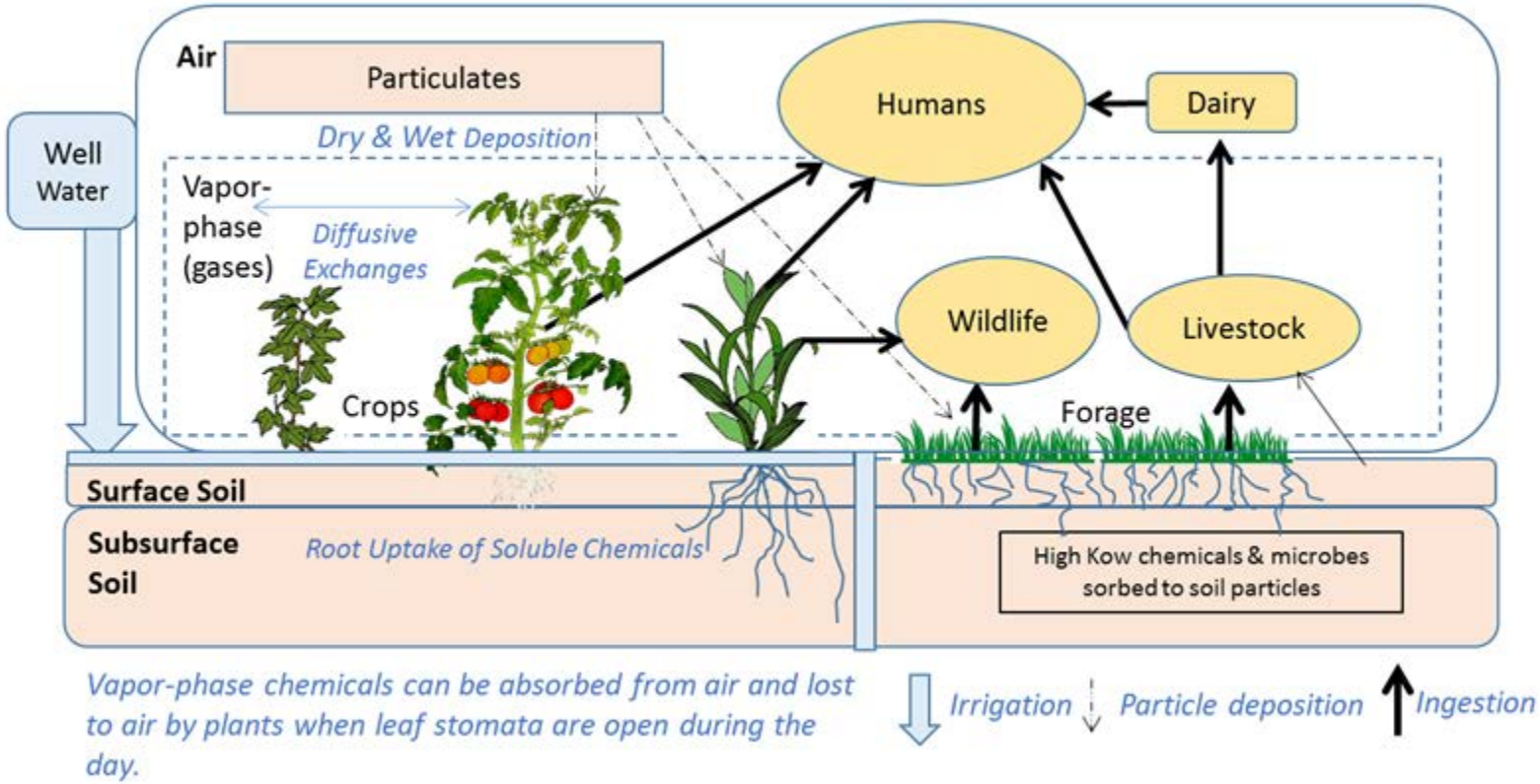


Figure C.23. Terrestrial Plants Module

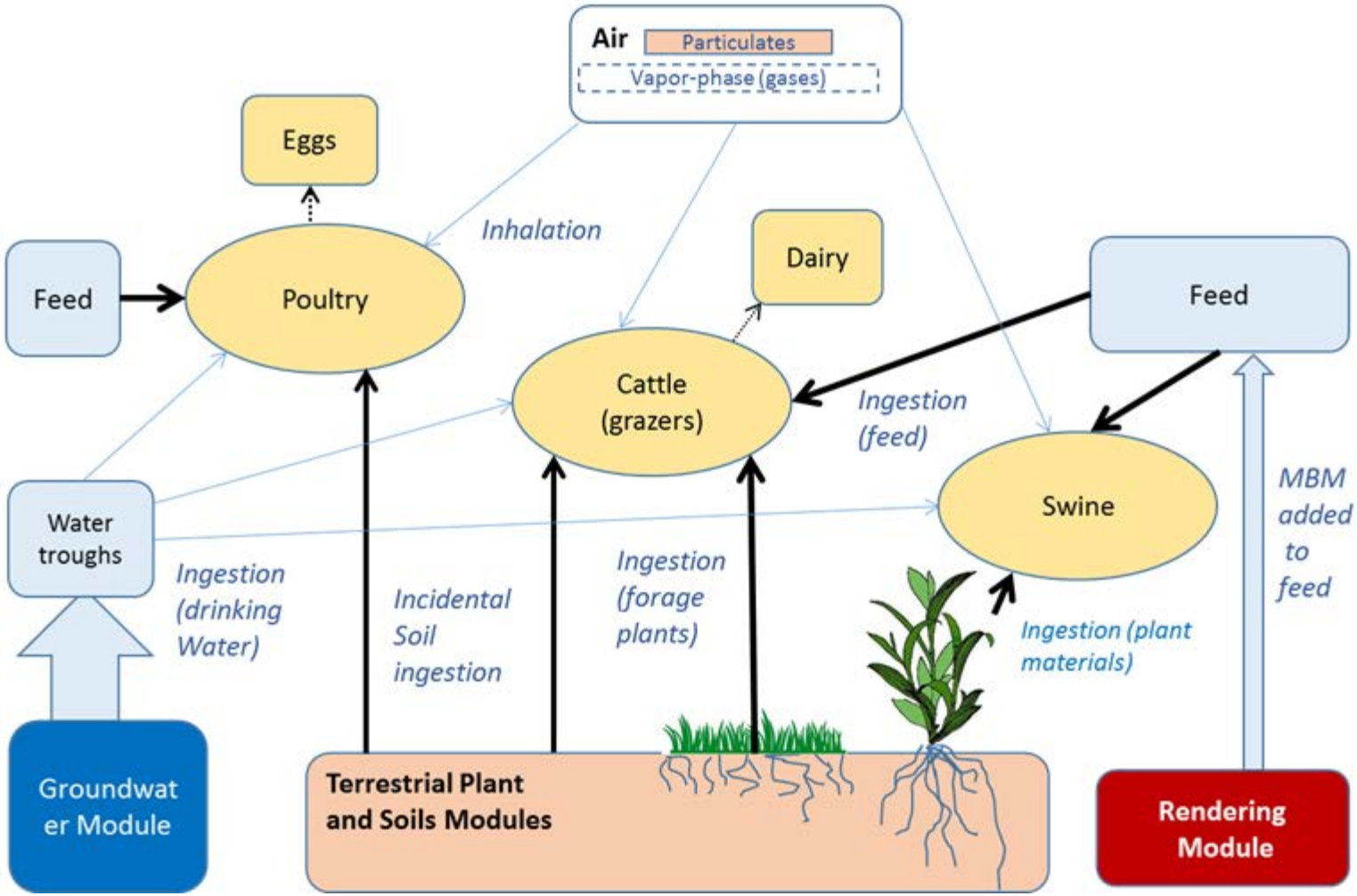


Figure C.24. Livestock Module

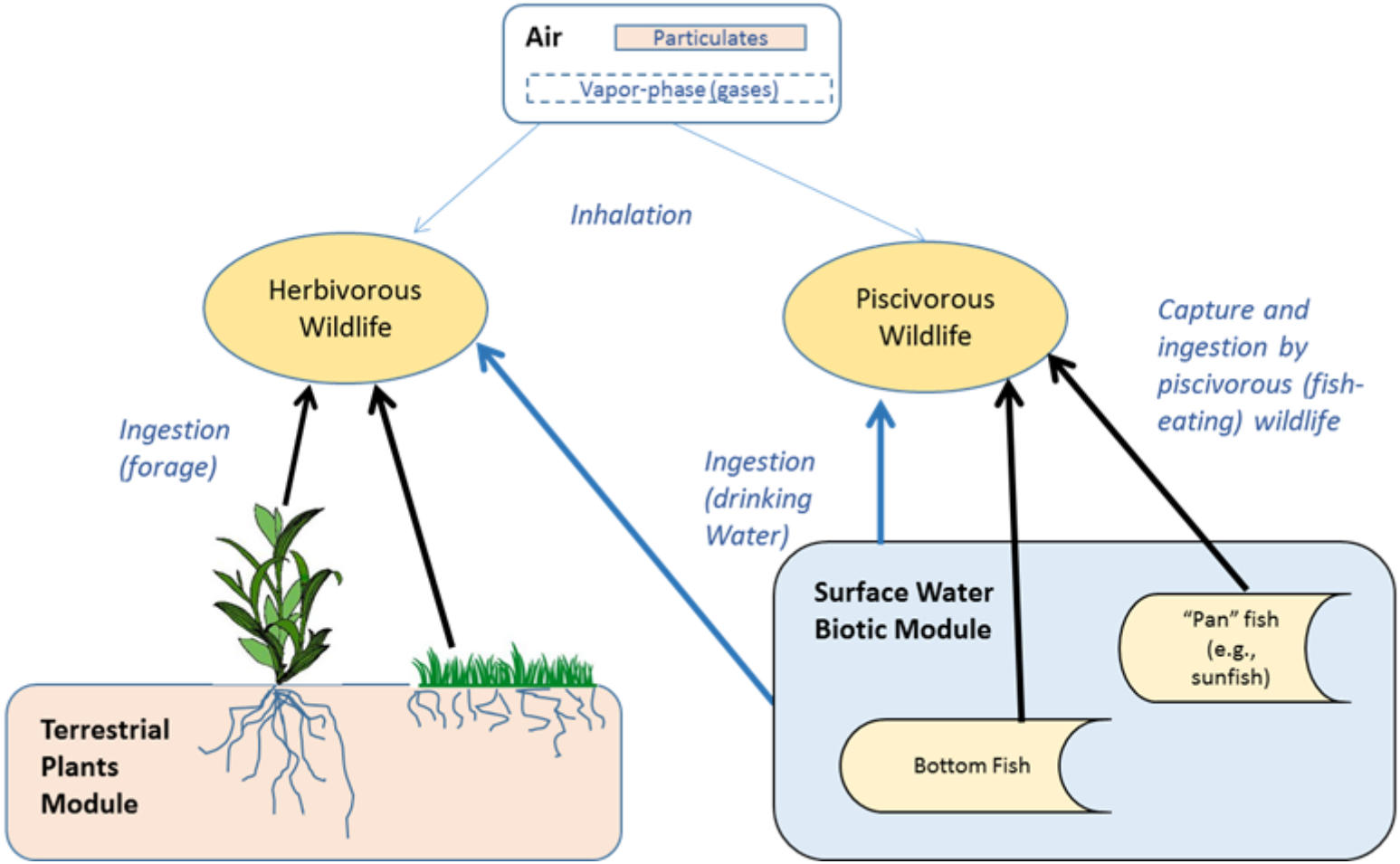


Figure C.25. Terrestrial Wildlife Module

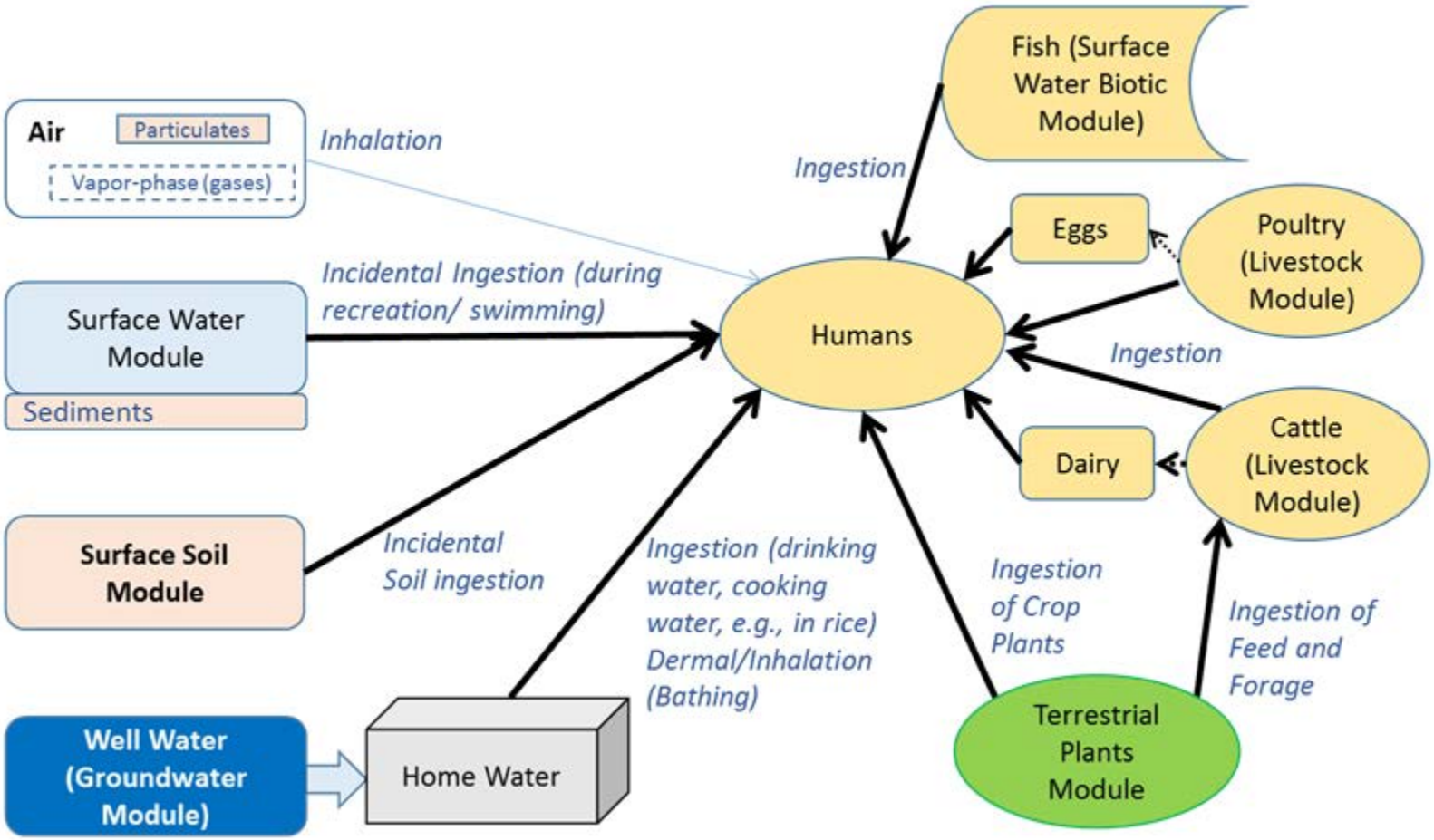


Figure C.26. Human Receptor Module

Appendix D. AERMOD Supporting Information

Section 4.1, Tables 4.1.1–4.1.3, of the main report present information for Iowa used in the AERMOD modeling of chemical dispersion in air and dry and wet deposition rates from open-pyre and air-curtain burning. This appendix presents additional details on how AERMOD works and on chemical-specific information used in the model.

USEPA's AERMINUTE pre-processor (version 14337) processes sub-hourly wind data, which are subsequently processed with the albedo, surface-roughness, and Bowen-ratio (used to estimate latent heat flux) data using AERMET (version 14134). Some missing values for some hours is typical across a year of data; with the 2014 Iowa City data, approximately 2% of hours were missing values for critical parameters such that dispersion modeling would not be possible for those hours.

After running AERMET, the missing values were populated with averages or typical values for 2014 at the station. Values averaged from a small number of surrounding hours were used for missing values of wind speed and direction, temperature, and mixing height; when those surrounding hours were all missing, values averaged from the closest non-missing hours were used for wind speed and direction, and values averaged from the same time of day on surrounding days were used for temperature and mixing height. The substituted values for wind direction were not direct averages of other wind directions; rather, the wind vectors used in the averaging calculation were first broken down into their scalar components, averaged, and then the substitution vector was calculated. Wind speeds that were originally 0 m/s (causing AERMOD to not estimate dispersion during those times) were replaced with 0.28 m/s, a default value suggested in AERMOD's user's guide.

Station-average values (from 2014) for the same month and hour of day were used for missing values of sensible heat flux, surface friction velocity, and convective velocity scale. A similar method was used for missing values of Monin-Obukov length[23], but the averaging was conditional upon the sign of the sensible heat flux (conditionally-average negative values of

[23] "The Monin-Obukhov length compares the ratio of turbulent kinetic energy produced by shear to that produced by buoyancy." Clifton A et al. 2012. Turbine inflow characterization at the National Wind Technology Center. Presented at the 50th AIAA Aerospace Sciences Meeting, Nashville, TN.

Monin-Obukov length when sensible heat flux was positive; and vice-versa). September was the month with the greatest number of hours missing critical meteorology data (66 hr missing), followed by April and January (about 30 hr missing for each).

This appendix includes three tables that describe the AERMOD modeling used in this assessment. Table D.1 summarizes data used to estimate particle deposition rates. Table D.2 summarizes constants used in the modeling. Table D.3 reviews air emission rate modeling concerns.

Table D.1. To estimate particle deposition rates, AERMOD can use either of two different sets of particle information. One set of inputs works for chemicals when the chemical is sorbed to particles of a known size distribution. This set of deposition parameters is used for inorganic chemicals released from coal burning in an open pyre.

The other set of inputs is used when the particle-size distribution is not known, but less than about 10% of the chemical mass is sorbed to particles greater than 10 µm. In this case, there are two parameter values required for each simulated chemical: (1) the fraction of the mass of total particles with sorbed chemical and aerosol particles that are 2.5 µm or less in diameter (i.e., $PM_{2.5}$) and (2) the mass-mean diameters (MMD). We modeled all organics (including the PAH) using this set of deposition parameters. Ranges of particle MMDs and mass fractions are derived from Table 4 of Bond et al. (2002). The modeled chemicals are bound to fly ash; therefore, we identified the range of density values for fly ash from EPRI (2009; 65–100 lbs/ft3 = 1.04–1.76 g/cm^3) and calculated the mean value (1.4 g/cm^3) to use as particle density.

For PAHs released from carcasses in open pyres and from ACB pits, almost all naphthalene (i.e., 99–100%) is released in vapor phase and remains in vapor phase after cooling, hence naphthalene was modeled as 99–100% $PM_{2.5}$, with a MMD of 0.1 µm. For PAHs of higher molecular weights and more rings, the fraction sorbing to larger particles can increase and the MMD increases to 0.2 or 0.3 µm depending on the chemical. For PAHs, Hays et al. (2003) reported a mass mean diameter of 0.3 µm for wood (oak and Douglas fir) with low moisture content (i.e., 13%) and 0.6 µm for the same woods with high moisture content (>24%). We also assume particles are somewhat smaller when released from an air-curtain burner (ACB) unit,

because much of the fly ash is captured under the air curtain and is recirculated and reburned, breaking up the larger particles.

For PAHs, heavy metals, and other chemicals, Lamberg et al. (2011) presented particle size distributions for wood burning in different types of small-scale combustion units. Particles ranged from 0.07–1.0 µm, with peaks around 0.1 to 0.3 in diameter. Particle sizes for wood combustion reported by Kortelainen et al. (2015) peaked around 0.1–0.2 µm for wood chips burned in a 40-kW combustor with a moving grate.

The 0.15-µm MMD for PAH compounds larger than naphthalene emitted to air from the open-pyre burning of hay bales (or straw) are based on Zhang et al. (2011) measurements from burning corn stover and wheat straw and assuming a relatively uniform particle size for burning straw. For naphthalene, however, which would be released in vapor-phase, a diameter of 0.01 µm was assumed for aerosol particles to the extent they might be formed. Note that the fraction of the chemical less than 2.5 µm in diameter includes vapors and condensation of vapors into or onto very small particles, which could be inhaled by animals. Although data for PAH emissions from other types of fuels indicated that up to 12% of the higher molecular weight PAHs might sorb to particles larger than 2.5 µm, Zhang et al. (2011) data for crop straw residue burning indicated that virtually all particles were smaller than 1 µm, and therefore less than 2.5 µm.

Given the difficulty in identifying particle size distributions associated with the different fuels, different burn temperatures, and different chemicals, we ran AERMOD for PAHs in carcasses with mean particle diameters of 0.1 and 1.0 µm. We found negligible effects on the pattern of deposition with distance from the combustion unit. We conclude that air deposition estimates were insensitive to the assigned mean particle size within that range.

Table D.2. Nearly all values for diffusivity and Henry's Law Constant, needed for AERMOD modeling of vapor deposition, were available from EPA's *Human Health Risk Assessment Protocol* (HHRAP) *for Hazardous Waste Combustion Facilities* (USEPA 2005). Values of cuticular resistance, also required for vapor deposition, were available for some chemicals from Wesely et al. (2002). Plant cuticular resistance (CR) indicates the potential for organic vapor-phase chemicals to penetrate the external waxy cuticle of a leaf to the leaf interior at any time of day. Cuticular resistance is proportional to a chemical's octanol-water partitioning coefficient

(Kow). That contrasts with water vapors and other volatile hydrophilic chemicals, which are released only from the stomata (holes in the cuticle and leaf epidermis) on the undersurface of leaves. The stomata also allow absorption of carbon dioxide from the air and release oxygen to the air during daylight hours.

For values of CR for organic chemicals not available from Wesely et al. (2002), a value equal to a chemical with a similar Kow and structure was assumed. For three PAHs, CR values are based on other PAHs with the same number of rings (cyclopenta[c,d]pyrene=BaP; indeno[1,2,3-cd]-pyrene and benzo[b]chrysene = dibenzo[a,h]anthracene). For eight dioxin/furans, we used CR values for other 2,3,7,8-substituted congeners with the same number of chlorine atoms. No CR values are available for metals; hence, we followed Wesely et al. (2002) and used the value of 10^7 s/m for the CR for all modeled metals. For diffusivity values not available from HHRAP documentation (USEPA 2005), values are from Wesely et al. (2002) or estimated based on molecular weight according to equations A3-2a and A3-2b in Volume 2, Appendix A, of HHRAP (USEPA 2005).

For values of Henry's Law Constant (HLC) not available from HHRAP (USEPA 2005), we use values for some chemicals found with the National Institutes of Health (e.g., ToxNet, http://toxnet.nlm.nih.gov/) and the Royal Society of Chemistry (e.g., ChemSpider, http://www.chemspider.com/). For metals, HHRAP recommends an HLC of zero if a measured value was not available from the literature (i.e., assumes that metals are nonvolatile at ambient temperatures and are insoluble in water). However, AERMOD cannot run if the HCL is set to zero. We therefore set the HCL value for chromium, copper, iron, and manganese to the HCL value of 2533 Pascal cubic meters per mole (Pa-m^3/mol) in HHRAP for lead, nickel, and zinc.

Table D.3. To model air dispersion and deposition from land-based combustion methods, AERMOD requires emission rates for vapor-phase and particle phase separately. The measurements should be made post-dilution with ambient air and cooling to ambient air temperatures, which induces condensation of some chemicals to aerosols and particles depending on their boiling points. For chemicals in vapor phase at ambient temperatures, there would be negligible net deposition to soils and surface waters around the source. For the emission rates input to AERMOD in g/s listed in Table D.3, see the emission rate original data and calculations

as described in the main report and in other appendices. Appendix A describes the derivation of PAH air emission factors (EFs in g/s) by congener for carcasses and each fuel type; Appendix B provides the derivation of dioxin/furan EFs by fuel type.

Table D.1. Parameterization of Emitted Particles.

Poll. Group	Pollutant	Pyre Carcass		ACB Carcass		Pyre Coal					Pyre Hay		Pyre Wood		ACB Wood	
		Frac $PM_{2.5}$	Diam (µm)	Frac $PM_{2.5}$	Diam (µm)	Diam (µm)	Mass Frac	Dens (g/cm^3)	Frac $PM_{2.5}$	Diam (µm)	Frac $PM_{2.5}$	Diam (µm)	Frac $PM_{2.5}$	Diam (µm)	Frac $PM_{2.5}$	Diam (µm)
PAH	Naph-thalene	0.99	0.1	0.99	0.1	NM	NM	NM	NM	NM	1	0.01	NM	NM	0.99	0.1
PAH	Acenaph-thylene	0.95	0.2	0.95	0.2	NA	NA	NA	0.95	0.2	1	0.15	0.99	0.3	0.95	0.2
PAH	Phenan-threne	0.95	0.2	0.95	0.2	NA	NA	NA	0.95	0.2	0.99	0.15	0.99	0.3	0.95	0.2
PAH	Fluorene	0.95	0.2	0.95	0.2	NA	NA	NA	0.95	0.2	0.99	0.15	0.99	0.3	0.95	0.2
PAH	Acenaph-thene	0.95	0.2	0.95	0.2	NA	NA	NA	0.95	0.2	0.99	0.15	0.99	0.3	NM	NM
PAH	Anthracene	0.95	0.2	0.95	0.2	NA	NA	NA	0.95	0.2	0.99	0.15	0.99	0.3	0.95	0.2
PAH	Pyrene	0.93	0.3	0.93	0.3	NA	NA	NA	0.93	0.3	0.99	0.15	0.99	0.3	0.93	0.3
PAH	Chrysene	0.93	0.3	0.93	0.3	NA	NA	NA	0.93	0.3	0.99	0.15	0.99	0.3	0.93	0.3
PAH	Fluoran-thene	0.93	0.3	0.93	0.3	NA	NA	NA	0.93	0.3	0.99	0.15	0.99	0.3	0.93	0.3
PAH	Benzo[a]-anthracene	0.93	0.3	0.93	0.3	NA	NA	NA	0.93	0.3	0.99	0.15	0.99	0.3	0.93	0.3
PAH	Benzo[a]-pyrene	0.9	0.3	0.90	0.3	NA	NA	NA	0.90	0.3	0.99	0.15	0.99	0.3	0.90	0.3
PAH	Benzo[e]-pyrene	0.9	0.3	0.90	0.3	NA	NA	NA	0.90	0.3	0.99	0.15	0.99	0.3	0.90	0.3
PAH	Benzo[b]-fluoran-thene	0.9	0.3	0.90	0.3	NA	NA	NA	0.90	0.3	0.99	0.15	0.99	0.3	0.90	0.3
PAH	Benzo[k]-fluoran-thene	0.9	0.3	0.90	0.3	NA	NA	NA	0.90	0.3	0.99	0.15	0.99	0.3	0.90	0.3
PAH	Cyclo-penta[c,d]-pyrene	0.9	0.3	0.90	0.3	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM
PAH	Perylene	0.9	0.3	0.90	0.3	NM	NM	NM	NM	NM	0.99	0.15	0.99	0.3	0.90	0.3
PAH	Dibenz[a,h] anthracene	0.88	0.2	0.88	0.2	NA	NA	NA	0.88	0.4	0.99	0.15	0.99	0.3	0.88	0.3

Poll. Group	Pollutant	Pyre Carcass		ACB Carcass		Pyre Coal					Pyre Hay		Pyre Wood		ACB Wood	
		Frac $PM_{2.5}$	Diam (µm)	Frac $PM_{2.5}$	Diam (µm)	Diam (µm)	Mass Frac	Dens (g/cm^3)	Frac $PM_{2.5}$	Diam (µm)	Frac $PM_{2.5}$	Diam (µm)	Frac $PM_{2.5}$	Diam (µm)	Frac $PM_{2.5}$	Diam (µm)
PAH	Indeno-[1,2,3-c,d]-pyrene	0.88	0.2	0.88	0.2	NA	NA	NA	0.88	0.4	0.99	0.15	0.99	0.3	0.88	0.3
PAH	Benzo[g,h,i]-perylene	0.88	0.2	0.88	0.2	NA	NA	NA	0.88	0.4	0.99	0.15	0.99	0.3	0.88	0.3
PAH	Benzo[b]-chrysene	0.88	0.2	0.88	0.2	NM	NM	NM	NM	NM	NM	NM	0.99	0.3	NM	NM
PAH	Coronene	0.88	0.2	0.88	0.2	NA	NA	NA	0.88	0.4	NM	NM	0.99	0.3	0.88	0.3
Dioxin	HeptaCDD, 1,2,3,4,6,7,8	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM	0.99	0.2	0.99	0.2
Dioxin	HeptaCDF, 1,2,3,4,6,7,8	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM	0.99	0.2	0.99	0.2
Dioxin	HeptaCDF, 1,2,3,4,7,8,9	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM	0.99	0.2	0.99	0.2
Dioxin	HexaCDD, 1,2,3,4,7,8-	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM	0.99	0.2	0.99	0.2
Dioxin	HexaCDD, 1,2,3,6,7,8-	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM	0.99	0.2	0.99	0.2
Dioxin	HexaCDD, 1,2,3,7,8,9 -	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM	0.99	0.2	0.99	0.2
Dioxin	HexaCDF, 1,2,3,4,7,8-	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM	0.99	0.2	0.99	0.2
Dioxin	HexaCDF, 1,2,3,6,7,8-	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM	0.99	0.2	0.99	0.2
Dioxin	HexaCDF, 1,2,3,7,8,9-	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM	0.99	0.2	0.99	0.2
Dioxin	HexaCDF, 2,3,4,6,7,8-	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM	0.99	0.2	0.99	0.2
Dioxin	OctaCDD, 1,2,3,4,6,7,8,9-	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM	0.99	0.2	0.99	0.1

Poll. Group	Pollutant	Pyre Carcass		ACB Carcass		Pyre Coal					Pyre Hay		Pyre Wood		ACB Wood	
		Frac $PM_{2.5}$	Diam (µm)	Frac $PM_{2.5}$	Diam (µm)	Diam (µm)	Mass Frac	Dens (g/cm^3)	Frac $PM_{2.5}$	Diam (µm)	Frac $PM_{2.5}$	Diam (µm)	Frac $PM_{2.5}$	Diam (µm)	Frac $PM_{2.5}$	Diam (µm)
Dioxin	OctaCDF, 1,2,3,4,6,7, 8,9-	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM	0.99	0.2	0.99	0.2
Dioxin	PentaCDD, 1,2,3,7,8-	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM	0.99	0.2	0.99	0.2
Dioxin	PentaCDF, 1,2,3,7,8-	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM	0.99	0.2	0.99	0.2
Dioxin	PentaCDF, 2,3,4,7,8-	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM	0.99	0.2	0.99	0.2
Dioxin	TetraCDD, 2,3,7,8-	NM	NM	NM	NM	NM	NM	NM	NM	NM	0.99	0.15	0.99	0.2	0.99	0.2
Dioxin	TetraCDF, 2,3,7,8-	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM	0.99	0.2	0.99	0.2
Metal	Arsenic	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM	0.99	0.3	0.99	0.2
Metal	Cadmium	0.7	0.6	0.99	0.2	NM	NM	NM	NM	NM	NM	NM	0.99	0.3	0.99	0.2
Metal	Chromium	0.55	1.2	0.99	0.2	0.1 0.375 0.75 1.75 6.25 25	0.54 0.27 0.07 0.08 0.02 0.02	1.4 1.4 1.4 1.4 1.4 1.4	NA	NA	NM	NM	0.99	0.3	0.99	0.2
Metal	Copper	0.7	1.0	0.99	0.2	0.1 0.375 0.75 1.75 6.25 25	0.54 0.27 0.07 0.08 0.02 0.02	1.4 1.4 1.4 1.4 1.4 1.4	NA	NA	NM	NM	0.99	0.3	0.99	0.2
Metal	Iron	0.7	1.0	0.99	0.2	0.1 0.375 0.75 1.75 6.25 25	0.54 0.27 0.07 0.08 0.02 0.02	1.4 1.4 1.4 1.4 1.4 1.4	NA	NA	NM	NM	0.99	0.3	0.99	0.2

Poll. Group	Pollutant	Pyre Carcass		ACB Carcass		Pyre Coal					Pyre Hay		Pyre Wood		ACB Wood	
		Frac $PM_{2.5}$	Diam (µm)	Frac $PM_{2.5}$	Diam (µm)	Diam (µm)	Mass Frac	Dens (g/cm^3)	Frac $PM_{2.5}$	Diam (µm)	Frac $PM_{2.5}$	Diam (µm)	Frac $PM_{2.5}$	Diam (µm)	Frac $PM_{2.5}$	Diam (µm)
Metal	Lead	0.75	0.5	0.99	0.2	0.1 0.375 0.75 1.75 6.25 25	0.54 0.27 0.07 0.08 0.02 0.02	1.4 1.4 1.4 1.4 1.4 1.4	NA	NA	NM	NM	0.99	0.3	0.99	0.2
Metal	Manganese	0.45	1.8	0.99	0.2	0.1 0.375 0.75 1.75 6.25 25	0.54 0.27 0.07 0.08 0.02 0.02	1.4 1.4 1.4 1.4 1.4 1.4	NA	NA	NM	NM	0.99	0.3	0.99	0.2
Metal	Nickel	0.6	1.0	0.99	0.2	0.1 0.375 0.75 1.75 6.25 25	0.54 0.27 0.07 0.08 0.02 0.02	1.4 1.4 1.4 1.4 1.4 1.4	NA	NA	NM	NM	0.99	0.3	0.99	0.2
Metal	Zinc	0.8	0.4	0.99	0.2	0.1 0.375 0.75 1.75 6.25 25	0.54 0.27 0.07 0.08 0.02 0.02	1.4 1.4 1.4 1.4 1.4 1.4	NA	NA	NM	NM	0.99	0.3	0.99	0.2

Abbreviations: Dens = particle densities (g/cm^3) corresponding to the particulate diameter classes in the "Diam" column; Diam = mass-mean particulate diameter (µm); Frac $PM_{2.5}$ = mass fraction of particles 2.5 µm in diameter or less; Mass Frac = particle mass fractions corresponding to the particulate diameter classes in the "Diam" column; NA = this particulate size scheme not used; NM = this pollutant not modeled for this combusted material from this management option; PAH = polyaromatic hydrocarbon; ACB = air-curtain burner

Note: Pyre-Wood includes kindling. Pyre-Hay is for hay bales or straw.

Table D.2. Parameterization of Emitted Vapor-phase Pollutants.

Pollutant Group	Pollutant	Diffusivity in Air (cm^2/s)	Diffusivity in Water (cm^2/s)	Cuticular Resistance to Uptake by Lipids for Individual Leaves (s/cm)	Henry's Law Constant (Pa m^3/mol)
PAH	Naphthalene	5.90E-02	7.50E-06	3.65E+02	4.86E+01
PAH	Acenaphthylene	6.65E-02	7.07E-01	3.59E+01	1.27E+01
PAH	Phenanthrene	1.00E-03	1.00E-05	2.33E+01	2.33E+00
PAH	Fluorene	1.00E-03	1.00E-05	9.56E+01	6.48E+00
PAH	Acenaphthene	1.00E-03	1.00E-05	1.17E+02	1.62E+01
PAH	Anthracene	1.00E-03	1.00E-05	3.10E+01	6.59E+00
PAH	Pyrene	1.00E-03	1.00E-05	3.88E+00	1.11E+00
PAH	Chrysene	1.00E-03	1.00E-05	4.43E-01	9.63E+00
PAH	Fluoranthene	1.00E-03	1.00E-05	5.01E+00	1.62E+00
PAH	Benzo[a]anthracene	5.10E-02	9.00E-06	3.55E+00	3.45E-01
PAH	Benzo[a]pyrene	4.30E-02	9.00E-06	4.41E-01	1.11E-01
PAH	Benzo[e]pyrene	5.13E-02	4.44E-01	8.55E-02	2.00E-02
PAH	Benzo[b]fluoranthene	1.00E-03	1.00E-05	1.33E+02	1.12E+01
PAH	Benzo[k]fluoranthene	1.00E-03	1.00E-05	1.95E-01	8.41E-02
PAH	Cyclopenta[c,d]pyrene	5.12E-02	5.92E-06	4.41E-01	4.12E-01
PAH	Perylene	5.13E-02	4.44E-01	1.86E-02	3.04E+02
PAH	Dibenz[a,h]anthracene	1.00E-03	1.00E-05	2.09E-03	1.52E-03
PAH	Indeno[1,2,3-c,d]pyrene	1.00E-03	1.00E-05	2.09E-03	1.62E-01
PAH	Benzo[g,h,i]perylene	5.05E-02	4.16E-01	5.62E-01	2.78E-02
PAH	Benzo[b]chrysene	4.46E-02	5.16E-06	2.09E-03	4.95E-02
PAH	Coronene	4.85E-02	3.89E-01	3.82E-03	4.35E+01
Dioxin	HeptaCDD, 1,2,3,4,6,7,8-	9.05E-02	8.00E-06	5.97E-01	1.22E+00
Dioxin	HeptaCDF, 1,2,3,4,6,7,8-	2.03E-02	8.00E-06	1.27E+01	1.43E+00
Dioxin	HeptaCDF, 1,2,3,4,7,8,9-	2.03E-02	8.00E-06	1.27E+01	1.42E+00
Dioxin	HexaCDD, 1,2,3,4,7,8-	9.44E-02	8.00E-06	1.20E+00	1.08E+00
Dioxin	HexaCDD, 1,2,3,6,7,8-	9.44E-02	8.00E-06	1.20E+00	1.11E+00
Dioxin	HexaCDD, 1,2,3,7,8,9 -	9.44E-02	8.00E-06	1.20E+00	1.11E+00

Table D.2. Parameterization of Emitted Vapor-phase Pollutants.

Pollutant Group	Pollutant	Diffusivity in Air (cm^2/s)	Diffusivity in Water (cm^2/s)	Cuticular Resistance to Uptake by Lipids for Individual Leaves (s/cm)	Henry's Law Constant (Pa m^3/mol)
Dioxin	HexaCDF, 1,2,3,4,7,8-	2.12E-02	8.00E-06	1.11E+01	1.45E+00
Dioxin	HexaCDF, 1,2,3,6,7,8-	2.12E-02	8.00E-06	1.11E+01	7.41E-01
Dioxin	HexaCDF, 1,2,3,7,8,9-	2.12E-02	8.00E-06	1.11E+01	1.11E+00
Dioxin	HexaCDF, 2,3,4,6,7,8-	2.12E-02	8.00E-06	1.11E+01	1.11E+00
Dioxin	OctaCDD, 1,2,3,4,6,7,8,9-	8.69E-02	8.00E-06	4.94E+00	6.84E-01
Dioxin	OctaCDF, 1,2,3,4,6,7,8,9-	1.95E-02	8.00E-06	1.42E+00	1.90E-01
Dioxin	PentaCDD, 1,2,3,7,8-	9.88E-02	8.00E-06	5.47E-01	2.63E-01
Dioxin	PentaCDF, 1,2,3,7,8-	2.23E-02	8.00E-06	3.99E+00	5.07E-01
Dioxin	PentaCDF, 2,3,4,7,8-	2.23E-02	8.00E-06	3.99E+00	5.05E-01
Dioxin	TetraCDD, 2,3,7,8-	1.04E-01	5.60E-06	7.84E+00	3.33E+00
Dioxin	TetraCDF, 2,3,7,8-	2.35E-02	6.01E-06	9.67E+00	1.46E+00

Abbreviations: mol = moles; s = seconds.

Table D.3. Modeled Emission Rates (g/s) for Vapor-phase and Particle-phase Pollutants.

Pollutant	Pyre Carcass		ACB Carcass		Pyre Coal		Pyre Hay Bales		Pyre Wood/Kindling		ACB Wood	
	V	P	V	P	V	P	V	P	V[a]	P	V[a]	Total
PAHs												
Naph-thalene	3.49E-02	9.90E-04	4.46E-04	4.60E-05	NM	NM	2.49E-03	2.51E-5	NM	NM	0	5.61E-05
Acenaph-thylene	3.42E-03	4.28E-05	6.33E-05	1.44E-06	1.96E-08	7.87E-11	1.17E-04	1.08E-5	0	1.21E-06	0	2.28E-05
Phenan-threne	4.31E-03	2.17E-03	7.19E-05	2.88E-06	2.15E-06	1.68E-09	9.25E-05	1.21E-4	0	5.52E-05	0	1.63E-05
Fluorene	2.05E-03	1.13E-04	1.58E-05	2.88E-06	1.21E-07	1.81E-09	1.92E-05	1.12E-5	0	2.90E-06	0	1.87E-07
Acenaph-thene	7.98E-04	9.69E-05	5.75E-06	2.88E-06	1.40E-08	ND	4.77E-05	4.30E-5	0	4.11E-08	NM	NM
Anthracene	1.06E-03	5.45E-04	1.44E-06	7.19E-07	5.33E-08	5.25E-11	1.72E-05	2.21E-5	0	1.98E-06	0	1.54E-06
Pyrene	1.52E-03	7.35E-03	1.44E-05	2.88E-06	1.14E-07	1.97E-09	1.04E-05	5.19E-5	0	8.66E-06	0	1.14E-05
Chrysene	1.95E-04	3.85E-04	5.75E-06	1.44E-06	3.78E-08	1.83E-08	6.89E-06	2.12E-5	0	1.80E-05	0	8.13E-07
Fluoran-thene	1.51E-03	5.84E-03	1.58E-05	2.88E-06	2.16E-07	1.05E-10	1.11E-05	5.38E-5	0	9.25E-06	0	9.76E-06
Benzo[a]-anthracene	1.93E-04	4.92E-04	2.16E-06	4.31E-07	3.78E-09	1.92E-09	6.63E-06	1.74E-5	0	1.93E-05	0	6.67E-07
Benzo[a]-pyrene	2.30E-04	1.05E-04	1.44E-06	7.19E-07	ND	4.49E-09	2.69E-05	6.72E-5	0	3.02E-05	0	1.22E-06
Benzo[e]-pyrene	3.40E-04	4.52E-04	2.16E-06	7.19E-07	3.81E-09	4.49E-08	ND	1.13E-4	0	1.90E-05	0	4.92E-07
Benzo[b]-fluoran-thene	1.88E-04	2.15E-04	2.88E-06	7.19E-07	4.67E-09	2.68E-08	ND	7.25E-5	0	1.68E-05	0	9.76E-07
Benzo[k]-fluoran-thene	1.88E-04	2.15E-04	2.88E-06	7.19E-07	4.67E-09	2.68E-08	7.95E-06	2.70E-5	0	1.68E-05	0	7.81E-07
Cyclo-penta[c,d]-pyrene	5.54E-05	7.30E-05	5.03E-06	1.44E-07	NM	NM	NA	NA	NM	NM	NM	NM

Pollutant	Pyre Carcass		ACB Carcass		Pyre Coal		Pyre Hay Bales		Pyre Wood/Kindling		ACB Wood	
	V	P	V	P	V	P	V	P	V[a]	P	V[a]	Total
Perylene	1.06E-04	7.43E-05	4.31E-06	1.44E-06	NM	NM	ND	2.40E-5	0	4.39E-06	0	1.71E-06
Dibenz[a,h] anthracene	3.71E-04	2.48E-04	1.44E-06	7.19E-07	ND	1.55E-08	ND	1.01E-5	0	1.51E-06	0	8.94E-07
Indeno-[1,2,3-c,d]-pyrene	1.27E-03	1.02E-03	2.88E-06	7.19E-07	ND	2.18E-08	ND	9.54E-5	0	1.65E-05	0	2.60E-06
Benzo[g,h,i] -perylene	3.70E-04	4.37E-04	2.88E-06	1.44E-06	ND	2.88E-08	8.83E-06	1.01E-5	0	8.44E-06	0	6.75E-08
Benzo[b]-chrysene	2.24E-04	9.69E-05	5.75E-06	1.44E-06	NM	NM	NA	NM	0	1.05E-06	NM	NM
Coronene	3.51E-04	2.17E-04	4.31E-06	1.44E-06	ND	2.94E-08	NA	NM	0	3.73E-06	0	1.64E-06
Dioxins												
HeptaCDD, 1,2,3,4,6,7,8 -	NM	NM	NM	NM	NM	NM	NM	NM	2.27E-12	1.19E-11	1.49E-10	7.83E-10
HeptaCDF, 1,2,3,4,6,7,8 -	NM	NM	NM	NM	NM	NM	NM	NM	4.82E-13	2.53E-12	2.12E-10	1.11E-09
HeptaCDF, 1,2,3,4,7,8,9 -	NM	NM	NM	NM	NM	NM	NM	NM	9.93E-14	5.21E-13	2.27E-11	1.19E-10
HexaCDD, 1,2,3,4,7,8-	NM	NM	NM	NM	NM	NM	NM	NM	6.12E-13	1.04E-12	7.12E-11	1.21E-10
HexaCDD, 1,2,3,6,7,8-	NM	NM	NM	NM	NM	NM	NM	NM	7.00E-13	1.19E-12	8.52E-11	1.45E-10
HexaCDD, 1,2,3,7,8,9 -	NM	NM	NM	NM	NM	NM	NM	NM	8.75E-13	1.49E-12	1.98E-10	3.37E-10
HexaCDF, 1,2,3,4,7,8-	NM	NM	NM	NM	NM	NM	NM	NM	5.17E-13	7.45E-13	2.74E-10	3.94E-10
HexaCDF, 1,2,3,6,7,8-	NM	NM	NM	NM	NM	NM	NM	NM	2.38E-13	3.43E-13	3.05E-10	4.39E-10
HexaCDF, 1,2,3,7,8,9-	NM	NM	NM	NM	NM	NM	NM	NM	4.66E-13	6.70E-13	1.30E-10	1.87E-10

Pollutant	Pyre Carcass		ACB Carcass		Pyre Coal		Pyre Hay Bales		Pyre Wood/Kindling		ACB Wood	
	V	P	V	P	V	P	V	P	V[a]	P	V[a]	Total
HexaCDF, 2,3,4,6,7,8-	NM	NM	NM	NM	NM	NM	NM	NM	7.24E-13	1.04E-12	1.40E-10	2.02E-10
OctaCDD, 1,2,3,4,6,7,8,9-	NM	NM	NM	NM	NM	NM	NM	NM	1.49E-12	2.83E-11	1.84E-10	3.50E-09
OctaCDF, 1,2,3,4,6,7,8,9-	NM	NM	NM	NM	NM	NM	NM	NM	3.41E-13	8.19E-12	2.95E-11	7.08E-10
PentaCDD, 1,2,3,7,8-	NM	NM	NM	NM	NM	NM	NM	NM	2.82E-12	1.04E-12	2.24E-10	8.29E-11
PentaCDF, 1,2,3,7,8-	NM	NM	NM	NM	NM	NM	NM	NM	3.48E-12	1.64E-12	9.07E-10	4.27E-10
PentaCDF, 2,3,4,7,8-	NM	NM	NM	NM	NM	NM	NM	NM	3.80E-12	1.79E-12	8.68E-10	4.08E-10
TetraCDD, 2,3,7,8-	NM	NM	NM	NM	NM	NM	ND	1.7E-11	4.30E-12	8.19E-13	2.19E-10	4.17E-11
TetraCDF, 2,3,7,8-	NM	NM	NM	NM	NM	NM	NM	NM	3.77E-12	1.19E-12	2.27E-09	7.18E-10
Metals (b)												
Arsenic	0	0	0	0	0	1.04E-05	NM	NM	0	1.09E-05	0	1.04E-05
Cadmium	0	3.04E-05	0	6.73E-06	NM	NM	NM	NM	0	8.11E-06	0	6.30E-05
Chromium	0	2.30E-04	0	6.90E-05	0	1.08E-04	NM	NM	0	3.62E-06	0	2.61E-04
Copper	0	1.15E-04	0	3.26E-05	0	1.34E-04	NM	NM	0	1.34E-05	0	3.34E-04
Iron	0	7.23E-03	0	1.84E-03	0	7.72E-02	NM	NM	0	2.87E-04	0	1.83E-02
Lead	0	2.75E-04	0	1.12E-04	0	5.01E-05	NM	NM	0	3.06E-05	0	2.15E-04
Manganese	0	8.49E-05	0	2.71E-05	0	6.47E-04	NM	NM	0	7.31E-05	0	2.48E-02
Nickel	0	2.86E-04	0	8.00E-05	0	4.77E-06	NM	NM	0	4.35E-06	0	7.07E-05
Zinc	0	2.78E-04	0	1.17E-04	0	1.56E-04	NM	NM	0	2.29E-03	0	5.95E-03

Abbreviations: 0 = assumed to be zero; ACB = air-curtain burning; NA = not among analytes – not selected for measurement; ND = not detected; NM = not modeled; P = particulate phase; s = seconds; V = vapor phase; CDD = chlorinated dibenzodioxins; CDF = chlorinated dibenzofurans.

[a] For PAHs from wood combustion, only particles sampled and analyzed for PAH content; however, samples obtained post condensation (Hays et al. 2003). Presumably vapor-phase PAHs did not deposit near the open pyre or ACB unit.

[b] It was assumed that inorganic metals all would condense upon mixing with cooler ambient air and therefore all would be found in particulate phase outside the rising plume from the fire. The vapor-phase metal emissions therefore are all set equal to zero.

D.1. References

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Appendix E. Description of the HHRAP Soil and Surface Water (SSW) Screening Model

E.1. Introduction

This appendix provides further information on the model used in the exposure assessment for livestock carcass management options to estimate the fate and transport of chemicals in the soil, surface water, and sediment compartments of the hypothetical farm site. The model is based primarily on methods provided by the USEPA's *Human Health Risk Assessment Protocol* (HHRAP) *for Hazardous Waste Combustion Facilities* (USEPA 2005) for hazardous waste combustion units (USEPA 2005). For this reason, the model is titled the HHRAP Soil and Surface Water Screening Model (hereafter referred to as the SSW Screening Model or SSW).

The fate and transport of chemicals through the modeled environment is estimated in the SSW Screening Model using a set of algorithms to predict long-term, steady-state concentrations in environmental media from continuous sources. Conceptually, the modeled environment, a hypothetical water body and the surrounding watershed, is evaluated with respect to the chemical loads and losses to each of three "compartments" or categories of environmental media: (1) air, (2) watershed soil, and (3) the water body of interest (inclusive of both the water column and the underlying benthic sediment). Within each of those three media types, equilibrium between chemical and environmental phases is assumed (e.g., between dissolved and sorbed fractions of chemical present in surface soil, in pore water, and sorbed to soil particles). Note that for the water body, the assumption of equilibrium conditions drives partitioning between the water column, including both freely dissolved chemical and chemical sorbed to suspended sediments, and the benthic sediments, including both dissolved chemical in sediment pore water and chemical sorbed to benthic sediment particles.

The algorithms also assume steady-state conditions within each compartment given the total mass of chemical added to the system as a whole. Loading and loss processes from the compartments are assumed to occur via deposition, diffusion, erosion, runoff, leaching, volatilization, and sediment burial processes. Chemical partitioning between phases within a compartment is calculated assuming equilibrium conditions. As in the HHRAP equations, the algorithms in the SSW Screening Model do not maintain a chemical mass balance, and no

chemical feedback mechanisms are included. For example, the volatilization of chemical from a lake of 10 to 10,000s of acres does not significantly affect the concentration of chemical in air.

E.2. Use of HHRAP Framework

USEPA developed HHRAP to facilitate multi-pathway, site-specific risk assessments for facilities burning hazardous waste. However, the algorithms in HHRAP can be applied for air sources other than combustors. HHRAP is available from USEPA as document and companion parameters database.[24] The HHRAP document is intended to provide a transparent, comprehensive, defensible, and scientifically-supported approach and algorithms that risk assessors can use to inform decision-making for permitting a hazardous waste combustion facility. The HHRAP protocol is a "model" in the broader sense (i.e., a conceptual approach for estimating fate and transport, exposure, and risk) rather than a computational tool that can be operated by a user to provide numerical results (such as a computer program). The protocol document contains recommended procedures for estimating chemical concentrations in environmental media, associated human exposures, and the resulting risks for exposed individuals.

We based the Excel™-based SSW Screening Model on the HHRAP algorithms to estimate soil, surface water, and sediment concentrations. Algorithms from HHRAP are peer reviewed, and the documentation is familiar to risk assessors. As compiled by USEPA, HHRAP default values for parameters provide a valuable starting point for configuring the datasets included in the SSW. For those reasons, the SSW is expected to be robust while flexibly allowing interpretation of the data available for input.

Where possible, the parameter names, symbols, and equations included in the SSW Screening Model are consistent with the information presented in USEPA's HHRAP documentation. In this appendix, cross-references to HHRAP equations are provided where relevant. One important difference between the expressions presented in HHRAP and equations used the SSW is the incorporation of the chemical source term. For this project, AERMOD is used to estimate total chemical deposited from air to soils over 48 hours for combustion-based management options,

[24] EPA's HHRAP document and companion parameters database is available for download from: http://www3.epa.gov/epawaste/hazard/tsd/td/combust/risk.htm.

not the equations in HHRAP. The AERMOD deposition rates are input to the SSW Screening Model, which then estimates the soil concentrations soon after the burns and the soil concentrations once again for one year later (after losses via microbial and abiotic degradation processes and chemical losses from erosion and runoff). The SSW also is used to estimate chemical transport from soils to surface water (the lake) via runoff and erosion. The SSW equations that simulate chemical runoff and erosion are based on the same conceptual relationships as those included in the HHRAP expressions. Finally, concentrations of chemicals in the top 20 cm of surface soils following amendment with finished compost are calculated off-line. From those, the SSW Screening Model estimates losses from microbial and abiotic degradation and losses via erosion and runoff over one year, and reports the quantities remaining at one year. Inputs for the SSW Screening Model for combustion-based carcass management options differ from those for compost-amended soils (part of the composting option). For both of the on-site combustion options, AERMOD results (total deposition from air over a 48-hr burn) are input to the SSW. AERMOD predicts location-specific deposition rates in a grid of cells 250 x 250 meters distributed across a 500-acre (202-hectare) watershed. The maximum total deposition rate for each chemical predicted by AERMOD is input to SSW. That is equivalent to using the location of maximum deposition to represent the entire watershed.

For burial, there is no runoff or erosion, only leaching of chemical from the buried carcasses toward groundwater. For composting, there is a very small amount of leaching from the compost windrow to groundwater and limited erosion and runoff that carry chemicals to the lake (e.g., Table 5.3.10 in the report). We assume that a compost windrow decomposes over one year. The finished compost is tilled into 10 acres of land one edge of which is adjacent to the lake. (We could not adapt the HHRAP equations to allow intervening “clean” and vegetated soils to intercept erosion and runoff from the compost-amended 10 acres prior to its reaching the lake.) As a consequence, the SSW Model estimated substantial erosion and runoff of chemicals into the lake, where the inorganics in water were accumulated in fish (e.g., Table 5.3.12 in the main report).

For burial, we focus on the first year of leaching to groundwater, because the quantity of chemicals in leachate is highest during the first year; lower quantities of chemical remain in the burial trench over subsequent years. We did not calculate chemical-specific leaching rate

constants to estimate the declining chemical quantities leaching each year for the 20 to 30 following years (see main report, Section 3.4.1, Table 3.4.3). The approach used to estimate the degree to which subsurface soils filter out a fraction of each chemical (i.e., chemical in leachate or in percolating water sorbs to soil particles) is described in Section 4.3.1 of the main report.

For the combustion-based options, we estimate leaching from buried bottom ash over the first year after the ash burial with similar methods.

E.3. Fate and Transport Modeling Outputs

The fate and transport processes included in the SSW Screening Model are characterized using equations representing mass transfer of chemicals to or from environmental media (i.e., chemical loading to or chemical loss from the watershed soil and the water body) or partitioning among phases (e.g., particle and aqueous phases) within each major environmental medium. Chemical loading equations are expressed as the change of mass of chemical per unit area in one year. Chemical losses from erosion of surface soils and runoff are represented as a first-order rate constant per year; SSW moves those losses into the surface water (lake). Additionally, PAHs are subject to congener-specific abiotic/biotic degradation represented as first-order rate constants. Elements cannot be "degraded," and 2,3,7,8-substituted dioxins and furans biodegrade very slowly if at all. The algorithms and parameters included in the SSW Screening Model are derived from – and in many cases, identical to – the equations and parameters presented in HHRAP (USEPA 2005). For clarity, equation and parameter terminology and symbols used in the SSW Screening Model are consistent with those included in HHRAP whenever possible (see Appendix F. for parameter symbols).

We present an overview of most of the fate and transport processes modeled in the SSW Screening Model (not including bioaccumulation) in Figure E.1. For the combustion-based management options, chemical gains to the watershed soils and the water body can occur directly, via direct air deposition of particle-bound chemical to the ground or water's surface or via diffusion of vapor-phase chemical into surface soils or surface water. Further loading to the water body can occur indirectly through subsequent watershed transfers to the water body via erosion and runoff. In addition to calculating chemical concentrations in the surface soil

following deposition, the SSW estimates losses from the watershed soils via runoff, erosion, leaching, and volatilization to estimate concentrations after one (or more) years.

For composting, we examine two phases. The first is possible leaching of decomposition products from the initial compost rows, which are covered a 0.6 m thick layer of woodchips and underlain by 0.6 m of woodchips. The second phase follows application of that compost to agricultural fields on-site. Amended soils might have higher concentrations of some chemicals (e.g., carbon, nitrogen, and heavy metals) that could affect lake ecosystems if there is substantial erosion or runoff from the amended soils to the lake.

The loading rates for compost application are limited to the portion of the watershed (10 acres) that would receive compost application with the finished compost applied at an agronomic rate (see Section 3.5 of the main report). The total of all chemicals applied per m^2 when the finished compost is amended to 10 acres of agricultural soil is used to estimate all chemical concentrations based on a horizontal 10-acres (4.05 hectares or 40,500 m^2) area and 20 cm depth for compost tilled into the soil. Those values serve as the concentration at time 0 for the amended soil, and the SSW Screening Model calculates subsequent movement of chemical via erosion, runoff, and volatilization for the year.

The final chemical concentrations in the amended soils following one year of losses provide the annual average soil concentration. The chemical mass on soil particles eroded to the lake is added to the lake sediments, and chemical mass in surface runoff is added to the lake water column. Chemical mass that leached from a source (calculated outside of the SSW as described in Section 4.3.1 of the main report) over one year also is subtracted from the 10 acres of amended soil. The bulk of vapor-phase chemicals formed during decomposition in the windrow is lost while the windrow is intact; therefore negligible volatilization of chemicals from compost-amended soils is expected.

For the combustion-based management options, vapor-phase and particle-phase deposition rates calculated by AERMOD are input to the SSW Screening Model which calculates total concentrations in soils over the 500 acre watershed. Then, the SSW predicts the fraction of each chemical deposited that erodes or runs off into the lake. SSW outputs include: (1) the total chemical concentrations in the lake water column including dissolved chemical and chemical

sorbed to suspended solids, and (2) the total chemical concentration in the bulk benthic sediment, including (a) chemical bound to sediment particles and (b) freely-dissolved chemical concentration in the sediment-associated pore (or interstitial) water.

For the combustion-based management options, possible contributions from precipitation percolating through buried ash to groundwater, and then reaching the lake, are added to the water column concentrations to estimate the final concentrations in the lake. As discussed in Section 4.5 of the main report, those concentration estimates are used to estimate chemical concentrations in fish tissues (see Appendices J and K).

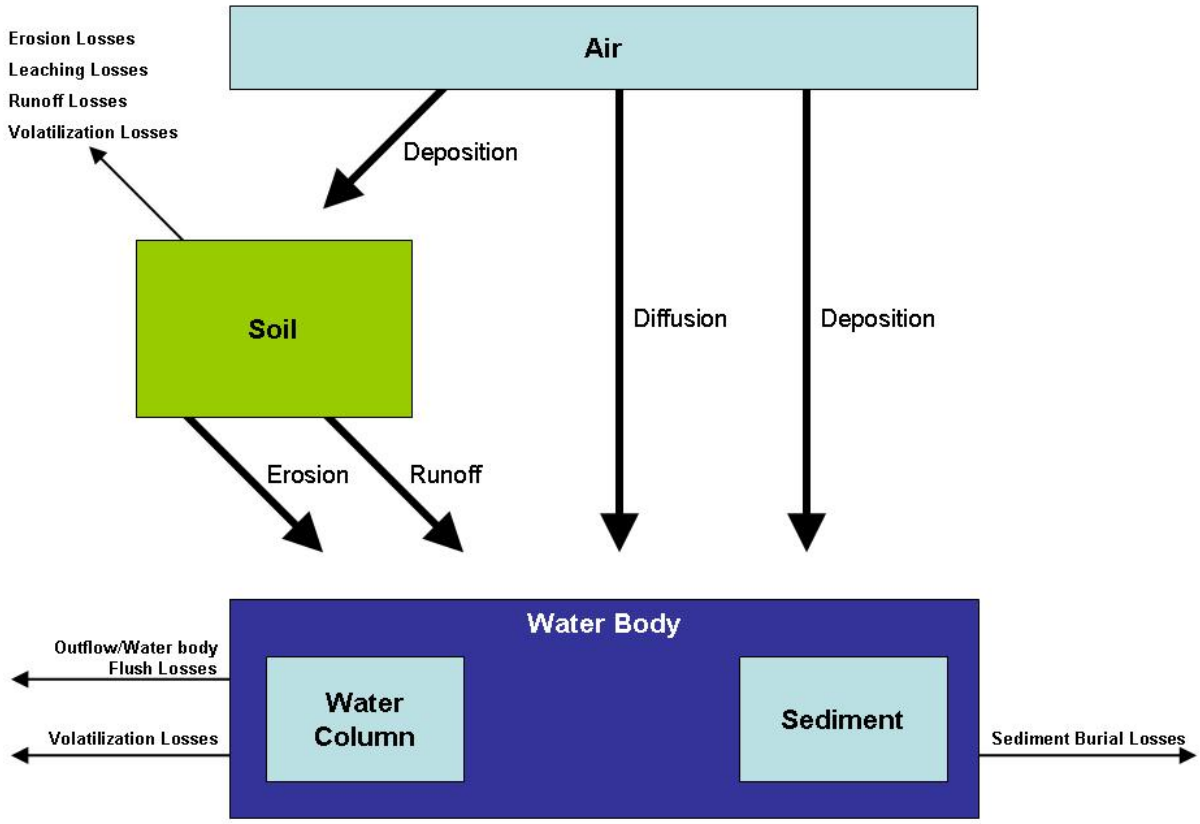

Figure E.1. SSW Screening Model fate and transport conceptual diagram.

For organic compounds, we estimate fish tissue concentrations with a companion steady-state equilibrium model, AQUAWEB, described in Appendix J (a biokinetic model for lipophilic organics; Arnot and Gobas 2004; AQUAWEB 2005). For inorganic chemicals, and fish tissue

concentrations are estimated with bioaccumulation factors documented in Appendix K. applied to the dissolved chemical concentration (not total chemical concentration). In AQUAWEB, chemicals sorbed to suspended sediment particles are not available for uptake via gills of water-column fish or invertebrates.

After total chemical loading to the water body is accounted for, losses via volatilization from surface water and via benthic sediment burial are calculated to estimate the "total water body concentration," inclusive of both the water column and sediment, after one (or more) year(s). Chemical concentrations in the water body that are needed for bioaccumulation calculations (i.e., chemical concentrations in the water column and in sediment) are then calculated based on the assumption of equilibrium partitioning between the water column and benthic sediment and between the dissolved and particle-sorbed phases in each of these compartments. Using the symbols and terminology included in the SSW Screening Model spreadsheets, the loading to the water body is expressed in Equation E.1.

$$L\_T = L\_DEP + L\_dif + L\_RI + L\_R + L\_E + L\_G \qquad \textbf{(Eqn. E.1)}$$

where:

L_T	=	Total chemical load to the water body (g/yr),
L_DEP	=	Deposition load to the water body (g/yr),
L_dif	=	Vapor-phase diffusion load to the water body (g/yr),
L_RI	=	Runoff load from impervious surfaces (g/yr),
L_R	=	Runoff load from pervious surfaces (g/yr),
L_E	=	Soil erosion load to the water body (g/yr), and
L_G	=	Groundwater recharge load to the water body (g/yr).

This is identical to the equation in HHRAP Table B-4-7 except for the addition of a contribution from groundwater, which is not included in HHRAP. The methods and assumptions used to estimate the rate of groundwater recharge to the on-site lake are discussed in Section 4.3 of the main report.

For equations for each source of loading in Equation E.1, as well as equations for estimating soil concentrations from deposition rates (including compost application), refer to the HHRAP documentation (USEPA 2005).

E.4. Parameterization

The HHRAP SSW Screening Model requires several dozen environmental and chemical parameter values to calculate concentrations in soils, surface water, and sediments (see Appendix F.). For organic chemicals, AQUAWEB requires additional environmental and chemical-specific biotic and abiotic parameter values to estimate bioaccumulation of chemicals in fish. To minimize set-up time and conduct model runs, sets of default values were developed for many of the parameters. USEPA developed default parameter values for the HHRAP SSW portion of the model. Abiotic inputs to the AQUAWEB model of bioaccumulation (i.e., concentrations of organic chemicals in the water column and sediments) were those estimated by the SSW portion of the model. For organic chemicals, AQUAWEB also estimated chemical-specific biological parameter values and final fish tissue concentrations using chemical octanol-water partitioning coefficient (Kow) and the aquatic food web as specified for this project. For inorganic chemicals, values for bioaccumulation factors in fish are as reported in the literature (Appendix K).

Appendix F lists the default values and other input parameter values for SSW. USEPA selected many of the parameter values for HHRAP. Where uncertainties were large or natural variability is high, USEPA selected somewhat conservative values to ensure that the model can be successfully used as intended (i.e., as a screening tool). For parameters for which USEPA did not recommend values for a national assessment, values were selected based on the same principal: to err on the conservative side where uncertainties are present to avoid underestimating the risks.

We used Arnot and Gobas (2004) AQUAWEB (2005, available online) to estimate bioaccumulation of nonionic organic chemicals in fish from the chemical concentrations in the water column and in the sediments calculated by the SSW Screening Model (including any additional quantities that might reach the lake from buried ash for the two on-site combustion options). Although USEPA developed an online version of the model, KABAM, for use in pesticide evaluations, that version allows processing of only one chemical at a time, and requires the user to input chemical-specific parameter values one-by-one in a series of input data screens.

AQUAWEB allows specification of all parameter values for up to 25 chemicals in an Excel™ spreadsheet, and the results are available immediately in table format for all 25 chemicals to facilitate comparisons.

This assessment uses a different aquatic food chain and several different environmental parameter values than those included in the online version of AQUQWEB for Lake Erie. We selected the values to be more representative of small to medium U.S. lakes. Appendix H presents the *abiotic* parameter values and rationale for their selection for input to the SSW and AQUAWEB. Appendix J presents the parameter values and rationale for their selection for the *biotic* components of AQUAWEB, including our definition of a food web that might occur in a 100-acre lake (Table J.5).

E.5. References

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USEPA (U.S. Environmental Protection Agency). 2005. *Human Health Risk Assessment Protocol for Hazardous Waste Combustion Facilities (HHRAP)*, Final. Washington, DC: U.S. Environmental Protection Agency, Office of Solid Waste. September. EPA/520/R-05/006.

Appendix F. Detailed Parameter Documentation Tables for the HHRAP SSW Excel™ Model

The main report lists the parameter values that were used as input to the HHRAP-based SSW Excel model. Where data or estimated parameter values were obtained from based on empirical equations developed by others, the source is cited (final column). For those parameter values for which the source is listed as "Assumed," the rationale is described in Section F.2, by parameter.

F.1. Input Parameter Values

Table F.1. Parameters for the HHRAP SSW Excel Model.

Inputs	Input Value	Units	Variable Name	Source for Default Value
0.0) Time period at beginning of emissions	0	yr	*T_1*	HHRAP (USEPA 2005)
0.1) Time period over which deposition occurs	1	yr	*tD*	HHRAP (USEPA 2005)
0.2) Length of exposure duration	1	yr	*T_2 j*	HHRAP (USEPA 2005)
0.3) Temperature	8.34	°C	*Tmp*	Average air temperature for Iowa; see main report Section 2.3.1
1. Characteristics of On-site Lake				
1.1) Water body surface area	404,686	m^2	*A_w*	Assumed (100 acres)
1.2) Total watershed area - for open pyre, ACB, and burial - for compost application	2,020,191 40,469	m^2	*A_L*	Assumed: calculated as 5 times the lake surface area (0.8 and 0.0156 square miles, respectively)
1.3) Maximum depth of lake	25	ft	*d_max*	Median depth of lakes in Minnesota, for which an extensive lake database is available online
1.4) Average water body depth	4.38	m	*d_wc*	Calculated from maximum depth and surface area as per Schupp (1992)
1.5) Cross-sectional area of lake	2784	m^2	*CA_w*	Calculated from surface area and average depth
1.6) Annual evaporation of water body	0.60	m/yr	*E_loss*	Geraghty et al. (1973)
1.7) Sediment organic carbon content	0.04	unitless	*OC_sed and f_ocbs*	HHRAP (USEPA 2005), App B, p B-274
1.9) Dissolved oxygen content	9.50	mg O_2/L	*DOC*	Calculated from SAT - see AQUAWEB documentation
1.10) Depth of upper benthic sediment layer	0.03	m	*d_bs*	HHRAP (USEPA 2005), App B, p B-228 (range 0.01 to 0.05)
1.11) Sediment delivered to waterbody	calculated	kg soil/m^2-yr	*SD_X_e*	Product of the sediment delivery ratio (*SD*) and the unit soil loss (*X_e*) in mg/m^2-yr

Inputs	Input Value	Units	Variable Name	Source for Default Value
1.12) Sediment delivery empirical intercept coefficient	1.9 [open pyre, ACB, burial] 2.1 [composting]	unitless	*a_sed*	Depends on watershed size; 1.9 for watershed between 0.1–1.0 square miles and 2.1 for smaller watersheds; Vanoni 1975 cited in HHRAP (USEPA 2005), App B, p B-223
1.13) Sediment delivery empirical slope coefficient	0.125	unitless	*b_sed*	Constant value; Vanoni 1975 cited in HHRAP (USEPA 2005), App B, p B-223
1.14) Drag coefficient	0.0011	unitless	*C_d*	HHRAP (USEPA2005), App B, p B-246
1.15) Dimensionless viscous sublayer thickness	4	unitless	*λ_z*	HHRAP (USEPA 2005), App B, p B-247
1.16) Von Karman's constant	0.4	unitless	*k_vk*	HHRAP (USEPA 2005), App B, p B-246
1.17) Water density (specific gravity)	1.00	g/cm^3	*ρ_w*	Pure water (no dissolved substances) highest density at 4°C (39.2°F); limited variation with temperature when liquid
1.18) Water viscosity (poise = g/cm-s)	1.31E-02	g/cm-s	*μ_w*	HHRAP (USEPA 2005), App B, p B-247; cites Weast 1979; decreases with increasing temperature [1.69E-02 at 25°C and 1 atm pressure]
1.19) Temperature correction factor	1.026	unitless	*θ*	HHRAP (USEPA 2005), App B, p B-243
2. Atmospheric Parameter Values				
2.1) Average annual wind speed	4.13	m/s	*W*	Based on Iowa data for 2014; see main report Section 2.3.1
2.2) Air viscosity	1.72E-04	g/cm-s	*μ_a*	At air temperature of 6°C
2.3) Air density	1.27E-03	g/cm^3	*ρ_a*	At temperature of 6°C
2.4) Universal gas constant	8.21E-05	atm-m^3/mol-K	*R_gas*	HHRAP (USEPA 2005), App B, p B-29
2.5) Dry particle deposition velocity	0.15	cm/s	*u_pdep*	Assumed; consistent with semivolatile chemicals
2.6) Dry vapor depositional velocity	1.5	cm/s	*u_vdep*	Assumed; conservative estimate consistent with value for nitric acid vapor
3. Soil & Watershed Parameters				
3.1) Fraction (proportion) of watershed that is impervious	0.05	unitless	*A_I_Frac*	Minimal impervious surfaces; assume 5%
3.2) Fraction of precipitation that is evapotranspired by plants	0.80	unitless	*f_evap*	Calculated; USGS 1994
3.3) Soil mixing zone depth: –Tilled soil [for composting] –Untilled Soil [other options]	 20 2	 cm cm	*Z_s*	HHRAP (USEPA 2005), App B, p B-5
3.4) Fraction organic content, soil	0.01	unitless	*f_ocs*	HHRAP (USEPA 2005)
3.5) Soil volumetric water content	0.20	mL/cm^3	*θ_sw*	HHRAP (USEPA 2005), App B, p B-16

Inputs	Input Value	Units	Variable Name	Source for Default Value
3.6) Soil bulk density	1.50	g soil/cm^3 soil	*BD*	HHRAP (USEPA 2005), App B, p B-15, based on loam soil
3.7) Solids particle density	2.7	g/cm^3	*ρ_soil*	HHRAP (USEPA 2005), App B, p B-30 based on Blake and Hartage (1996) and Hillel (1980)
3.8) Soil enrichment ratio (organic chemical)	3	unitless	*ER*	HHRAP (USEPA 2005), App B, p B-15,
3.9) Soil enrichment ratio (inorganic chemical)	1	unitless	*ER*	HHRAP (USEPA 2005), App B, p B-15,
3.10) Universal Soil Loss Equation (USLE)	10.24	tons/acre-year	*X_e*	Calculated using equation B-4-13 in HHRAP (USEPA 2005), App B, p 219
3.11) USLE erodibility factor	0.39	ton/acre	*K_erode*	Assumed; value of 0.39 is typical/conservative of average soil types
3.12) USLE length-slope factor	0.050	unitless	*LS*	As per client request; corresponds to a slope of 5%
3.13) USLE supporting practice factor	1.00	unitless	*PF*	Value of 1 assumes no supporting practices such as contour tillage, terracing, cover crop, or crops in place
3.14) USLE cover management factor	0.3	unitless	*C_var*	Assumed; values for croplands range from 0.05 to 0.5
3.15) Average evapotranspiration	77.66	cm/yr	*E_v*	Calculated as the product of annual precipitation and the fraction evapotranspired
4. Groundwater				
4.1) Aquifer Hydraulic Conductivity	11.12	cm/yr	*GWtoSW*	= 0.001 ft/day, selected based on Heath (1983), fig p 13
4.2) Residual water leached to groundwater	calculated	cm/yr	*TW*	Calculated; equation provided in Section E.2 - defaults to zero if water balance is negative

Abbreviations: ^ = raised to the power of (number following); ACB = air-curtain burning; App = Appendix; atm = atmospheres; °F = degrees Fahrenheit; fig = figure; ft = feet; HHRAP = *Human Health Risk Assessment Protocol for Hazardous Waste Combustion Facilities*; K = Kelvin; mol = moles; O_2 = oxygen; s = seconds; USLE = Universal Soil Loss Equation.

F.2. Rationale for Assumed Parameter Values

F-1.1. Surface Area of Lake = 100 acres. Prior to making any estimates of environmental concentrations that might result from management of 50 tons of livestock carcasses, it was decided to include a 100-acre lake to ensure that it was large enough to include sustainable populations of higher trophic level fish. Fish consumption from the lake, then, would be sustainable even with a 10% harvest rate by subsistence fishermen (report under development). This size lake has been included in analyses of commercial point sources of essentially

continuous emissions to air over 30 years or more. Based on this analysis, it was concluded that a smaller lake (e.g., 10 to 25 acres) might also provide sustainable fish populations at the much lower fish ingestion rates assumed for farmers in the carcass management scenarios.

Smaller lakes would provide less dilution for the unlined burial and compost applied to a field, resulting in higher surface-water concentrations for that option than with the current 100-acre lake assumption. For the open pyre and air-curtain burning options, a smaller lake would provide less dilution, but have a smaller watershed associated with it (assuming a 1:5 ratio [surface water area]:[watershed area]). On balance, however, higher surface water concentrations would be expected for the combustion-based management options for a smaller lake because of the reduced dilution. Similarly, if the quantity of livestock carcasses managed in a single location (e.g., single pyre, single burial pit) were higher, chemical concentrations in all environmental media near the site would be higher.

In reality, however, lake concentrations are likely to be lower than estimated for the four on-site scenarios considered in this project (burial, composting, open pyre and air-curtain burning), because the assessment assume no lake outflow via streams or recharge to groundwater. SSW Screening Model did simulate chemical losses from volatilization from the lake and from sediment burial. In reality, there tend to be groundwater inflows and outflows, and often significant stream outlets that become evident during rain events. Those processes would reduce chemical concentrations in a lake.

For compost application to soils, on the other hand, farmers should limit the loading rate per unit area based on the concentrations of nitrogen and possibly phosphorus in the finished compost. The SSW Screening Model did not allow separation of the area of compost application from the surface water (they must be considered to be adjacent). In reality, farmers probably would be allow at least a 100-ft buffer between a field receiving livestock-carcass finished compost, and their lake's surface water. Allowing any distance in this assessment would have reduced surface water concentrations of inorganic chemicals relative to those estimated for other carcass management methods in this report. Thus, the effect of compost application on surface water concentrations would depend not only on the size of the lake, but also on the orientation and shape of the area where the compost was applied.

Burial would continually need more land area if there was a need for ongoing carcass management on-site because of the need to not disturb existing trenches. Composting could reuse areas, if enough time to ensure adequate decomposition elapsed before adding more carcasses to the windrows. Burial of ash from either open pyre or air-curtain burning would affect the least land-surface area over the long-term, but other land uses are likely to be suspended while combustion activities and air-emission plume effects prevail.

F-1.2 Total watershed area = 500 acres (2,020,191 m^2) for open pyre, ACB, and burial (0.8 square miles). The size and shape of a watershed that supplies water and sediments to given lake depends on local geography, including ground elevation profiles and the number and type of creeks or streams that might enter the lake. For purposes of the scenarios, it was necessary assume a set watershed surface area. Watershed or drainage basin/lake area ratios (DB:LA) of 4:1 have been called "small" (Freedman 1995, p 125) and ratios of 19:1 called large (www.lakeviz.org/ourlakes/). In general, lakes with small DB:LA ratios have longer water retention times, with small DB:LA ratios of 6 corresponding with a retention time of over 2 years (Lillie and Mason 1983; Table 1 in Shaw et al. 2004). A DB:LA ratio of 5 was assumed to be consistent with the assumption of long retention time.

F-1.2b Total watershed area = 10 acres (40,469 m^2) for composting (0.0156 square miles). This calculated area is inaccurately termed a watershed, and is used as a surrogate to model the 10 acre area receiving an application of finished compost. This is a way to input a smaller acreage into the SSW Screening Model to simulate a 10-acre area of applied compost next to the lake.

F-2.5. Particle dry deposition velocity. Typically metals are emitted as primary particles (in particle form at the time of release), and the size distribution is characteristic of the mass size distribution of particle emissions from the source. On the other hand, most semi-volatiles tend to be in the gas phase at the time of release and condense onto pre-existing particles as the plume cools. The semi-volatiles thus tend to be associated with particles according to the surface area available for condensation. The surface area of particle emissions is weighted towards smaller particles than the mass size distribution, so the semi-volatiles will preferentially be found on smaller particles. The distribution of particle sizes in which or upon which a chemical is found affects the surface boundary resistance and thereby the deposition velocities that are expected.

Deposition velocities measured in Minnesota (Pratt et al. 1996) ranged from 0.09–0.15 cm/s for fine particles (nominal diameter cutpoint of $PM_{2.0}$), 0.28–0.42 cm/s for sulfur dioxide and 0.83–1.46 cm/s for nitric acid vapor. Since the surface area distribution of particles from a typical combustion source would typically peak in the fine particle range, using the upper bound on the fine particle deposition velocity (say 0.15 cm/s) would be a reasonable starting point deposition velocity for the semivolatile substances such as PAHs and dioxins/furans. A somewhat higher value (perhaps in the range of 0.2 cm/s) would be a reasonable value for the metals, since they may be associated with larger particle sizes. For the combustion-based carcass management options, however, we assume 0.15 cm/s for all particle deposition in the HHRAP-based SSW model. The value assumed for particle settling in the SSW model does not affect the total amount of chemical deposited per m^2 over the 48-hr burn, however, which is calculated by AERMOD.

F-2.5. Vapor dry deposition velocity. We assume a dry vapor deposition velocity of 1.5 cm/s to ensure that the SSW model will run. Again, that does not affect the total chemical deposited per m^2 which is calculated by AERMOD.

F-3.11. Universal Soil Loss Equation (USLE) erodibility factor. Specific soil types have different natural susceptibilities to erosion, depending on the specific makeup of their components (Wischmeier and Smith 1978). The soil-erodibility factor (*K_erode*) is used to specify the ease with which soil on a given field is eroded. A value of 0.39 was selected, which is slightly higher than the average value, for surface soils including the compost-amended soil over 10 acres. The compost windrow has an erodibility factor of zero.

F-3.13. USLE supporting practice factor. Supporting practices include contour tillage, stripcropping on the contour, and terracing and is used in calculations of runoff and erosion (not leaching). A value of 1 assumes no supporting practices. It is unlikely that users will have need to provide a USLE supporting practice factor *(PF)* value different from the default (*PF* = 1), as it is unlikely that an entire watershed will have significant supporting practices to reduce erosion. The cover management factor (*C_var*) represents the influence of the type of plants and other matter on the ground of a slope. The type of ground cover present on a field plays a major factor in determining the amount of soil eroded from a slope. Values of the cover management factor can range from less than 0.001 for dense grasses and undisturbed forestland to 1 for bare construction sites. Values for cropland typically range from 0.05 to 0.5, depending on tillage and

crop type. For the compost windrow, the *PF* value is set to 0 (i.e., no erosion) and for the compost-amended soil (10 acres) the *PF* is set to 1 (note that the shallow slope of 5% limits surface soil/applied-compost erosion).

F-3.14. USLE cover management factor. Values for the cover management depend on the type of tillage and species of crops. Some information on defining the cover management factor is available online at topsoil.nserl.purdue.edu/usle/AH_537.pdf.

F.3. References

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Appendix G. Supporting Information for Chemical Leaching from Burial, Composting, and Carcass Storage

Table G.1 through Table G.3 show the estimation of chemical-specific concentrations in drinking water for leaching from the carcass burial option and three time periods, based on leaching data from Pratt and Fonstad (2009). Table G.4 and Table G.5 show similar calculations for leaching from the temporary carcass storage pile and the compost windrow. Table G.6 provides a legend to the calculation columns in the tables.

G.1. References

Pratt DL, Fonstad TA (2009) Livestock mortalities burial leachate chemistry after two years of decomposition. *3rd International Symposium on Management of Animal Carcasses, Tissue, and Related By-products*; June 21-24, 2009; Reno, NV.

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Table G.1. Estimated Leaching and Well Water Concentration of Chemicals from Buried Carcasses During the First Week.[a,b]

Chemical	A	B	C	D	E	F	G
	Avg Conc. First Week (mg/L)	Kd (L/kg)	Total Released First Week (mg)	Total Filtered Back to Soil from Leachate First Week (mg)	Total Reaching Groundwater (mg)	Intercepted by 0.2 m Well Per Day, First Week (mg/d)	Avg Conc. In Drinking Water, First Week (mg/L) 1136 L/d
aluminum	1.7E+00	1.5E+03	1.3E+04	1.3E+04	2.2E-01	6.8E-05	**6.0E-08**
ammonium	5.2E+03	1.4E-01	3.9E+07	3.3E+07	5.9E+06	1.9E+03	**1.6E+00**
barium	3.0E-01	4.1E+01	2.3E+03	2.2E+03	1.4E+00	4.4E-04	**3.9E-07**
beryllium	0.0E+00	7.9E+02	0.0E+00	0.0E+00	0.0E+00	0.0E+00	**0.0E+00**
bicarbonate	3.5E+04	1.0E-02	2.6E+08	7.4E+07	1.9E+08	5.9E+04	**5.2E+01**
boron	0.0E+00	1.4E-01	0.0E+00	0.0E+00	0.0E+00	0.0E+00	**0.0E+00**
cadmium	0.0E+00	7.5E+01	0.0E+00	0.0E+00	0.0E+00	0.0E+00	**0.0E+00**
calcium	6.0E+01	1.4E-01	4.5E+05	3.8E+05	6.9E+04	2.1E+01	**1.9E-02**
chloride	2.6E+03	1.4E-01	2.0E+07	1.7E+07	3.0E+06	9.3E+02	**8.2E-01**
chromium	0.0E+00	1.9E+01	0.0E+00	0.0E+00	0.0E+00	0.0E+00	**0.0E+00**
cobalt	1.0E-01	4.5E+01	7.5E+02	7.5E+02	4.3E-01	1.3E-04	**1.2E-07**
copper	6.0E-01	4.3E+02	4.5E+03	4.5E+03	2.7E-01	8.4E-05	**7.4E-08**
inorganic C	6.9E+03	—	5.2E+07	0.0E+00	5.2E+07	1.6E+04	**1.4E+01**
organic C	4.3E+04	—	3.2E+08	0.0E+00	3.2E+08	1.0E+05	**8.9E+01**
iron	1.1E+02	6.5E+01	8.3E+05	8.2E+05	3.3E+02	1.0E-01	**9.0E-05**
lead	0.0E+00	9.0E+02	0.0E+00	0.0E+00	0.0E+00	0.0E+00	**0.0E+00**
magnesium	3.0E+01	1.4E-01	2.3E+05	1.9E+05	3.4E+04	1.1E+01	**9.4E-03**
manganese	5.0E-01	6.5E+01	3.8E+03	3.7E+03	1.5E+00	4.6E-04	**4.1E-07**
mercury	0.0E+00	2.0E-01	0.0E+00	0.0E+00	0.0E+00	0.0E+00	**0.0E+00**
molybdenum	1.8E+00	1.4E-01	1.4E+04	1.1E+04	2.1E+03	6.4E-01	**5.7E-04**
nickel	4.0E-01	6.5E+01	3.0E+03	3.0E+03	1.2E+00	3.7E-04	**3.3E-07**
nitrate/nitrite	2.3E+01	1.4E-01	1.7E+05	1.5E+05	2.6E+04	8.2E+00	**7.2E-03**
total N	1.8E+04	—	1.4E+08	0.0E+00	1.4E+08	4.3E+04	**3.8E+01**
phosphorus	9.2E+02	1.4E-01	6.9E+06	5.8E+06	1.1E+06	3.3E+02	**2.9E-01**
potassium	1.9E+03	1.4E-01	1.4E+07	1.2E+07	2.2E+06	6.8E+02	**6.0E-01**
selenium	0.0E+00	5.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	**0.0E+00**

Chemical	A	B	C	D	E	F	G
	Avg Conc. First Week (mg/L)	Kd (L/kg)	Total Released First Week (mg)	Total Filtered Back to Soil from Leachate First Week (mg)	Total Reaching Groundwater (mg)	Intercepted by 0.2 m Well Per Day, First Week (mg/d)	Avg Conc. In Drinking Water, First Week (mg/L) 1136 L/d
silicon	2.9E+01	1.4E-01	2.2E+05	1.8E+05	3.3E+04	1.0E+01	**9.1E-03**
silver	0.0E+00	8.3E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	**0.0E+00**
sodium	1.6E+03	1.4E-01	1.2E+07	1.0E+07	1.8E+06	5.7E+02	**5.0E-01**
strontium	7.0E-01	1.4E-01	5.3E+03	4.4E+03	8.0E+02	2.5E-01	**2.2E-04**
sulphate	3.7E+03	6.1E-02	2.8E+07	2.0E+07	8.2E+06	2.6E+03	**2.3E+00**
sulphur	1.2E+03	1.4E-01	9.0E+06	7.6E+06	1.4E+06	4.3E+02	**3.8E-01**
titanium	2.0E-01	1.4E-01	1.5E+03	1.3E+03	2.3E+02	7.1E-02	**6.3E-05**
vanadium	0.0E+00	1.0E+03	0.0E+00	0.0E+00	0.0E+00	0.0E+00	**0.0E+00**
zinc	3.5E+00	6.2E+01	2.6E+04	2.6E+04	1.1E+01	3.4E-03	**3.0E-06**
zirconium	2.0E-01	1.4E-01	1.5E+03	1.3E+03	2.3E+02	7.1E-02	**6.3E-05**

Abbreviations: "—" = not available; Kd = soil-water partitioning coefficient; NA = not analyzed; nd = not detected.

[a] See Section 4.3.1 of the main report for a description of the methods and calculations used to estimate leaching from buried carcasses to ground water and to estimate maximum likely chemical concentrations in groundwater as drawn up the well for household uses. Original leachate concentration data are from Pratt and Fonstad (2009). Leachate accumulated on top of 40 mil liner of pit, thus, concentrations of most chemicals increased over time as the carcasses continued to decompose. Exceptions include chemicals that might have off-gassed through the vent pipe and some that might have precipitated out of solution or sorbed to particles over time. Additional sampling dates included Nov 23, 2005, May 25, 2006, and October 26, 2006.

[b] As described in main report, Section 3.4, the initial fresh carcass weight = 45,359 kg. Young et al. (2001) estimated that 60% of a buried mammalian corpse degrades in the first year; 33% of the carcass mass is released during the first two months after burial; and half of that is released in the first week. Based on those estimates, the quantity of leachate released in the first week = 7,500 L was calculated; over the next 8–10 weeks = 15,000 L; and in the first year = 27,000 L. To estimate the total mg of chemical released over the first week (column I), concentrations from the first sample (August 17, column B) were multiplied by 7,500 L. To estimate the total mg of chemical released over the first 8–10 weeks (column J), the average concentration over the first three sampling dates (column D) was multiplied by 15,000 L. To estimate the total mg of chemical released over first year (column K), the average concentration over the first 12 months (column E) was multiplied by 27,000 L.

Table G.2. Estimated Leaching and Well Water Concentration of Chemicals from Buried Carcasses During the First Two Months.[a,b]

Chemical	A	B	C	D	E	F	G
	Avg Conc First Two Months (mg/L)	Kd (L/kg)	Total Released First Two Months (mg)	Total Filtered Back to Soil from Leachate First Two Months (mg)	Total Reaching Groundwater (mg)	Intercepted by 0.2 m Well Per Day, First Two Months (mg/d)	Avg Conc In Drinking Water, First Two Months (mg/L) 1136 L/d
aluminum	1.5E+00	1.5E+03	2.2E+04	2.2E+04	7.5E-01	2.7E-05	**1.0E-04**
ammonium	7.7E+03	1.4E-01	1.2E+08	8.5E+07	3.1E+07	1.1E+03	**0.0E+00**
barium	4.7E-01	4.1E+01	7.0E+03	7.0E+03	8.8E+00	3.2E-04	**4.7E-03**
beryllium	0.0E+00	7.9E+02	0.0E+00	0.0E+00	0.0E+00	0.0E+00	**3.3E-01**
bicarbonate	4.0E+04	1.0E-02	5.9E+08	9.7E+07	5.0E+08	1.8E+04	**0.0E+00**
boron	8.0E-01	1.4E-01	1.2E+04	8.8E+03	3.2E+03	1.2E-01	**0.0E+00**
cadmium	0.0E+00	7.5E+01	0.0E+00	0.0E+00	0.0E+00	0.0E+00	**5.2E-08**
calcium	3.7E+01	1.4E-01	5.5E+05	4.0E+05	1.5E+05	5.3E+00	**3.8E+00**
chloride	2.6E+03	1.4E-01	3.9E+07	2.9E+07	1.0E+07	3.7E+02	**2.2E+01**
chromium	0.0E+00	1.9E+01	0.0E+00	0.0E+00	0.0E+00	0.0E+00	**2.5E-05**
cobalt	0.0E+00	4.5E+01	0.0E+00	0.0E+00	0.0E+00	0.0E+00	**0.0E+00**
copper	9.0E-01	4.3E+02	1.4E+04	1.3E+04	1.6E+00	5.9E-05	**3.0E-03**
inorganic C	7.8E+03	—	1.2E+08	0.0E+00	1.2E+08	4.3E+03	**1.5E-07**
organic C	4.5E+04	—	6.8E+08	0.0E+00	6.8E+08	2.5E+04	**0.0E+00**
iron	6.6E+01	6.5E+01	1.0E+06	9.9E+05	7.9E+02	2.9E-02	**8.5E-05**
lead	0.0E+00	9.0E+02	0.0E+00	0.0E+00	0.0E+00	0.0E+00	**9.5E-08**
magnesium	2.3E+01	1.4E-01	3.5E+05	2.6E+05	9.3E+04	3.4E+00	**1.7E-03**
manganese	4.0E-01	6.5E+01	6.0E+03	6.0E+03	4.7E+00	1.7E-04	**7.3E+00**
mercury	0.0E+00	2.0E-01	0.0E+00	0.0E+00	0.0E+00	0.0E+00	**1.5E-01**
molybdenum	6.7E-01	1.4E-01	1.0E+04	7.4E+03	2.6E+03	9.6E-02	**2.6E-01**
nickel	2.5E-01	6.5E+01	3.8E+03	3.7E+03	3.0E+00	1.1E-04	**0.0E+00**
nitrate/nitrite	1.3E+01	1.4E-01	2.0E+05	1.4E+05	5.2E+04	1.9E+00	**3.4E-03**

Chemical	A	B	C	D	E	F	G
	Avg Conc First Two Months (mg/L)	Kd (L/kg)	Total Released First Two Months (mg)	Total Filtered Back to Soil from Leachate First Two Months (mg)	Total Reaching Groundwater (mg)	Intercepted by 0.2 m Well Per Day, First Two Months (mg/d)	Avg Conc In Drinking Water, First Two Months (mg/L) 1136 L/d
total N	1.5E+04	—	2.3E+08	0.0E+00	2.3E+08	8.3E+03	**0.0E+00**
phosphorus	1.2E+03	1.4E-01	1.8E+07	1.3E+07	4.7E+06	1.7E+02	**2.7E-01**
potassium	2.0E+03	1.4E-01	3.1E+07	2.2E+07	8.1E+06	2.9E+02	**5.5E-05**
selenium	0.0E+00	5.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	**1.1E+00**
silicon	2.7E+01	1.4E-01	4.1E+05	3.0E+05	1.1E+05	3.9E+00	**2.0E-01**
silver	0.0E+00	8.3E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	**0.0E+00**
sodium	2.1E+03	1.4E-01	3.2E+07	2.3E+07	8.3E+06	3.0E+02	**0.0E+00**
strontium	4.3E-01	1.4E-01	6.5E+03	4.8E+03	1.7E+03	6.3E-02	**1.5E-06**
sulphate	4.8E+03	6.1E-02	7.3E+07	3.9E+07	3.3E+07	1.2E+03	**0.0E+00**
sulphur	1.6E+03	1.4E-01	2.4E+07	1.8E+07	6.3E+06	2.3E+02	**1.0E-04**
titanium	0.0E+00	1.4E-01	0.0E+00	0.0E+00	0.0E+00	0.0E+00	**0.0E+00**
vanadium	0.0E+00	1.0E+03	0.0E+00	0.0E+00	0.0E+00	0.0E+00	**4.7E-03**
zinc	3.7E+00	6.2E+01	5.5E+04	5.5E+04	4.6E+01	1.7E-03	**3.3E-01**
zirconium	0.0E+00	1.4E-01	0.0E+00	0.0E+00	0.0E+00	0.0E+00	**0.0E+00**

Abbreviations: "—"= not available; Avg = Average; Conc = Concentration; Kd = soil-water partitioning coefficient.

[a] See Section 4.3.1 of the main report for a description of the methods and calculations used to estimate leaching from buried carcasses to ground water and to estimate maximum likely chemical concentrations in groundwater as drawn up the well for household uses. Original leachate concentration data are from Pratt and Fonstad (2009). Leachate accumulated on top of 40 mil liner of pit, thus, concentrations of most chemicals increased over time as the carcasses continued to decompose. Exceptions include chemicals that might have off-gassed through the vent pipe and some that might have precipitated out of solution or sorbed to particles over time. Additional sampling dates included Nov 23, 2005, May 25, 2006, and October 26, 2006.

[b] As described in main report, Section 3.4, the initial fresh carcass weight = 45,359 kg. Young et al. (2001) estimated that 60% of a buried mammalian corpse degrades in the first year; 33% of the carcass mass is released during the first two months after burial; and half of that is released in the first week. Based on those estimates, the quantity of leachate released in the first week = 7,500 L was calculated; over the next 8–10 weeks = 15,000 L; and in the first year = 27,000 L. To estimate the total mg of chemical released over the first week (column I), concentrations from the first sample (August 17, column B) were multiplied by 7,500 L. To estimate the total mg of chemical released over the first 8–10 weeks (column J), the average concentration over the first three sampling dates (column D) was multiplied by 15,000 L. To estimate the total mg of chemical released over first year (column K), the average concentration over the first 12 months (column E) was multiplied by 27,000 L.

Table G.3. Estimated Leaching and Well Water Concentration of Chemicals from Buried Carcasses During the First Year.[a,b]

Chemical	A	B	C	D	E	F	G
	Avg Conc First Year (mg/L)	Kd (L/kg)	Total Released First Year (mg)	Total Filtered Back to Soil from Leachate First Year (mg)	Total Reaching Groundwater (mg)	Intercepted by 0.2 m Well Per Day, First Year (mg/d)	Avg Conc In Drinking Water, First Year (mg/L) 1136 L/d
aluminum	6.7E-01	1.5E+03	1.8E+04	1.1E+04	7.1E+03	4.2E-02	**3.7E-05**
ammonium	0.0E+00	1.4E-01	0.0E+00	0.0E+00	0.0E+00	0.0E+00	**0.0E+00**
barium	3.8E+01	4.1E+01	1.0E+06	6.2E+05	4.0E+05	2.4E+00	**2.1E-03**
beryllium	2.5E+03	7.9E+02	6.7E+07	4.1E+07	2.6E+07	1.6E+02	**1.4E-01**
bicarbonate	0.0E+00	1.0E-02	0.0E+00	0.0E+00	0.0E+00	0.0E+00	**0.0E+00**
boron	4.2E-03	1.4E-01	1.1E+02	1.1E+02	2.3E-01	1.4E-06	**1.2E-09**
cadmium	7.8E-01	7.5E+01	2.1E+04	2.1E+04	4.5E+00	2.7E-05	**2.4E-08**
calcium	9.2E+03	1.4E-01	2.5E+08	0.0E+00	2.5E+08	1.5E+03	**1.3E+00**
chloride	5.6E+04	1.4E-01	1.5E+09	0.0E+00	1.5E+09	9.0E+03	**8.0E+00**
chromium	3.3E+01	1.9E+01	8.8E+05	8.8E+05	1.3E+03	7.5E-03	**6.6E-06**
cobalt	0.0E+00	4.5E+01	0.0E+00	0.0E+00	0.0E+00	0.0E+00	**0.0E+00**
copper	1.9E+01	4.3E+02	5.1E+05	3.1E+05	2.0E+05	1.2E+00	**1.1E-03**
inorganic C	2.7E-01	—	7.3E+03	7.3E+03	1.0E+01	6.2E-05	**5.5E-08**
organic C	0.0E+00	—	0.0E+00	0.0E+00	0.0E+00	0.0E+00	**0.0E+00**
iron	1.8E-01	6.5E+01	4.9E+03	3.0E+03	1.9E+03	1.2E-02	**1.0E-05**
lead	6.5E-02	9.0E+02	1.8E+03	1.8E+03	2.5E+00	1.5E-05	**1.3E-08**
magnesium	5.9E+00	1.4E-01	1.6E+05	9.6E+04	6.2E+04	3.7E-01	**3.3E-04**
manganese	1.8E+04	6.5E+01	4.9E+08	0.0E+00	4.9E+08	3.0E+03	**2.6E+00**
mercury	1.2E+03	2.0E-01	3.2E+07	1.9E+07	1.2E+07	7.5E+01	**6.6E-02**
molybdenum	2.1E+03	1.4E-01	5.6E+07	3.4E+07	2.2E+07	1.3E+02	**1.2E-01**
nickel	0.0E+00	6.5E+01	0.0E+00	0.0E+00	0.0E+00	0.0E+00	**0.0E+00**
nitrate/nitrite	2.4E+01	1.4E-01	6.5E+05	3.9E+05	2.5E+05	1.5E+00	**1.3E-03**
total N	0.0E+00	—	0.0E+00	0.0E+00	0.0E+00	0.0E+00	**0.0E+00**
phosphorus	2.0E+03	1.4E-01	5.4E+07	3.3E+07	2.1E+07	1.3E+02	**1.1E-01**
potassium	2.9E-01	1.4E-01	7.9E+03	4.8E+03	3.1E+03	1.9E-02	**1.6E-05**
selenium	5.0E+03	5.0E+00	1.4E+08	5.4E+07	8.2E+07	4.9E+02	**4.3E-01**

Chemical	A	B	C	D	E	F	G
	Avg Conc First Year (mg/L)	Kd (L/kg)	Total Released First Year (mg)	Total Filtered Back to Soil from Leachate First Year (mg)	Total Reaching Groundwater (mg)	Intercepted by 0.2 m Well Per Day, First Year (mg/d)	Avg Conc In Drinking Water, First Year (mg/L) 1136 L/d
silicon	1.7E+03	1.4E-01	4.5E+07	2.7E+07	1.8E+07	1.1E+02	**9.4E-02**
silver	8.3E-03	8.3E+00	2.3E+02	1.4E+02	8.8E+01	5.3E-04	**4.7E-07**
sodium	0.0E+00	1.4E-01	0.0E+00	0.0E+00	0.0E+00	0.0E+00	**0.0E+00**
strontium	2.6E+00	1.4E-01	7.1E+04	7.1E+04	1.1E+02	6.4E-04	**5.6E-07**
sulphate	8.3E-03	6.1E-02	2.3E+02	1.4E+02	8.8E+01	5.3E-04	**4.7E-07**
sulphur	6.7E-01	1.4E-01	1.8E+04	1.1E+04	7.1E+03	4.2E-02	**3.7E-05**
titanium	0.0E+00	1.4E-01	0.0E+00	0.0E+00	0.0E+00	0.0E+00	**0.0E+00**
vanadium	3.8E+01	1.0E+03	1.0E+06	6.2E+05	4.0E+05	2.4E+00	**2.1E-03**
zinc	2.5E+03	6.2E+01	6.7E+07	4.1E+07	2.6E+07	1.6E+02	**1.4E-01**
zirconium	0.0E+00	1.4E-01	0.0E+00	0.0E+00	0.0E+00	0.0E+00	**0.0E+00**

Abbreviations: "—"= not available; Avg = Average; Conc = Concentration; Kd = soil-water partitioning coefficient.

[a] See Section 4.3.1 of the main report for a description of the methods and calculations used to estimate leaching from buried carcasses to ground water and to estimate maximum likely chemical concentrations in groundwater as drawn up the well for household uses. Original leachate concentration data are from Pratt and Fonstad (2009). Leachate accumulated on top of 40 mil liner of pit, thus, concentrations of most chemicals increased over time as the carcasses continued to decompose. Exceptions include chemicals that might have off-gassed through the vent pipe and some that might have precipitated out of solution or sorbed to particles over time. Additional sampling dates included Nov 23, 2005, May 25, 2006, and October 26, 2006.

[b] As described in main report, Section 3.4, the initial fresh carcass weight = 45,359 kg. Young et al. (2001) estimated that 60% of a buried mammalian corpse degrades in the first year; 33% of the carcass mass is released during the first two months after burial; and half of that is released in the first week. Based on those estimates, the quantity of leachate released in the first week = 7,500 L was calculated; over the next 8–10 weeks = 15,000 L; and in the first year = 27,000 L. To estimate the total mg of chemical released over the first week (column I), concentrations from the first sample (August 17, column B) were multiplied by 7,500 L. To estimate the total mg of chemical released over the first 8–10 weeks (column J), the average concentration over the first three sampling dates (column D) was multiplied by 15,000 L. To estimate the total mg of chemical released over first year (column K), the average concentration over the first 12 months (column E) was multiplied by 27,000 L.

Table G.4. Estimated Leaching and Well Water Concentration of Chemicals from Carcass Storage During the First Two Days.[a,b]

Chemical	A	B	C	D	E	F	G
	Avg Conc First Week (mg/L)	Kd (L/kg)	Total Released, Two Days (mg)	Total Filtered Back to Soil from Leachate, Two Days (mg)	Total Reaching Groundwater (mg)	Intercepted by 0.2 m Well Per Day, Two Days (mg/d)	Avg Conc In Drinking Water, Two Days (mg/L) 1136 L/d
aluminum	1.7E+00	1.5E+03	3.6E+03	3.6E+03	2.2E-01	1.1E-03	**2.7E-09**
ammonium	5.2E+03	1.4E-01	1.1E+07	6.8E+06	4.4E+06	2.2E+04	**5.2E-02**
barium	3.0E-01	4.1E+01	6.4E+02	6.4E+02	1.4E+00	7.2E-03	**1.7E-08**
beryllium	0.0E+00	7.9E+02	0.0E+00	0.0E+00	0.0E+00	0.0E+00	**0.0E+00**
bicarbonate	3.5E+04	1.0E-02	7.5E+07	7.3E+06	6.8E+07	3.4E+05	**8.1E-01**
boron	0.0E+00	1.4E-01	0.0E+00	0.0E+00	0.0E+00	0.0E+00	**0.0E+00**
cadmium	0.0E+00	7.5E+01	0.0E+00	0.0E+00	0.0E+00	0.0E+00	**0.0E+00**
calcium	6.0E+01	1.4E-01	1.3E+05	7.8E+04	5.0E+04	2.5E+02	**6.0E-04**
chloride	2.6E+03	1.4E-01	5.6E+06	3.4E+06	2.2E+06	1.1E+04	**2.6E-02**
chromium	0.0E+00	1.9E+01	0.0E+00	0.0E+00	0.0E+00	0.0E+00	**0.0E+00**
cobalt	1.0E-01	4.5E+01	2.1E+02	2.1E+02	4.4E-01	2.2E-03	**5.3E-09**
copper	6.0E-01	4.3E+02	1.3E+03	1.3E+03	2.8E-01	1.4E-03	**3.3E-09**
inorganic C	6.9E+03	—	1.5E+07	0.0E+00	1.5E+07	7.3E+04	**1.8E-01**
organic C	4.3E+04	—	9.2E+07	0.0E+00	9.2E+07	4.6E+05	**1.1E+00**
iron	1.1E+02	6.5E+01	2.4E+05	2.4E+05	3.3E+02	1.7E+00	**4.0E-06**
lead	0.0E+00	9.0E+02	0.0E+00	0.0E+00	0.0E+00	0.0E+00	**0.0E+00**
magnesium	3.0E+01	1.4E-01	6.4E+04	3.9E+04	2.5E+04	1.3E+02	**3.0E-04**
manganese	5.0E-01	6.5E+01	1.1E+03	1.1E+03	1.5E+00	7.5E-03	**1.8E-08**
mercury	0.0E+00	2.0E-01	0.0E+00	0.0E+00	0.0E+00	0.0E+00	**0.0E+00**
molybdenum	1.8E+00	1.4E-01	3.9E+03	2.3E+03	1.5E+03	7.5E+00	**1.8E-05**
nickel	4.0E-01	6.5E+01	8.6E+02	8.5E+02	1.2E+00	6.0E-03	**1.5E-08**
nitrate/nitrite	2.3E+01	1.4E-01	4.9E+04	3.0E+04	1.9E+04	9.6E+01	**2.3E-04**
total N	1.8E+04	—	3.9E+07	0.0E+00	3.9E+07	1.9E+05	**4.7E-01**
phosphorus	9.2E+02	1.4E-01	2.0E+06	1.2E+06	7.7E+05	3.8E+03	**9.3E-03**
potassium	1.9E+03	1.4E-01	4.1E+06	2.5E+06	1.6E+06	7.9E+03	**1.9E-02**

Chemical	A	B	C	D	E	F	G
	Avg Conc First Week (mg/L)	Kd (L/kg)	Total Released, Two Days (mg)	Total Filtered Back to Soil from Leachate, Two Days (mg)	Total Reaching Groundwater (mg)	Intercepted by 0.2 m Well Per Day, Two Days (mg/d)	Avg Conc In Drinking Water, Two Days (mg/L) 1136 L/d
selenium	0.0E+00	5.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	**0.0E+00**
silicon	2.9E+01	1.4E-01	6.2E+04	3.8E+04	2.4E+04	1.2E+02	**2.9E-04**
silver	0.0E+00	8.3E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	**0.0E+00**
sodium	1.6E+03	1.4E-01	3.4E+06	2.1E+06	1.3E+06	6.7E+03	**1.6E-02**
strontium	7.0E-01	1.4E-01	1.5E+03	9.1E+02	5.9E+02	2.9E+00	**7.0E-06**
sulphate	3.7E+03	6.1E-02	7.9E+06	3.2E+06	4.8E+06	2.4E+04	**5.7E-02**
sulphur	1.2E+03	1.4E-01	2.6E+06	1.6E+06	1.0E+06	5.0E+03	**1.2E-02**
titanium	2.0E-01	1.4E-01	4.3E+02	2.6E+02	1.7E+02	8.3E-01	**2.0E-06**
vanadium	0.0E+00	1.0E+03	0.0E+00	0.0E+00	0.0E+00	0.0E+00	**0.0E+00**
zinc	3.5E+00	6.2E+01	7.5E+03	7.5E+03	1.1E+01	5.5E-02	**1.3E-07**
zirconium	2.0E-01	1.4E-01	4.3E+02	2.6E+02	1.7E+02	8.3E-01	**2.0E-06**

Abbreviations: "—" = not available; Avg = Average; Conc = Concentration; Kd = soil-water partitioning coefficient.

[a] See Section 4.3.1 of the main report for a description of the methods and calculations used to estimate leaching from buried carcasses to ground water and to estimate maximum likely chemical concentrations in groundwater as drawn up the well for household uses. Original leachate concentration data are from Pratt and Fonstad (2009). Leachate accumulated on top of 40 mil liner of pit, thus, concentrations of most chemicals increased over time as the carcasses continued to decompose. Exceptions include chemicals that might have off-gassed through the vent pipe and some that might have precipitated out of solution or sorbed to particles over time. Additional sampling dates included Nov 23, 2005, May 25, 2006, and October 26, 2006.

[b] As described in main report, Section 3.4, the initial fresh carcass weight = 45,359 kg. Young et al. (2001) estimated that 60% of a buried mammalian corpse degrades in the first year; 33% of the carcass mass is released during the first two months after burial; and half of that is released in the first week. Based on those estimates, the quantity of leachate released in the first week = 7,500 L was calculated; over the next 8–10 weeks = 15,000 L; and in the first year = 27,000 L. To estimate the total mg of chemical released over the first week (column I), concentrations from the first sample (August 17, column B) were multiplied by 7,500 L. To estimate the total mg of chemical released over the first 8–10 weeks (column J), the average concentration over the first three sampling dates (column D) was multiplied by 15,000 L. To estimate the total mg of chemical released over first year (column K), the average concentration over the first 12 months (column E) was multiplied by 27,000 L.

Table G.5. Estimated Leaching and Well Water Concentration of Chemicals from a Windrow During the First Year.[a,b]

Chemical	A	B	C	D	E	F	G	H
	Avg Conc First Year (mg/L)	Kd (L/kg)	Total Released from Carcasses (mg/yr)	Total Released from Windrow (mg/yr)	Total Filtered Back to Soil from Leachate First Year (mg/yr)	Total Reaching Groundwater (mg/yr)	Intercepted by 0.2 m Well, First Year (mg/yr)	Avg Conc In Drinking Water, First Year (mg/L) 1136 L/d
aluminum	6.7E-01	1.5E+03	1.7E+04	8.4E+02	8.4E+02	5.2E-02	1.7E-04	**4.1E-10**
ammonium	0.0E+00	1.4E-01	3.0E+08	1.5E+07	9.0E+06	5.8E+06	1.9E+04	**4.6E-02**
barium	3.8E+01	4.1E+01	4.7E+03	2.4E+02	2.4E+02	5.3E-01	1.8E-03	**4.2E-09**
beryllium	2.5E+03	7.9E+02	na	na	na	na	na	na
bicarbonate	0.0E+00	1.0E-02	1.3E+09	6.4E+07	6.2E+06	5.8E+07	1.9E+05	**4.6E-01**
boron	4.2E-03	1.4E-01	1.8E+04	9.0E+02	5.5E+02	3.5E+02	1.2E+00	**2.8E-06**
cadmium	7.8E-01	7.5E+01	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	**0.0E+00**
calcium	9.2E+03	1.4E-01	1.0E+06	5.1E+04	3.1E+04	2.0E+04	6.5E+01	**1.6E-04**
chloride	5.6E+04	1.4E-01	6.7E+07	3.4E+06	2.0E+06	1.3E+06	4.3E+03	**1.0E-02**
chromium	3.3E+01	1.9E+01	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	**0.0E+00**
cobalt	0.0E+00	4.5E+01	1.1E+02	5.6E+00	5.6E+00	1.2E-02	3.8E-05	**9.1E-11**
copper	1.9E+01	4.3E+02	2.1E+04	1.0E+03	1.0E+03	2.3E-01	7.4E-04	**1.8E-09**
inorganic C	2.7E-01	—	2.5E+08	1.2E+07	0.0E+00	1.2E+07	4.1E+04	**9.9E-02**
organic C	0.0E+00	—	1.5E+09	7.5E+07	0.0E+00	7.5E+07	2.5E+05	**6.0E-01**
iron	1.8E-01	6.5E+01	8.8E+05	4.4E+04	4.4E+04	6.3E+01	2.1E-01	**4.9E-07**
lead	6.5E-02	9.0E+02	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	**0.0E+00**
magnesium	5.9E+00	1.4E-01	5.1E+05	2.5E+04	1.5E+04	1.0E+04	3.3E+01	**7.9E-05**
manganese	1.8E+04	6.5E+01	7.3E+03	3.6E+02	3.6E+02	5.2E-01	1.7E-03	**4.1E-09**
mercury	1.2E+03	2.0E-01	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	**0.0E+00**
molybdenum	2.1E+03	1.4E-01	4.9E+03	2.4E+02	1.5E+02	9.6E+01	3.1E-01	**7.6E-07**
nickel	0.0E+00	6.5E+01	1.8E+03	8.8E+01	8.8E+01	1.3E-01	4.1E-04	**9.9E-10**
nitrate/nitrite	2.4E+01	1.4E-01	1.6E+05	7.9E+03	4.8E+03	3.1E+03	1.0E+01	**2.5E-05**
total N	0.0E+00	—	4.9E+08	2.5E+07	0.0E+00	2.5E+07	8.1E+04	**2.0E-01**
phosphorus	2.0E+03	1.4E-01	3.2E+07	1.6E+06	9.6E+05	6.2E+05	2.0E+03	**4.9E-03**
potassium	2.9E-01	1.4E-01	5.6E+07	2.8E+06	1.7E+06	1.1E+06	3.6E+03	**8.7E-03**

Chemical	A	B	C	D	E	F	G	H
	Avg Conc First Year (mg/L)	Kd (L/kg)	Total Released from Carcasses (mg/yr)	Total Released from Windrow (mg/yr)	Total Filtered Back to Soil from Leachate First Year (mg/yr)	Total Reaching Groundwater (mg/yr)	Intercepted by 0.2 m Well, First Year (mg/yr)	Avg Conc In Drinking Water, First Year (mg/L) 1136 L/d
selenium	5.0E+03	5.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	**0.0E+00**
silicon	1.7E+03	1.4E-01	6.5E+05	3.2E+04	2.0E+04	1.3E+04	4.2E+01	**1.0E-04**
silver	8.3E-03	8.3E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	**0.0E+00**
sodium	0.0E+00	1.4E-01	5.4E+07	2.7E+06	1.7E+06	1.1E+06	3.5E+03	**8.5E-03**
strontium	2.6E+00	1.4E-01	7.9E+03	4.0E+02	2.4E+02	1.6E+02	5.1E-01	**1.2E-06**
sulphate	8.3E-03	6.1E-02	1.4E+08	6.8E+06	2.7E+06	4.1E+06	1.3E+04	**3.2E-02**
sulphur	6.7E-01	1.4E-01	4.5E+07	2.3E+06	1.4E+06	8.9E+05	2.9E+03	**7.0E-03**
titanium	0.0E+00	1.4E-01	2.3E+02	1.1E+01	6.8E+00	4.4E+00	1.4E-02	**3.5E-08**
vanadium	3.8E+01	1.0E+03	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	**0.0E+00**
zinc	2.5E+03	6.2E+01	7.1E+04	3.6E+03	3.6E+03	5.3E+00	1.7E-02	**4.2E-08**
zirconium	0.0E+00	1.4E-01	2.3E+02	1.1E+01	6.8E+00	4.4E+00	1.4E-02	**3.5E-08**

Abbreviations: "—" = not available; Avg = Average; Conc = Concentration; Kd = soil-water partitioning coefficient; na = not analyzed.

[a] See Section 4.3.1 of the main report for a description of the methods and calculations used to estimate leaching from buried carcasses to ground water and to estimate maximum likely chemical concentrations in groundwater as drawn up the well for household uses. Original leachate concentration data are from Pratt and Fonstad (2009). Leachate accumulated on top of 40 mil liner of pit, thus, concentrations of most chemicals increased over time as the carcasses continued to decompose. Exceptions include chemicals that might have off-gassed through the vent pipe and some that might have precipitated out of solution or sorbed to particles over time. Additional sampling dates included Nov 23, 2005, May 25, 2006, and October 26, 2006.

[b] As described in main report, Section 3.4, the initial fresh carcass weight = 45,359 kg. Young et al. (2001) estimated that 60% of a buried mammalian corpse degrades in the first year; 33% of the carcass mass is released during the first two months after burial; and half of that is released in the first week. Based on those estimates, the quantity of leachate released in the first week = 7,500 L was calculated; over the next 8–10 weeks = 15,000 L; and in the first year = 27,000 L. To estimate the total mg of chemical released over the first week (column I), concentrations from the first sample (August 17, column B) were multiplied by 7,500 L. To estimate the total mg of chemical released over the first 8–10 weeks (column J), the average concentration over the first three sampling dates (column D) was multiplied by 15,000 L. To estimate the total mg of chemical released over first year (column K), the average concentration over the first 12 months (column E) was multiplied by 27,000 L.

Table G.6. Documentation of Columns A through H in Tables G.1 – G.5.

Column	Description of Column Data or Calculation	Origin of Values or Equation Parameters
A	Average concentration in burial leachate for time period indicated.	Data presented in Pratt and Fondstad (2009).
B	Chemical-specific solid-liquid partition coefficient. Used to estimate equilibrium distribution of chemical between soil & leachate.	HHRAP companion database and other sources.
C	Total amount of chemical (mg) leached from carcass in time period indicated. See footnote b to the tables for information about the leachate volumes.	(Col. A) x 7,500 liters fluid leached in first week, (Col. A) x 15,000 liters fluid leached in first two months, and (Col. A) x 27,000 liters fluid leached in first year.
D	Windrow scenario only. Total chemical released from windrow to ground below. Percentage assumption based on Glanville et al. (2006) and Donaldson et al. (2012).	(Col. C) x 5% [the percentage of leachate that is not absorbed by woodchips or other carbon bulking material].
E	Amount of chemical (mg) absorbed to soil as the leachate passes through vadose zone soil.	[(Col. B) x [dry weight of soil saturated by leachate, in kg] x (Col. C)] / [volume of leachate in L) + (Col. B) x dry weight of soil saturated by leachate, in kg)]. For the windrow scenario only, substitute Col. D for Col. C. See section 4.3.1 of the main report a discussion of this equation. Dry weights of soil saturated by leachate: • burial scenario – 291,600 kg, • storage pile scenario – 23,112 kg, and • windrow scenario – 14,580 kg. These are estimated assuming a water-filled soil porosity of 0.2 (unitless) and a solids particle density of 2.7 g/cm^3, both HHRAP defaults.
F	Amount of chemical (mg) that reaches the groundwater aquifer.	(Col. C. – Col. E). For the windrow scenario only, substitute Col. D for Col. C.
G	Amount of chemical intercepted by the drinking water well per day.	(Col. F/[number of days during period indicated] x (fraction plume intercepted)]. See main report, Section 4.3.5 for further discussion of methods for well water concentrations. Fraction of plume intercepted (Section 4.3.5): • burial scenario – 0.0022, • storage pile scenario – 0.0050, and • windrow scenario – 0.0033.
H	Average chemical concentration (mg/L) in drinking water.	[(Col. G) / 1,136 L/d).

Abbreviations: ^ = raised to the power of; Col. = column; d = days; HHRAP = *Human Health Risk Assessment Protocol for Hazardous Waste Combustion Facilities*; mo = month; wk = w.

Appendix H. Supporting Information for Chemical Leaching from Combustion Ash

Section 4.3.2 of the main report describes the data and calculations used to estimate chemical leaching of from ash to groundwater for the on-site open burning and air-curtain burning options. Table H.1 through Table H.8 documents the derivation of data and calculations for buried ash. Documentation in Table H.8 provides further details of these estimation methods, including data and assumptions about the amount of ash produced by each option (Table H.1), the area of ash disposal (Table H.2), the precipitation that infiltrates the ash and becomes leachate and soil properties used in partitioning calculations (Table H.3), concentrations of chemicals in ash from open burning (Table H.4) and air-curtain burning (Table H.5), formulas used to estimate leaching (Table H.86 and Table H.7), and a key to the columns in Table H.6 and Table H.7 (Table H.8).

H.1. References

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Table H.1. Quantities of Fuels and Ash for On-site Combustion-based Carcass Management Options.

Management Option	Combusted Material	Fuel Mass Per 100 cattle (each weighing 1,000 lbs)			Percent Ash	Total Ash Remaining (tons)	Total Ash Remaining (kg)
		kg	lb	U.S. Tons			
Combustion Fuels							
Open Burning	300 hay bales (3 per carcass[a] x 20 kg per bale[b])	6,000	13,228	7	1.00%[d]	0.07	60
	300 heavy timbers, 8 ft^3 each (3 per carcass[a] x 500 kg/m^3 per railroad tie[b])	33,980	74,913	37	1.00%[d]	0.37	340
	50 lbs kindling [per carcass] x 100 cows = 5,000 lbs	2,268	5,000	3	1.00%[d]	0.03	23
	10,000 lbs coal [100 lbs/carcass[a]]	4,536	10,000	5	2.00%[e]	0.10	91
	100 gal gasoline [1 gallon per animal[a]]	286	630	0	0.00%	0.00	-
	Total	**47,070**	**103,771**	**52**	--	**0.57**	**513**
Air-curtain Burning	Wood (4:1 wood to carcass ratio. 50 U.S. tons carcass requires 200 tons wood)	181,437	399,999	200	0.27%[f]	0.55	498
	200 gal diesel inside unit (NABCC 2004)	642	1,415	1	~0.00%	0.00	-
	168 gal diesel blower fuel (3.5 gal/hr[c] x 48 hr burn)	539	1,189	1	~0.00%	0.00	-
	Total	**182,172**	**401,620**	**201**	--	0.55	**498**
Ash from Carcass Combustion							
Open Burning	100 carcasses; 1000 lb each; 50 tons total	45,359	100,000	50	6.00%[g]	3.00	**2,722**
Air-curtain	100 carcasses; 1000 lb each; 50 tons total	45,359	100,000	50	6.00%[g]	3.00	**2,722**
Total Ash from Carcasses and fuels							
Open Burning						**3.6**	**3.235**
Air-curtain Burning						**3.5**	**3,220**

Abbreviations: ft = feet; gal = gallons; hr = hours; lbs = pounds.
[a] USDA (2005)
[b] Watkiss and Smith (2001)
[c] Air Burners, Inc. (2012)
[d] Pitman (2006)
[e] Butalia et al. (2015)
[f] Narodoslawsky and Obernberger (1996)
[g] NRC 2000

Table H.2. Ash Disposal Areas.

Management Option	Area Basis	Ash Disposal Area

		ft^2	m^2
Open Burning	Cover ash in place. Disposal area is the same as the pyre area: 8 ft x 300 ft [a]	2,400	223
Air-curtain Burning	Bury ash in a pit assumed to have the same dimensions as the air-curtain burner: 11.40m × 3.6m [b]	441	41

Abbreviations: ft = feet; ft^2 = square feet.

[a] USDA (2005).

[b] Air Burners, Inc. (2012).

Table H.3. Precipitation and Soil Assumptions for Leaching Calculations.

Parameter No.	Meteorological or Soil Parameter	Estimate	Basis of Estimate
P1	Total annual precipitation	96.84 cm/yr	Meteorological data (see main report, Section 2.1.1)
P2	Number of rain events per year	168 events/yr	Meteorological data (see main report, Section 2.1.1)
P3	Total precipitation hours	435 hr/yr	Meteorological data (see main report, Section 2.1.1)
P4	Precipitation per event	0.5764 cm/event	Calculated: P1/P2
P5	Precipitation per rain hour	0.2226 cm/rain hr	Calculated: P1/P3
P6	Average hours per event	2.6 hr	Calculated: P3/P2
P7	Water volume per m^2 of surface area per event	5764 cm^3 (5.8 L)	Calculated: P4 * 100 cm * 100 cm
P8	Total volume of water per m^2 per year	968.4 L	Calculated: P7*P2
P9	Water-filled soil porosity	0.2 dimensionless	HHRAP default (USEPA 2005)
P10	Soil particle density	2.7 g/cm^3 (2.7 kg/L)	HHRAP default (USEPA 2005)
P11	Volume of soil per m^2 area saturated per rain event	29 L (0.029 m^3)	Calculated: P7/P9
P12	Dry weight of saturated soil	62 kg	Calculated: P11 * (1 – P9) * P10
P13	Depth of unsaturated soil zone	1 m	Assumed
P14	Depth of soil saturated per rain event	0.029 m	Calculated: P11/1 m^2
P15	Number of soil layers in unsaturated zone	35	Calculated: P13/P14

Abbreviations: HHRAP = *Human Health Risk Assessment Protocol for Hazardous Waste Combustion Facilities*; hr = hours.

Table H.4. Estimated Chemical Concentrations in Ash from Open Burning.

Chemical (PAH number of rings)	Chemical Conc. In Ash (µg/kg)			Chemical Mass in Ash (mg)				Chem. Conc. In Pyre Ash (mg/kg)	Chem. Conc. In Pyre Ash (µg/kg)
	Ash from Carcasses	Ash from Wood Fuels	Ash from Coal	Ash from Carcasses	Ash from Wood Fuels	Ash from Coal	Total		
	A	B	C	D	E	F	G	H	I
Napthalene (2)	1.2E+02	3E+03	2.3E+02	3.3E+02	1.2E+03	2.1E+01	1.5E+03	4.7E-01	4.7E+02
Acenapthylene (3)	5.0E+00	1E+02	nd	1.4E+01	4.8E+01	na	6.2E+01	1.9E-02	1.9E+01
Phenanthrene (3)	4.6E+01	1E+03	3.1E+02	1.3E+02	4.5E+02	2.8E+01	6.0E+02	1.9E-01	1.9E+02
Fluorene (3)	1.5E+01	3E+02	2.8E+02	4.1E+01	1.5E+02	2.5E+01	2.1E+02	6.5E-02	6.5E+01
Acenaphthene (3)	1.0E+01	2E+02	1.9E+02	2.7E+01	9.7E+01	1.7E+01	1.4E+02	4.4E-02	4.4E+01
Anthracene (3)	3.3E+01	8E+02	nd	8.9E+01	3.2E+02	na	4.1E+02	1.3E-01	1.3E+02
Pyrene (4)	2.5E+01	6E+02	2.6E+02	6.8E+01	2.4E+02	2.3E+01	3.3E+02	1.0E-01	1.0E+02
Chrysene (4)	3.2E+01	7E+02	2.1E+02	8.7E+01	3.1E+02	1.9E+01	4.2E+02	1.3E-01	1.3E+02
Fluoranthene (4)	2.5E+01	6E+02	2.9E+02	6.8E+01	2.4E+02	2.6E+01	3.4E+02	1.0E-01	1.0E+02
Benzo[a]anthracene (4)	1.0E+01	2E+02	2.9E+02	2.7E+01	9.7E+01	2.7E+01	1.5E+02	4.7E-02	4.7E+01
Benzo[a]pyrene (5)	3.5E+01	8E+02	8.7E+02	9.5E+01	3.4E+02	7.9E+01	5.1E+02	1.6E-01	1.6E+02
Benzo[e]pyrene (5)	1.5E+01	3E+02	na	4.1E+01	1.5E+02	na	1.9E+02	5.8E-02	5.8E+01
Benzo[b]fluoranthene (5)	1.5E+01	3E+02	3.6E+02	4.1E+01	1.5E+02	3.2E+01	2.2E+02	6.8E-02	6.8E+01
Benzo[k]fluoranthene (5)	1.0E+01	2E+02	4.2E+02	2.7E+01	9.7E+01	3.8E+01	1.6E+02	5.0E-02	5.0E+01
Cyclopenta[c,d]pyrene (5)	2.0E+01	5E+02	na	5.4E+01	1.9E+02	na	2.5E+02	7.7E-02	7.7E+01
Perylene (5)	2.5E+01	6E+02	na	6.8E+01	2.4E+02	na	3.1E+02	9.6E-02	9.6E+01
Dibenz[a,h]anthracene (6)	4.1E+01	9E+02	2.5E+02	1.1E+02	4.0E+02	2.2E+01	5.3E+02	1.6E-01	1.6E+02
Indeno[1,2,3-cd] pyrene (6)	3.8E+01	9E+02	2.6E+02	1.0E+02	3.7E+02	2.4E+01	5.0E+02	1.5E-01	1.5E+02
Benzo[g,h,i]perylene (6)	2.2E+01	5E+02	1.1E+02	6.0E+01	2.1E+02	9.5E+00	2.8E+02	8.7E-02	8.7E+01
Benzo[b]chrysene (6)	1.9E+01	4E+02	na	5.2E+01	1.8E+02	na	2.4E+02	7.3E-02	7.3E+01
Coronene (7)	1.7E+02	4E+03	na	4.6E+02	1.6E+03	na	2.1E+03	6.5E-01	6.5E+02
Total PAHs								2.9E+00	2.9E+03
OctaCDD, 1,2,3,4,6,7,8,9-	na	3.0E-02	na	na	1.3E-02	na	1.3E-02	3.9E-06	3.9E-03
OctaCDF, 1,2,3,4,6,7,8,9-	na	1.9E-03	na	na	8.0E-04	na	8.0E-04	2.5E-07	2.5E-04
HeptaCDD, 1,2,3,4,6,7,8-	na	9.0E-03	na	na	3.8E-03	na	3.8E-03	1.2E-06	1.2E-03
HeptaCDF, 1,2,3,4,6,7,8-	na	6.0E-03	na	na	2.5E-03	na	2.5E-03	7.8E-07	7.8E-04
HeptaCDF, 1,2,3,4,7,8,9-	na	1.8E-03	na	na	7.6E-04	na	7.6E-04	2.4E-07	2.4E-04
HexaCDD, 1,2,3,4,7,8-	na	1.7E-03	na	na	7.2E-04	na	7.2E-04	2.2E-07	2.2E-04

Chemical (PAH number of rings)	Chemical Conc. In Ash (µg/kg)			Chemical Mass in Ash (mg)				Chem. Conc. In Pyre Ash (mg/kg)	Chem. Conc. In Pyre Ash (µg/kg)
	Ash from Carcasses	Ash from Wood Fuels	Ash from Coal	Ash from Carcasses	Ash from Wood Fuels	Ash from Coal	Total		
	A	B	C	D	E	F	G	H	I
HexaCDF, 1,2,3,4,7,8-	na	1.8E-03	na	na	7.6E-04	na	7.6E-04	2.4E-07	2.4E-04
HexaCDD, 1,2,3,6,7,8-	na	1.1E-03	na	na	4.6E-04	na	4.6E-04	1.4E-07	1.4E-04
HexaCDF, 1,2,3,6,7,8-	na	7.0E-03	na	na	3.0E-03	na	3.0E-03	9.1E-07	9.1E-04
HexaCDD, 1,2,3,7,8,9 -	na	1.7E-03	na	na	7.2E-04	na	7.2E-04	2.2E-07	2.2E-04
HexaCDF, 1,2,3,7,8,9-	na	1.0E-03	na	na	4.2E-04	na	4.2E-04	1.3E-07	1.3E-04
PentaCDD, 1,2,3,7,8-	na	1.7E-03	na	na	7.2E-04	na	7.2E-04	2.2E-07	2.2E-04
PentaCDF, 1,2,3,7,8-	na	4.0E-03	na	na	1.7E-03	na	1.7E-03	5.2E-07	5.2E-04
HexaCDF, 2,3,4,6,7,8-	na	1.3E-03	na	na	5.5E-04	na	5.5E-04	1.7E-07	1.7E-04
PentaCDF, 2,3,4,7,8-	na	3.5E-03	na	na	1.5E-03	na	1.5E-03	4.6E-07	4.6E-04
TetraCDD, 2,3,7,8-	na	8.0E-04	na	na	3.4E-04	na	3.4E-04	1.0E-07	1.0E-04
TetraCDF, 2,3,7,8-	na	4.0E-03	na	na	1.7E-03	na	1.7E-03	5.2E-07	5.2E-04
Total Dioxins/furans								1.0E-05	1.0E-02
Arsenic	nd	3.0E+03	1.4E+02	na	1.3E+03	1.3E+01	1.3E+03	3.9E-01	3.9E+02
Cadmium	3.1E+02	1.2E+03	0.0E+00	8.4E+02	4.9E+02	0.0E+00	1.3E+03	4.1E-01	4.1E+02
Chromium, total	5.5E+03	1.9E+05	5.2E+04	1.5E+04	7.9E+04	4.7E+03	9.9E+04	3.0E+01	3.0E+04
Copper	2.3E+04	1.5E+05	4.8E+04	6.3E+04	6.2E+04	4.3E+03	1.3E+05	4.0E+01	4.0E+04
Iron	1.2E+04	1.2E+07	4.9E+07	3.2E+04	5.0E+06	4.5E+06	9.5E+06	2.9E+03	2.9E+06
Lead	1.3E+03	7.7E+03	1.7E+04	3.6E+03	3.3E+03	1.6E+03	8.5E+03	2.6E+00	2.6E+03
Manganese	2.3E+03	1.2E+07	2.8E+05	6.4E+03	5.2E+06	2.5E+04	5.2E+06	1.6E+03	1.6E+06
Nickel	8.1E+03	2.7E+04	4.2E+04	2.2E+04	1.1E+04	3.8E+03	3.7E+04	1.2E+01	1.2E+04
Zinc	3.2E+03	4.9E+05	5.7E+04	8.8E+03	2.1E+05	5.2E+03	2.2E+05	6.8E+01	6.8E+04

Abbreviations: na = not applicable; nd = no data; PAH = polycyclic aromatic hydrocarbon.

Table H.5. Estimated Chemical Concentrations in Ash from Air-Curtain Burning.

Chemical (PAH number of rings)	Chemical Conc. In Ash (µg/kg)			Total Chemical Mass in Ash (mg)				Chem. Conc. In Pyre Ash (mg/kg)	Chem. Conc. In Pyre Ash (µg/kg)
	Ash from Carcasses	Ash from Wood	Ash from Coal	Ash from Carcasses	Ash from Wood	Ash from Coal	Total		
	A	B	C	D	E	F	G	H	I
Napthalene (2)	8.6E+01	2E+03	na	2.3E+02	9.8E+02	0.0E+00	1.2E+03	3.8E-01	3.8E+02
Acenapthylene (3)	1.9E+01	4E+02	na	5.2E+01	2.2E+02	0.0E+00	2.7E+02	8.4E-02	8.4E+01
Phenanthrene (3)	6.5E+01	1E+03	na	1.8E+02	7.4E+02	0.0E+00	9.2E+02	2.9E-01	2.9E+02
Fluorene (3)	1.2E+01	3E+02	na	3.3E+01	1.4E+02	0.0E+00	1.7E+02	5.3E-02	5.3E+01
Acenaphthene (3)	2.5E+01	6E+02	na	6.8E+01	2.9E+02	0.0E+00	3.5E+02	1.1E-01	1.1E+02
Anthracene (3)	1.5E+01	3E+02	na	4.1E+01	1.7E+02	0.0E+00	2.1E+02	6.6E-02	6.6E+01
Pyrene (4)	2.3E+01	5E+02	na	6.3E+01	2.6E+02	0.0E+00	3.3E+02	1.0E-01	1.0E+02
Chrysene (4)	1.0E+01	2E+02	na	2.7E+01	1.1E+02	0.0E+00	1.4E+02	4.4E-02	4.4E+01
Fluoranthene (4)	5.0E+01	1E+03	na	1.4E+02	5.7E+02	0.0E+00	7.1E+02	2.2E-01	2.2E+02
Benzo[a]anthracene (4)	5.0E+00	1E+02	na	1.4E+01	5.7E+01	0.0E+00	7.1E+01	2.2E-02	2.2E+01
Benzo[a]pyrene (5)	6.0E+00	1E+02	na	1.6E+01	6.9E+01	0.0E+00	8.5E+01	2.6E-02	2.6E+01
Benzo[e]pyrene (5)	5.0E+00	1E+02	na	1.4E+01	5.7E+01	0.0E+00	7.1E+01	2.2E-02	2.2E+01
Benzo[b]fluoranthene (5)	3.0E+00	7E+01	na	8.2E+00	3.4E+01	0.0E+00	4.2E+01	1.3E-02	1.3E+01
Benzo[k]fluoranthene (5)	2.3E+01	5E+02	na	6.3E+01	2.6E+02	0.0E+00	3.3E+02	1.0E-01	1.0E+02
Cyclopenta[c,d]pyrene (5)	7.0E+00	2E+02	na	1.9E+01	8.0E+01	0.0E+00	9.9E+01	3.1E-02	3.1E+01
Perylene (5)	8.0E+00	2E+02	na	2.2E+01	9.1E+01	0.0E+00	1.1E+02	3.5E-02	3.5E+01
Dibenz[a,h]anthracene (6)	3.0E+00	7E+01	na	8.2E+00	3.4E+01	0.0E+00	4.2E+01	1.3E-02	1.3E+01
Indeno[1,2,3-c,d] pyrene (6)	4.0E+00	9E+01	na	1.1E+01	4.6E+01	0.0E+00	5.7E+01	1.8E-02	1.8E+01
Benzo[g,h,i]perylene (6)	3.0E+01	7E+02	na	8.2E+01	3.4E+02	0.0E+00	4.2E+02	1.3E-01	1.3E+02
Benzo[b]chrysene (6)	1.5E+01	3E+02	na	4.1E+01	1.7E+02	0.0E+00	2.1E+02	6.6E-02	6.6E+01
Coronene (7)	6.0E+01	1E+03	na	1.6E+02	6.9E+02	0.0E+00	8.5E+02	2.6E-01	2.6E+02
Total PAHs								**2.1E+00**	**2.1E+3**
OctaCDD, 1,2,3,4,6,7,8,9-	na	3.0E-02	na	na	1.5E-02	na	1.5E-02	4.6E-06	4.6E-03
OctaCDF, 1,2,3,4,6,7,8,9-	na	1.9E-03	na	na	9.5E-04	na	9.5E-04	2.9E-07	2.9E-04
HeptaCDD, 1,2,3,4,6,7,8-	na	9.0E-03	na	na	4.5E-03	na	4.5E-03	1.4E-06	1.4E-03
HeptaCDF, 1,2,3,4,6,7,8-	na	6.0E-03	na	na	3.0E-03	na	3.0E-03	9.3E-07	9.3E-04
HeptaCDF, 1,2,3,4,7,8,9-	na	1.8E-03	na	na	9.0E-04	na	9.0E-04	2.8E-07	2.8E-04
HexaCDD, 1,2,3,4,7,8-	na	1.7E-03	na	na	8.5E-04	na	8.5E-04	2.6E-07	2.6E-04

Chemical (PAH number of rings)	Chemical Conc. In Ash (µg/kg)			Total Chemical Mass in Ash (mg)				Chem. Conc. In Pyre Ash (mg/kg)	Chem. Conc. In Pyre Ash (µg/kg)
	Ash from Carcasses	Ash from Wood	Ash from Coal	Ash from Carcasses	Ash from Wood	Ash from Coal	Total		
	A	B	C	D	E	F	G	H	I
HexaCDF, 1,2,3,4,7,8-	na	1.8E-03	na	na	9.0E-04	na	9.0E-04	2.8E-07	2.8E-04
HexaCDD, 1,2,3,6,7,8-	na	1.1E-03	na	na	5.5E-04	na	5.5E-04	1.7E-07	1.7E-04
HexaCDF, 1,2,3,6,7,8-	na	7.0E-03	na	na	3.5E-03	na	3.5E-03	1.1E-06	1.1E-03
HexaCDD, 1,2,3,7,8,9 -	na	1.7E-03	na	na	8.5E-04	na	8.5E-04	2.6E-07	2.6E-04
HexaCDF, 1,2,3,7,8,9-	na	1.0E-03	na	na	5.0E-04	na	5.0E-04	1.5E-07	1.5E-04
PentaCDD, 1,2,3,7,8-	na	1.7E-03	na	na	8.5E-04	na	8.5E-04	2.6E-07	2.6E-04
PentaCDF, 1,2,3,7,8-	na	4.0E-03	na	na	2.0E-03	na	2.0E-03	6.2E-07	6.2E-04
HexaCDF, 2,3,4,6,7,8-	na	1.3E-03	na	na	6.5E-04	na	6.5E-04	2.0E-07	2.0E-04
PentaCDF, 2,3,4,7,8-	na	3.5E-03	na	na	1.7E-03	na	1.7E-03	5.4E-07	5.4E-04
TetraCDD, 2,3,7,8-	na	8.0E-04	na	na	4.0E-04	na	4.0E-04	1.2E-07	1.2E-04
TetraCDF, 2,3,7,8-	na	4.0E-03	na	na	2.0E-03	na	2.0E-03	6.2E-07	6.2E-04
Total Dioxins/furans								**1.2E-05**	**1.2E-02**
Arsenic	nd	3.0E+03	na	na	1.5E+03	0.0E+00	1.5E+03	4.6E-01	4.6E+02
Cadmium	3.0E+01	1.2E+03	na	8.2E+01	5.8E+02	0.0E+00	6.6E+02	2.1E-01	2.1E+02
Chromium, total	3.7E+03	1.9E+05	na	1.0E+04	9.3E+04	0.0E+00	1.0E+05	3.2E+01	3.2E+04
Copper	1.2E+04	1.5E+05	na	3.2E+04	7.3E+04	0.0E+00	1.1E+05	3.3E+01	3.3E+04
Iron	4.1E+05	1.2E+07	na	1.1E+06	5.9E+06	0.0E+00	7.0E+06	2.2E+03	2.2E+06
Lead	3.6E+04	7.7E+03	na	9.7E+04	3.8E+03	0.0E+00	1.0E+05	3.1E+01	3.1E+04
Manganese	8.6E+03	1.2E+07	na	2.3E+04	6.1E+06	0.0E+00	6.1E+06	1.9E+03	1.9E+06
Nickel	7.2E+03	2.7E+04	na	2.0E+04	1.4E+04	0.0E+00	3.3E+04	1.0E+01	1.0E+04
Zinc	8.9E+04	4.9E+05	na	2.4E+05	2.4E+05	0.0E+00	4.8E+05	1.5E+02	1.5E+05

Abbreviations: Chem. = Chemical; Conc. =Concentration; na = not applicable; nd = no data; PAH = polycyclic aromatic hydrocarbon.

Table H.6. Estimated Leaching of Chemicals from Ash and Partitioning with Subsurface Soil – Open Burning.[a]

Chemical	A	B	C	D	E	F	G	H	I	J	K
	Total in Ash (mg)	Chem. per area (mg / m2)	Kd (L/kg)	Amount Leached to Water in Ash Layer, per Rain Event (mg/m^2)	Amount Filtered from Leachate to Soil, per Rain Event (mg/m^2)	Amount Remaining in Leachate after Filter per Rain Event (mg/m^2)	Total Leached to Aquifer First Rain Event (mg)	Fraction Leached in Ash Layer per Rain Event	Total Leached per Year (mg)	Total Intercepted by Well per Year (mg)	Ann. Avg Conc. In Well Water (mg/L)
Napthalene	1.5E+03	6.9E+00	8.9E+01	3.1E-02	3.0E-02	3.2E-05	7.1E-03	4.6E-06	1.2E+0	2.6E-03	**6.3E-09**
Acenapthylene	6.2E+01	2.8E-01	2.8E+01	4.0E-03	3.9E-03	1.3E-05	2.9E-03	4.7E-05	4.9E-01	1.1E-03	**2.6E-09**
Phenanthrene	6.0E+02	2.7E+00	2.0E+03	5.4E-04	5.4E-04	2.5E-08	5.6E-06	9.3E-09	9.3E-04	2.0E-06	**4.9E-12**
Fluorene	2.1E+02	9.5E-01	5.8E+02	6.5E-04	6.5E-04	1.0E-07	2.3E-05	1.1E-07	3.9E-03	8.6E-06	**2.1E-11**
Acenaphthene	1.4E+02	6.3E-01	3.7E+02	6.8E-04	6.8E-04	1.7E-07	3.8E-05	2.7E-07	6.4E-03	1.4E-05	**3.4E-11**
Anthracene	4.1E+02	1.8E+00	1.8E+03	4.1E-04	4.1E-04	2.2E-08	4.8E-06	1.2E-08	8.1E-04	1.8E-06	**4.3E-12**
Pyrene	3.3E+02	1.5E+00	5.1E+03	1.2E-04	1.2E-04	2.1E-09	4.7E-07	1.4E-09	7.9E-05	1.7E-07	**4.2E-13**
Chrysene	4.2E+02	1.9E+00	3.0E+04	2.5E-05	2.5E-05	7.6E-11	1.7E-08	4.1E-11	2.8E-06	6.2E-09	**1.5E-14**
Fluoranthene	3.4E+02	1.5E+00	1.1E+03	5.6E-04	5.6E-04	4.9E-08	1.1E-05	3.2E-08	1.8E-03	4.0E-06	**9.6E-12**
Benzo[a]anthracene	1.5E+02	6.8E-01	2.7E+04	1.0E-05	1.0E-05	3.5E-11	7.7E-09	5.1E-11	1.3E-06	2.8E-09	**6.8E-15**
Benzo[a]pyrene	5.1E+02	2.3E+00	7.3E+04	1.3E-05	1.3E-05	1.6E-11	3.6E-09	7.0E-12	6.0E-07	1.3E-09	**3.2E-15**
Benzo[e]pyrene	1.9E+02	8.4E-01	9.9E+03	3.3E-05	3.3E-05	3.1E-10	7.0E-08	3.7E-10	1.2E-05	2.6E-08	**6.2E-14**
Benzo[b]fluoranthene	2.2E+02	9.8E-01	7.9E+04	5.0E-06	5.0E-06	5.8E-12	1.3E-09	6.0E-12	2.2E-07	4.8E-10	**1.2E-15**
Benzo[k]fluoranthene	1.6E+02	7.3E-01	7.4E+04	3.9E-06	3.9E-06	4.8E-12	1.1E-09	6.6E-12	1.8E-07	4.0E-10	**9.6E-16**
Cyclopenta[c,d]pyrene	2.5E+02	1.1E+00	2.0E+02	2.2E-03	2.2E-03	1.0E-06	2.3E-04	9.1E-07	3.8E-02	8.3E-05	**2.0E-10**
Perylene	3.1E+02	1.4E+00	2.7E+03	2.1E-04	2.1E-04	7.3E-09	1.6E-06	5.2E-09	2.7E-04	6.0E-07	**1.4E-12**
Dibenz[a,h]anthracene	5.3E+02	2.4E+00	1.3E+05	7.1E-06	7.1E-06	4.9E-12	1.1E-09	2.0E-12	1.8E-07	4.0E-10	**9.6E-16**
Indeno[1,2,3-c,d]pyrene	5.0E+02	2.2E+00	2.3E+05	3.8E-06	3.8E-06	1.5E-12	3.4E-10	6.9E-13	5.8E-08	1.3E-10	**3.0E-16**
Benzo[g,h,i]perylene	2.8E+02	1.3E+00	3.9E+04	1.3E-05	1.3E-05	3.1E-11	7.0E-09	2.5E-11	1.2E-06	2.6E-09	**6.2E-15**
Benzo[b]chrysene	2.4E+02	1.1E+00	1.3E+03	3.2E-04	3.2E-04	2.3E-08	5.1E-06	2.2E-08	8.6E-04	1.9E-06	**4.5E-12**
Coronene	2.1E+03	9.4E+00	1.9E+03	2.0E-03	2.0E-03	9.5E-08	2.1E-05	1.0E-08	3.6E-03	7.8E-06	**1.9E-11**

Chemical	A	B	C	D	E	F	G	H	I	J	K
	Total in Ash (mg)	Chem. per area (mg / m2)	Kd (L/kg)	Amount Leached to Water in Ash Layer, per Rain Event (mg/m^2)	Amount Filtered from Leachate to Soil, per Rain Event (mg/m^2)	Amount Remaining in Leachate after Filter per Rain Event (mg/m^2)	Total Leached to Aquifer First Rain Event (mg)	Fraction Leached in Ash Layer per Rain Event	Total Leached per Year (mg)	Total Intercepted by Well per Year (mg)	Ann. Avg Conc. In Well Water (mg/L)
Total PAHs											**9.2E-09**
OctaCDD, 1,2,3,4,6,7,8,9-	1.3E-02	5.7E-05	7.3E+06	3.1E-12	3.1E-12	3.9E-20	8.7E-18	6.8E-16	1.4E-15	3.1E-18	**7.5E-24**
OctaCDF, 1,2,3,4,6,7,8,9-	8.0E-04	3.6E-06	4.6E+06	3.1E-13	3.1E-13	6.2E-21	1.4E-18	1.7E-15	2.2E-16	4.9E-19	**1.2E-24**
HeptaCDD, 1,2,3,4,6,7,8-	3.8E-03	1.7E-05	4.6E+06	1.5E-12	1.5E-12	2.9E-20	6.5E-18	1.7E-15	1.1E-15	2.3E-18	**5.6E-24**
HeptaCDF, 1,2,3,4,6,7,8-	2.5E-03	1.1E-05	1.2E+06	3.9E-12	3.9E-12	3.1E-19	6.9E-17	2.7E-14	1.2E-14	2.5E-17	**6.1E-23**
HeptaCDF, 1,2,3,4,7,8,9-	7.6E-04	3.4E-06	1.2E+06	1.2E-12	1.2E-12	9.3E-20	2.1E-17	2.7E-14	3.5E-15	7.6E-18	**1.8E-23**
HexaCDD, 1,2,3,4,7,8-	7.2E-04	3.2E-06	2.9E+05	4.4E-12	4.4E-12	1.4E-18	3.1E-16	4.3E-13	5.2E-14	1.1E-16	**2.8E-22**
HexaCDF, 1,2,3,4,7,8-	7.6E-04	3.4E-06	4.6E+05	2.9E-12	2.9E-12	5.9E-19	1.3E-16	1.7E-13	2.2E-14	4.8E-17	**1.2E-22**
HexaCDD, 1,2,3,6,7,8-	4.6E-04	2.1E-06	9.2E+05	9.0E-13	9.0E-13	9.0E-20	2.0E-17	4.3E-14	3.4E-15	7.4E-18	**1.8E-23**
HexaCDF, 1,2,3,6,7,8-	3.0E-03	1.3E-05	4.6E+05	1.1E-11	1.1E-11	2.3E-18	5.1E-16	1.7E-13	8.5E-14	1.9E-16	**4.5E-22**
HexaCDD, 1,2,3,7,8,9 -	7.2E-04	3.2E-06	9.2E+05	1.4E-12	1.4E-12	1.4E-19	3.1E-17	4.3E-14	5.2E-15	1.1E-17	**2.7E-23**
HexaCDF, 1,2,3,7,8,9-	4.2E-04	1.9E-06	4.6E+05	1.6E-12	1.6E-12	3.3E-19	7.3E-17	1.7E-13	1.2E-14	2.7E-17	**6.4E-23**
PentaCDD, 1,2,3,7,8-	7.2E-04	3.2E-06	2.0E+05	6.3E-12	6.3E-12	2.9E-18	6.5E-16	9.0E-13	1.1E-13	2.4E-16	**5.7E-22**
PentaCDF, 1,2,3,7,8-	1.7E-03	7.6E-06	2.9E+05	1.1E-11	1.1E-11	3.4E-18	7.6E-16	4.5E-13	1.3E-13	2.8E-16	**6.8E-22**
HexaCDF, 2,3,4,6,7,8-	5.5E-04	2.5E-06	4.6E+05	2.1E-12	2.1E-12	4.2E-19	9.4E-17	1.7E-13	1.6E-14	3.5E-17	**8.4E-23**
PentaCDF, 2,3,4,7,8-	1.5E-03	6.6E-06	1.5E+05	1.8E-11	1.8E-11	1.1E-17	2.5E-15	1.7E-12	4.3E-13	9.3E-16	**2.3E-21**
TetraCDD, 2,3,7,8-	3.4E-04	1.5E-06	2.9E+05	2.1E-12	2.1E-12	6.6E-19	1.5E-16	4.3E-13	2.5E-14	5.4E-17	**1.3E-22**
TetraCDF, 2,3,7,8-	1.7E-03	7.6E-06	5.8E+04	5.2E-11	5.2E-11	8.2E-17	1.8E-14	1.1E-11	3.1E-12	6.7E-15	**1.6E-20**
Total Dioxins/furans											**2.1E-20**

Chemical	A	B	C	D	E	F	G	H	I	J	K
	Total in Ash (mg)	Chem. per area (mg / m2)	Kd (L/kg)	Amount Leached to Water in Ash Layer, per Rain Event (mg/m^2)	Amount Filtered from Leachate to Soil, per Rain Event (mg/m^2)	Amount Remaining in Leachate after Filter per Rain Event (mg/m^2)	Total Leached to Aquifer First Rain Event (mg)	Fraction Leached in Ash Layer per Rain Event	Total Leached per Year (mg)	Total Intercepted by Well per Year (mg)	Ann. Avg Conc. In Well Water (mg/L)
Arsenic	1.3E+03	5.7E+00	2.9E+01	7.7E-02	7.7E-02	2.5E-04	5.5E-02	4.3E-05	9.2E+0	2.0E-02	**4.9E-08**
Cadmium	1.3E+03	6.0E+00	7.5E+01	3.2E-02	3.2E-02	3.9E-05	8.7E-03	6.5E-06	1.5E+0	3.2E-03	**7.7E-09**
Chromium, total	9.9E+04	4.4E+02	1.9E+01	9.1E+00	9.0E+00	4.4E-02	9.8E+00	9.9E-05	1.6E+03	3.6E+00	**8.6E-06**
Copper	1.3E+05	5.8E+02	4.3E+02	5.4E-01	5.4E-01	1.2E-04	2.6E-02	2.0E-07	4.3E+0	9.4E-03	**2.3E-08**
Iron	9.5E+06	4.3E+04	6.5E+01	2.6E+02	2.6E+02	3.7E-01	8.2E+01	8.6E-06	1.4E+04	3.0E+01	**7.3E-05**
Lead	8.5E+03	3.8E+01	9.0E+02	1.7E-02	1.7E-02	1.7E-06	3.8E-04	4.5E-08	6.4E-02	1.4E-04	**3.4E-10**
Manganese	5.2E+06	2.3E+04	6.5E+01	1.4E+02	1.4E+02	2.0E-01	4.5E+01	8.6E-06	7.6E+03	1.7E+01	**4.0E-05**
Nickel	3.7E+04	1.7E+02	6.5E+01	1.0E+00	1.0E+00	1.4E-03	3.2E-01	8.6E-06	5.4E+01	1.2E-01	**2.9E-07**
Mercury	1.4E+00	6.1E-03	2.0E-01	4.0E-03	2.8E-03	1.3E-03	2.8E-01	2.1E-01	1.4E+00	3.0E-03	**7.1E-09**
Zinc	2.2E+05	9.8E+02	6.2E+01	6.3E+00	6.3E+00	9.3E-03	2.1E+00	9.5E-06	3.5E+02	7.6E-01	**1.8E-06**

Abbreviations: Chem. = Chemical; Conc. =Concentration; PAH = polycyclic aromatic hydrocarbons.

[a] See Section 4.3.2 of the main report for a description of the methods and calculations used estimate partitioning between ash and infiltrating precipitation and leachate and subsurface soil.

Table H.7. Estimated Leaching of Chemicals from Ash and Partitioning with Subsurface Soil – Air-Curtain Burning.[a]

Chemical	A	B	C	D	E	F	G	H	I	J	K
	Total in Ash (mg)	Chem. per area (mg / m^2)	Kd (L/kg)	Amount Leached to Water in Ash Layer, First Rain Event (mg/m^2)	Amount Filtered from Leachate to Soil, per Rain Event (mg/m^2)	Amount Remaining in Leachate After Filter per Rain Event (mg/m^2)	Total Leached to Aquifer, First Rain Event (mg)	Fraction Leached in Ash Layer per Rain Event	Total Leached per Year (mg)	Total Intercepted by Well per Year (mg)	Ann. Avg. Conc. In Well Water (mg/L)
Napthalene	1.2E+03	3.0E+01	8.9E+01	2.4E-02	2.4E-02	2.5E-05	1.0E-03	8.5E-07	1.7E-01	3.1E-03	**7.4E-09**
Acenapthylene	2.7E+02	6.6E+00	2.8E+01	1.7E-02	1.7E-02	5.8E-05	2.4E-03	8.9E-06	4.0E-01	7.0E-03	**1.7E-08**
Phenanthrene	9.2E+02	2.2E+01	2.0E+03	8.3E-04	8.3E-04	3.9E-08	1.6E-06	1.7E-09	2.7E-04	4.7E-06	**1.1E-11**
Fluorene	1.7E+02	4.1E+00	5.8E+02	5.3E-04	5.3E-04	8.4E-08	3.5E-06	2.0E-08	5.8E-04	1.0E-05	**2.5E-11**
Acenaphthene	3.5E+02	8.6E+00	3.7E+02	1.7E-03	1.7E-03	4.3E-07	1.8E-05	5.0E-08	3.0E-03	5.3E-05	**1.3E-10**
Anthracene	2.1E+02	5.2E+00	1.8E+03	2.2E-04	2.2E-04	1.1E-08	4.6E-07	2.2E-09	7.8E-05	1.4E-06	**3.3E-12**
Pyrene	3.3E+02	7.9E+00	5.1E+03	1.1E-04	1.1E-04	2.1E-09	8.5E-08	2.6E-10	1.4E-05	2.5E-07	**6.1E-13**
Chrysene	1.4E+02	3.4E+00	3.0E+04	8.4E-06	8.4E-06	2.6E-11	1.1E-09	7.5E-12	1.8E-07	3.1E-09	**7.6E-15**
Fluoranthene	7.1E+02	1.7E+01	1.1E+03	1.2E-03	1.2E-03	1.0E-07	4.2E-06	5.9E-09	7.1E-04	1.2E-05	**3.0E-11**
Benzo[a]anthracene	7.1E+01	1.7E+00	2.7E+04	4.7E-06	4.7E-06	1.6E-11	6.7E-10	9.4E-12	1.1E-07	2.0E-09	**4.7E-15**
Benzo[a]pyrene	8.5E+01	2.1E+00	7.3E+04	2.1E-06	2.1E-06	2.7E-12	1.1E-10	1.3E-12	1.8E-08	3.2E-10	**7.8E-16**
Benzo[e]pyrene	7.1E+01	1.7E+00	9.9E+03	1.3E-05	1.3E-05	1.2E-10	4.9E-09	6.9E-11	8.2E-07	1.4E-08	**3.5E-14**
Benzo[b]fluoranthene	4.2E+01	1.0E+00	7.9E+04	9.7E-07	9.7E-07	1.1E-12	4.7E-11	1.1E-12	7.9E-09	1.4E-10	**3.3E-16**
Benzo[k]fluoranthene	3.3E+02	7.9E+00	7.4E+04	7.8E-06	7.8E-06	9.7E-12	4.0E-10	1.2E-12	6.7E-08	1.2E-09	**2.8E-15**
Cyclopenta[c,d]-pyrene	9.9E+01	2.4E+00	2.0E+02	8.9E-04	8.8E-04	4.1E-07	1.7E-05	1.7E-07	2.8E-03	4.9E-05	**1.2E-10**
Perylene	1.1E+02	2.8E+00	2.7E+03	7.6E-05	7.6E-05	2.7E-09	1.1E-07	9.7E-10	1.8E-05	3.2E-07	**7.8E-13**
Dibenz[a,h] anthracene	4.2E+01	1.0E+00	1.3E+05	5.7E-07	5.7E-07	3.9E-13	1.6E-11	3.8E-13	2.7E-09	4.7E-11	**1.1E-16**
Indeno[1,2,3-cd] pyrene	5.7E+01	1.4E+00	2.3E+05	4.4E-07	4.4E-07	1.8E-13	7.2E-12	1.3E-13	1.2E-09	2.1E-11	**5.1E-17**
Benzo[g,h,i]perylene	4.2E+02	1.0E+01	3.9E+04	2.0E-05	2.0E-05	4.7E-11	1.9E-09	4.6E-12	3.3E-07	5.7E-09	**1.4E-14**
Benzo[b]chrysene	2.1E+02	5.2E+00	1.3E+03	2.9E-04	2.9E-04	2.1E-08	8.5E-07	4.0E-09	1.4E-04	2.5E-06	**6.1E-12**

Chemical	A	B	C	D	E	F	G	H	I	J	K
	Total in Ash (mg)	Chem. per area (mg / m^2)	Kd (L/kg)	Amount Leached to Water in Ash Layer, First Rain Event (mg/m^2)	Amount Filtered from Leachate to Soil, per Rain Event (mg/m^2)	Amount Remaining in Leachate After Filter per Rain Event (mg/m^2)	Total Leached to Aquifer, First Rain Event (mg)	Fraction Leached in Ash Layer per Rain Event	Total Leached per Year (mg)	Total Intercepted by Well per Year (mg)	Ann. Avg. Conc. In Well Water (mg/L)
Coronene	8.5E+02	2.1E+01	1.9E+03	8.0E-04	8.0E-04	3.9E-08	1.6E-06	1.9E-09	2.7E-04	4.7E-06	**1.1E-11**
Total PAHs											**2.5E-08**
OctaCDD, 1,2,3,4,6,7,8,9-	1.5E-02	3.6E-04	7.3E+06	3.7E-12	3.7E-12	4.6E-20	1.9E-18	1.3E-16	2.8E-16	4.9E-18	**1.2E-23**
OctaCDF, 1,2,3,4,6,7,8,9-	9.5E-04	2.3E-05	4.6E+06	3.7E-13	3.7E-13	7.3E-21	3.0E-19	3.2E-16	5.3E-17	9.3E-19	**2.2E-24**
HeptaCDD, 1,2,3,4,6,7,8-	4.5E-03	1.1E-04	4.6E+06	1.7E-12	1.7E-12	3.5E-20	1.4E-18	3.2E-16	2.5E-16	4.4E-18	**1.1E-23**
HeptaCDF, 1,2,3,4,6,7,8-	3.0E-03	7.3E-05	1.2E+06	4.6E-12	4.6E-12	3.7E-19	1.5E-17	5.0E-15	2.5E-15	4.4E-17	**1.1E-22**
HeptaCDF, 1,2,3,4,7,8,9-	9.0E-04	2.2E-05	1.2E+06	1.4E-12	1.4E-12	1.1E-19	4.5E-18	5.0E-15	7.5E-16	1.3E-17	**3.2E-23**
HexaCDD, 1,2,3,4,7,8-	8.5E-04	2.1E-05	2.9E+05	5.2E-12	5.2E-12	1.6E-18	6.8E-17	8.0E-14	1.1E-14	2.0E-16	**4.8E-22**
HexaCDF, 1,2,3,4,7,8-	9.0E-04	2.2E-05	4.6E+05	3.5E-12	3.5E-12	7.0E-19	2.9E-17	3.2E-14	4.8E-15	8.4E-17	**2.0E-22**
HexaCDD, 1,2,3,6,7,8-	5.5E-04	1.3E-05	9.2E+05	1.1E-12	1.1E-12	1.1E-19	4.4E-18	8.0E-15	7.4E-16	1.3E-17	**3.1E-23**
HexaCDF, 1,2,3,6,7,8-	3.5E-03	8.5E-05	4.6E+05	1.3E-11	1.3E-11	2.7E-18	1.1E-16	3.2E-14	1.9E-14	3.3E-16	**7.9E-22**
HexaCDD, 1,2,3,7,8,9 -	8.5E-04	2.1E-05	9.2E+05	1.6E-12	1.6E-12	1.6E-19	6.8E-18	8.0E-15	1.1E-15	2.0E-17	**4.8E-23**
HexaCDF, 1,2,3,7,8,9-	5.0E-04	1.2E-05	4.6E+05	1.9E-12	1.9E-12	3.9E-19	1.6E-17	3.2E-14	2.7E-15	4.7E-17	**1.1E-22**
PentaCDD, 1,2,3,7,8-	8.5E-04	2.1E-05	2.0E+05	7.5E-12	7.5E-12	3.4E-18	1.4E-16	1.7E-13	2.4E-14	4.2E-16	**1.0E-21**
PentaCDF, 1,2,3,7,8-	2.0E-03	4.9E-05	2.9E+05	1.3E-11	1.3E-11	4.1E-18	1.7E-16	8.4E-14	2.8E-14	4.9E-16	**1.2E-21**
HexaCDF, 2,3,4,6,7,8-	6.5E-04	1.6E-05	4.6E+05	2.5E-12	2.5E-12	5.0E-19	2.1E-17	3.2E-14	3.5E-15	6.1E-17	**1.5E-22**
PentaCDF, 2,3,4,7,8-	1.7E-03	4.2E-05	1.5E+05	2.1E-11	2.1E-11	1.4E-17	5.5E-16	3.2E-13	9.3E-14	1.6E-15	**3.9E-21**

Chemical	A	B	C	D	E	F	G	H	I	J	K
	Total in Ash (mg)	Chem. per area (mg / m^2)	Kd (L/kg)	Amount Leached to Water in Ash Layer, First Rain Event (mg/m^2)	Amount Filtered from Leachate to Soil, per Rain Event (mg/m^2)	Amount Remaining in Leachate After Filter per Rain Event (mg/m^2)	Total Leached to Aquifer, First Rain Event (mg)	Fraction Leached in Ash Layer per Rain Event	Total Leached per Year (mg)	Total Intercepted by Well per Year (mg)	Ann. Avg. Conc. In Well Water (mg/L)
TetraCDD, 2,3,7,8-	4.0E-04	9.7E-06	2.9E+05	2.4E-12	2.4E-12	7.8E-19	3.2E-17	8.0E-14	5.4E-15	9.4E-17	**2.3E-22**
TetraCDF, 2,3,7,8-	2.0E-03	4.9E-05	5.8E+04	6.1E-11	6.1E-11	9.7E-17	4.0E-15	2.0E-12	6.7E-13	1.2E-14	**2.8E-20**
Total Dioxins/furans											**3.7E-20**
Arsenic	1.5E+03	3.6E+01	2.9E+01	9.2E-02	9.2E-02	2.9E-04	1.2E-02	8.0E-06	2.0E+00	3.5E-02	**8.5E-08**
Cadmium	6.6E+02	1.6E+01	7.5E+01	1.6E-02	1.6E-02	1.9E-05	8.0E-04	1.2E-06	1.3E-01	2.4E-03	**5.7E-09**
Chromium, total	1.0E+05	2.5E+03	1.9E+01	9.7E+00	9.7E+00	4.7E-02	1.9E+00	1.9E-05	3.2E+02	5.7E+00	**1.4E-05**
Copper	1.1E+05	2.6E+03	4.3E+02	4.4E-01	4.4E-01	9.5E-05	3.9E-03	3.7E-08	6.5E-01	1.1E-02	**2.8E-08**
Iron	7.0E+06	1.7E+05	6.5E+01	1.9E+02	1.9E+02	2.7E-01	1.1E+01	1.6E-06	1.9E+03	3.3E+01	**8.0E-05**
Lead	1.0E+05	2.5E+03	9.0E+02	2.0E-01	2.0E-01	2.1E-05	8.5E-04	8.4E-09	1.4E-01	2.5E-03	**6.0E-09**
Manganese	6.1E+06	1.5E+05	6.5E+01	1.7E+02	1.7E+02	2.4E-01	9.9E+00	1.6E-06	1.7E+03	2.9E+01	**7.0E-05**
Nickel	3.3E+04	8.1E+02	6.5E+01	9.1E-01	9.1E-01	1.3E-03	5.3E-02	1.6E-06	8.9E+00	1.6E-01	**3.8E-07**
Mercury	1.6E+00	3.9E-02	2.0E-01	1.0E-02	7.1E-03	3.3E-03	1.4E-01	8.5E-02	1.6E+00	2.8E-02	**6.7E-08**
Zinc	4.8E+05	1.2E+04	6.2E+01	1.4E+01	1.4E+01	2.1E-02	8.6E-01	1.8E-06	1.4E+02	2.5E+00	**6.1E-06**

Abbreviations: Chem = Chemical; Conc =Concentration; PAH = polycyclic aromatic hydrocarbons.

[a] See Section 4.3.2 of the main report for a description of the methods and calculations used estimate partitioning between ash and infiltrating precipitation and leachate and subsurface soil.

Table H.8. Documentation of Columns in Tables H.6 and H.7.

Column in Tables H.6 and H.7	Description of Column Data or Calculation	Origin of Equation Parameters
A	Total mg of chemical in ash	From Table H.4 and Table H.5
B	Chemical per m^2 in the ash disposal area (mg/m^2)	Col. A divided by ash disposal area from Table H.2
C	Chemical-specific solid/liquid partition coefficient (Kd)	Kd values from literature and chemical databases
D	Rearrange Kd equation to estimate chemical leached to infiltrating precipitation from ash per rain event. See Section 4.3.2 of the main report. (mg/m^2)	(P7 from Table H.3 x Col. B) / (P12 from Table H.3 x Col. C + P7 from Table H.3); See Section 4.3.2 of the main report

Column in Tables H.6 and H.7	Description of Column Data or Calculation	Origin of Equation Parameters
E	Rearrange Kd equation to estimate fraction of chemical in leachate that partitions to vadose zone soil beneath the ash. A layer is the depth of soil saturated by the volume of leachate in a 1 m^2 area from the first rain event. (mg/m^2)	[Col. C x (P12 from Table H.3) x Col. D] / [P7 from Table H.3 + Col. C x P12 from Table H.3]; See Section 4.3.2 of the main report
F	Amount of chemical remaining in leachate after partitioning with soil, per m^2 and for the first rain event. (mg/m^2)	Col. D – Col. E
G	Total leached to groundwater in the first rain event (mg/event)	Col. F x ash disposal area from Table H.2
H	Fraction of chemical in ash that reaches groundwater per rain event. (unitless)	Col. G / Col. A
I	Total amount of chemical leached to ground water in first 1 year. (mg/yr)	Col. A - (Col. A x (1-(Col. H))^P2 in Table H.3)
J	Amount of chemical intercepted by the drinking water well per year (mg/yr)	(Col. I x (fraction plume intercepted)] See Section 4.3.5 for further discussion of methods for well water concentrations. Fraction of plume intercepted (See Section 4.3.5): • burial scenario – 0.0022 • storage pile scenario – 0.0050 • windrow scenario – 0.0033
K	Average chemical concentration (mg/L) in drinking water	[(Col J) / (1,136 L/d x 365 d/yr)

Abbreviations: ^ = raised to the power of; Col. = column; d = day; Kd = soil-water partitioning coefficient; yr = year.

Appendix I. Supporting Information for Groundwater Recharge to Surface Water

Concentrations of chemicals in surface water from groundwater recharge to the on-site lake were estimated for leaching from combustion ash, carcass burial, the compost windrow, or temporary carcass pile. Concentrations were estimated by dividing the mass of chemical (mg) that reached groundwater for each option by the volume of the lake converted to L. These estimates were made for two lake sizes, 40.5 ha and 4.05 ha (100 acres and 10 acres). Calculations to estimate the chemical mass leached from carcass burial, composting, and temporary carcass storage that reached groundwater are presented in Appendix G and for ash burial from the combustion-based options in Appendix H. The lake volumes and related parameters are presented in Table I.1. Concentration estimates are presented in Tables I.2 through I.6

Table I.1. Lake Parameters used to Estimate Chemical Concentrations in Surface Water from Groundwater Recharge.

Lake Parameter	40.5 ha Lake (100 ac)	4.05 ha Lake (10 ac)
Surface Area (m^2)	404,686	40,469
Average Depth (m)	4.38	3.02
Volume (L)	1.8E+09	1.2E+08

Abbreviations: ha = hectares; ac = acres.

Table I.2. Groundwater Recharge to Lake with Chemicals from Leachate from Buried Carcasses.

Chemical	A	B	C	D	E	F	G	H	I
	Chemical Reaching Groundwater Minus Well Intercept (mg/time period)			Concentration in Small Lake (mg/L)			Concentration in Large Lake (mg/L)		
	First Week	First Two Months	First Year	First Week	First Two Months	First Year	First Week	First Two Months	First Year
aluminum	2.2E-01	7.4E-01	1.0E+00	1.8E-09	6.1E-09	8.5E-09	1.2E-10	4.2E-10	5.9E-10
ammonium	5.9E+06	3.0E+07	1.2E+08	4.9E-02	2.5E-01	9.5E-01	3.3E-03	1.7E-02	6.6E-02
barium	1.4E+00	8.8E+00	1.1E+01	1.2E-08	7.2E-08	8.7E-08	7.9E-10	4.9E-09	6.0E-09
beryllium	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
bicarbonate	1.9E+08	5.0E+08	1.1E+09	1.5E+00	4.1E+00	9.4E+00	1.1E-01	2.8E-01	6.5E-01
boron	0.0E+00	3.2E+03	7.1E+03	0.0E+00	2.6E-05	5.8E-05	0.0E+00	1.8E-06	4.0E-06
cadmium	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
calcium	6.8E+04	1.5E+05	4.0E+05	5.6E-04	1.2E-03	3.3E-03	3.9E-05	8.2E-05	2.2E-04
chloride	3.0E+06	1.0E+07	2.6E+07	2.4E-02	8.4E-02	2.2E-01	1.7E-03	5.8E-03	1.5E-02
chromium	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
cobalt	4.3E-01	0.0E+00	2.3E-01	3.5E-09	0.0E+00	1.9E-09	2.4E-10	0.0E+00	1.3E-10
copper	2.7E-01	1.6E+00	4.5E+00	2.2E-09	1.3E-08	3.7E-08	1.5E-10	9.1E-10	2.5E-09
inorganic C	5.2E+07	1.2E+08	2.5E+08	4.2E-01	9.6E-01	2.0E+00	2.9E-02	6.6E-02	1.4E-01
organic C	3.2E+08	6.7E+08	1.5E+09	2.6E+00	5.5E+00	1.2E+01	1.8E-01	3.8E-01	8.5E-01
iron	3.3E+02	7.9E+02	1.2E+03	2.7E-06	6.4E-06	1.0E-05	1.8E-07	4.4E-07	7.1E-07
lead	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
magnesium	3.4E+04	9.2E+04	2.0E+05	2.8E-04	7.6E-04	1.6E-03	1.9E-05	5.2E-05	1.1E-04
manganese	1.5E+00	4.7E+00	1.0E+01	1.2E-08	3.9E-08	8.5E-08	8.4E-10	2.7E-09	5.8E-09
mercury	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
molybdenum	2.1E+03	2.6E+03	1.9E+03	1.7E-05	2.2E-05	1.6E-05	1.2E-06	1.5E-06	1.1E-06
nickel	1.2E+00	3.0E+00	2.5E+00	9.7E-09	2.4E-08	2.1E-08	6.7E-10	1.7E-09	1.4E-09
nitrate/nitrite	2.6E+04	5.2E+04	6.2E+04	2.1E-04	4.2E-04	5.1E-04	1.5E-05	2.9E-05	3.5E-05
total N	1.4E+08	2.3E+08	4.9E+08	1.1E+00	1.8E+00	4.0E+00	7.7E-02	1.3E-01	2.8E-01
phosphorus	1.0E+06	4.6E+06	1.2E+07	8.6E-03	3.8E-02	1.0E-01	5.9E-04	2.6E-03	7.0E-03
potassium	2.2E+06	8.1E+06	2.2E+07	1.8E-02	6.6E-02	1.8E-01	1.2E-03	4.5E-03	1.2E-02
selenium	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
silicon	3.3E+04	1.1E+05	2.5E+05	2.7E-04	8.7E-04	2.1E-03	1.9E-05	6.0E-05	1.4E-04
silver	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00

Chemical	A	B	C	D	E	F	G	H	I
	Chemical Reaching Groundwater Minus Well Intercept (mg/time period)			Concentration in Small Lake (mg/L)			Concentration in Large Lake (mg/L)		
	First Week	First Two Months	First Year	First Week	First Two Months	First Year	First Week	First Two Months	First Year
sodium	1.8E+06	8.3E+06	2.1E+07	1.5E-02	6.8E-02	1.7E-01	1.0E-03	4.7E-03	1.2E-02
strontium	8.0E+02	1.7E+03	3.1E+03	6.5E-06	1.4E-05	2.5E-05	4.5E-07	9.7E-07	1.8E-06
sulphate	8.2E+06	3.3E+07	8.2E+07	6.7E-02	2.7E-01	6.7E-01	4.6E-03	1.9E-02	4.6E-02
sulphur	1.4E+06	6.3E+06	1.8E+07	1.1E-02	5.2E-02	1.4E-01	7.7E-04	3.6E-03	1.0E-02
titanium	2.3E+02	0.0E+00	8.8E+01	1.9E-06	0.0E+00	7.2E-07	1.3E-07	0.0E+00	5.0E-08
vanadium	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
zinc	1.1E+01	4.5E+01	1.1E+02	8.9E-08	3.7E-07	8.7E-07	6.1E-09	2.6E-08	6.0E-08
zirconium	2.3E+02	0.0E+00	8.8E+01	1.9E-06	0.0E+00	7.2E-07	1.3E-07	0.0E+00	5.0E-08

Table I.3. Groundwater Recharge to Lake with Chemicals from Leachate from Carcass Storage Pile During First Two Days.

Chemical	A	D	G
	Chemical Reaching Groundwater Minus Well Intercept (mg/time period)	Concentration in Small Lake (mg/L)	Concentration in Large Lake (mg/L)
Aluminum	2.2E-01	1.8E-09	1.3E-10
Ammonium	4.3E+06	3.5E-02	2.4E-03
Barium	1.4E+00	1.2E-08	8.1E-10
Beryllium	0.0E+00	0.0E+00	0.0E+00
Bicarbonate	6.7E+07	5.5E-01	3.8E-02
Boron	0.0E+00	0.0E+00	0.0E+00
Cadmium	0.0E+00	0.0E+00	0.0E+00
Calcium	5.0E+04	4.1E-04	2.8E-05
Chloride	2.2E+06	1.8E-02	1.2E-03
Chromium	0.0E+00	0.0E+00	0.0E+00
Cobalt	4.4E-01	3.6E-09	2.5E-10
Copper	2.7E-01	2.2E-09	1.5E-10
Inorganic C	1.5E+07	1.2E-01	8.3E-03
Organic C	9.1E+07	7.5E-01	5.1E-02
Iron	3.3E+02	2.7E-06	1.9E-07
Lead	0.0E+00	0.0E+00	0.0E+00
Magnesium	2.5E+04	2.0E-04	1.4E-05
Manganese	1.5E+00	1.2E-08	8.5E-10
Mercury	0.0E+00	0.0E+00	0.0E+00
Molybdenum	1.5E+03	1.2E-05	8.5E-07
Nickel	1.2E+00	9.9E-09	6.8E-10
Nitrate/Nitrite	1.9E+04	1.6E-04	1.1E-05
Total N	3.9E+07	3.2E-01	2.2E-02
Phosphorus	7.7E+05	6.3E-03	4.3E-04
Potassium	1.6E+06	1.3E-02	8.9E-04
Selenium	0.0E+00	0.0E+00	0.0E+00
Silicon	2.4E+04	2.0E-04	1.4E-05
Silver	0.0E+00	0.0E+00	0.0E+00
Sodium	1.3E+06	1.1E-02	7.5E-04
Strontium	5.8E+02	4.8E-06	3.3E-07
Sulphate	4.7E+06	3.9E-02	2.7E-03
Sulphur	1.0E+06	8.2E-03	5.6E-04
Titanium	1.7E+02	1.4E-06	9.4E-08
Vanadium	0.0E+00	0.0E+00	0.0E+00
Zinc	1.1E+01	9.1E-08	6.2E-09
Zirconium	1.7E+02	1.4E-06	9.4E-08

Table I.4. Groundwater Recharge to Lake with Chemicals from Leachate from Windrow During First Year.

Chemical	A	D	G
	Chemical Reaching Groundwater Minus Well Intercept (mg/time period)	Concentration in Small Lake (mg/L)	Concentration in Large Lake (mg/L)
Aluminum	5.2E-02	4.2E-10	2.9E-11
Ammonium	5.8E+06	4.8E-02	3.3E-03
Barium	5.3E-01	4.4E-09	3.0E-10
Beryllium	na	na	na
Bicarbonate	5.7E+07	4.7E-01	3.2E-02
Boron	3.5E+02	2.9E-06	2.0E-07
Cadmium	0.0E+00	0.0E+00	0.0E+00
Calcium	2.0E+04	1.6E-04	1.1E-05
Chloride	1.3E+06	1.1E-02	7.4E-04
Chromium	0.0E+00	0.0E+00	0.0E+00
Cobalt	1.2E-02	9.4E-11	6.5E-12
Copper	2.2E-01	1.8E-09	1.3E-10
Inorganic C	1.2E+07	1.0E-01	7.0E-03
Organic C	7.5E+07	6.1E-01	4.2E-02
Iron	6.2E+01	5.1E-07	3.5E-08
Lead	0.0E+00	0.0E+00	0.0E+00
Magnesium	1.0E+04	8.2E-05	5.6E-06
Manganese	5.2E-01	4.2E-09	2.9E-10
Mercury	0.0E+00	0.0E+00	0.0E+00
Molybdenum	9.6E+01	7.8E-07	5.4E-08
Nickel	1.3E-01	1.0E-09	7.1E-11
Nitrate/Nitrite	3.1E+03	2.5E-05	1.8E-06
Total N	2.5E+07	2.0E-01	1.4E-02
Phosphorus	6.2E+05	5.1E-03	3.5E-04
Potassium	1.1E+06	9.0E-03	6.2E-04
Selenium	0.0E+00	0.0E+00	0.0E+00
Silicon	1.3E+04	1.0E-04	7.2E-06
Silver	0.0E+00	0.0E+00	0.0E+00
Sodium	1.1E+06	8.7E-03	6.0E-04
Strontium	1.6E+02	1.3E-06	8.8E-08
Sulphate	4.1E+06	3.3E-02	2.3E-03
Sulphur	8.8E+05	7.2E-03	5.0E-04
Titanium	4.4E+00	3.6E-08	2.5E-09
Vanadium	0.0E+00	0.0E+00	0.0E+00
Zinc	5.3E+00	4.3E-08	3.0E-09
Zirconium	4.4E+00	3.6E-08	2.5E-09

Abbreviations: na = not analyzed.

Table I.5. Groundwater Recharge to Lake with Chemicals Leached from Ash Buried After Open Burning.

Chemical (number of rings)	A Chemical Reaching Groundwater Minus Well Intercept (mg/yr)	B Concentration in Small Lake (mg/L)	C Concentration in Large Lake (mg/L)
Napthalene (2)	1.2E+00	9.7E-09	6.7E-10
Acenapthylene (3)	4.9E-01	4.0E-09	2.8E-10
Phenanthrene (3)	9.3E-04	7.6E-12	5.3E-13
Fluorene (3)	3.9E-03	3.2E-11	2.2E-12
Acenaphthene (3)	6.4E-03	5.3E-11	3.6E-12
Anthracene (3)	8.1E-04	6.7E-12	4.6E-13
Pyrene (4)	7.9E-05	6.5E-13	4.5E-14
Chrysene (4)	2.8E-06	2.3E-14	1.6E-15
Fluoranthene (4)	1.8E-03	1.5E-11	1.0E-12
Benzo[a]anthracene (4)	1.3E-06	1.1E-14	7.3E-16
Benzo[a]pyrene (5)	6.0E-07	4.9E-15	3.4E-16
Benzo[e]pyrene (5)	1.2E-05	9.6E-14	6.6E-15
Benzo[b]fluoranthene (5)	2.2E-07	1.8E-15	1.2E-16
Benzo[k]fluoranthene (5)	1.8E-07	1.5E-15	1.0E-16
Cyclopenta[c,d]pyrene (5)	3.8E-02	3.1E-10	2.1E-11
Perylene (5)	2.7E-04	2.2E-12	1.5E-13
Dibenz[a,h]anthracene (6)	1.8E-07	1.5E-15	1.0E-16
Indeno[1,2,3-c,d] pyrene (6)	5.7E-08	4.7E-16	3.2E-17
Benzo[g,h,i]perylene (6)	1.2E-06	9.6E-15	6.6E-16
Benzo[b]chrysene (6)	8.6E-04	7.0E-12	4.8E-13
Coronene (7)	3.5E-03	2.9E-11	2.0E-12
OctaCDD, 1,2,3,4,6,7,8,9-	1.4E-15	1.2E-23	8.0E-25
OctaCDF, 1,2,3,4,6,7,8,9-	2.2E-16	1.8E-24	1.3E-25
HeptaCDD, 1,2,3,4,6,7,8-	1.1E-15	8.7E-24	6.0E-25
HeptaCDF, 1,2,3,4,6,7,8-	1.2E-14	9.5E-23	6.6E-24
HeptaCDF, 1,2,3,4,7,8,9-	3.5E-15	2.8E-23	2.0E-24
HexaCDD, 1,2,3,4,7,8-	5.2E-14	4.3E-22	2.9E-23
HexaCDF, 1,2,3,4,7,8-	2.2E-14	1.8E-22	1.2E-23
HexaCDD, 1,2,3,6,7,8-	3.4E-15	2.8E-23	1.9E-24
HexaCDF, 1,2,3,6,7,8-	8.5E-14	7.0E-22	4.8E-23
HexaCDD, 1,2,3,7,8,9 -	5.2E-15	4.3E-23	2.9E-24
HexaCDF, 1,2,3,7,8,9-	1.2E-14	1.0E-22	6.9E-24
PentaCDD, 1,2,3,7,8-	1.1E-13	8.9E-22	6.1E-23
PentaCDF, 1,2,3,7,8-	1.3E-13	1.0E-21	7.2E-23
HexaCDF, 2,3,4,6,7,8-	1.6E-14	1.3E-22	8.9E-24
PentaCDF, 2,3,4,7,8-	4.3E-13	3.5E-21	2.4E-22
TetraCDD, 2,3,7,8-	2.4E-14	2.0E-22	1.4E-23

Chemical (number of rings)	A Chemical Reaching Groundwater Minus Well Intercept (mg/yr)	B Concentration in Small Lake (mg/L)	C Concentration in Large Lake (mg/L)
TetraCDF, 2,3,7,8-	3.1E-12	2.5E-20	1.7E-21
Arsenic	9.2E+00	7.5E-08	5.2E-09
Cadmium	1.5E+00	1.2E-08	8.2E-10
Chromium, total	1.6E+03	1.3E-05	9.2E-07
Copper	4.3E+00	3.5E-08	2.4E-09
Iron	1.4E+04	1.1E-04	7.8E-06
Lead	6.4E-02	5.3E-10	3.6E-11
Manganese	7.6E+03	6.2E-05	4.3E-06
Nickel	5.4E+01	4.4E-07	3.0E-08
Mercury	1.3E+00	1.1E-08	7.6E-10
Zinc	3.5E+02	2.9E-06	2.0E-07

Abbreviations: PAH = polycyclic aromatic hydrocarbons; yr = year.

Table I.6. Groundwater Recharge to Lake with Chemicals Leached from Ash Buried After Air-Curtain Burning.

Chemical (number of rings)	A Chemical Reaching Groundwater Minus Well Intercept (mg/yr)	B Concentration in Small Lake (mg/L)	C Concentration in Large Lake (mg/L)
Napthalene (2)	1.7E-01	1.4E-09	9.7E-11
Acenapthylene (3)	3.9E-01	3.2E-09	2.2E-10
Phenanthrene (3)	2.6E-04	2.1E-12	1.5E-13
Fluorene (3)	5.7E-04	4.7E-12	3.2E-13
Acenaphthene (3)	2.9E-03	2.4E-11	1.7E-12
Anthracene (3)	7.7E-05	6.3E-13	4.3E-14
Pyrene (4)	1.4E-05	1.2E-13	7.9E-15
Chrysene (4)	1.8E-07	1.4E-15	9.9E-17
Fluoranthene (4)	6.9E-04	5.7E-12	3.9E-13
Benzo[a]anthracene (4)	1.1E-07	9.0E-16	6.2E-17
Benzo[a]pyrene (5)	1.8E-08	1.5E-16	1.0E-17
Benzo[e]pyrene (5)	8.1E-07	6.6E-15	4.6E-16
Benzo[b]fluoranthene (5)	7.7E-09	6.3E-17	4.4E-18
Benzo[k]fluoranthene (5)	6.6E-08	5.4E-16	3.7E-17
Cyclopenta[c,d]pyrene (5)	2.8E-03	2.3E-11	1.6E-12
Perylene (5)	1.8E-05	1.5E-13	1.0E-14
Dibenz[a,h]anthracene (6)	2.6E-09	2.2E-17	1.5E-18
Indeno[1,2,3-c,d] pyrene (6)	1.2E-09	9.8E-18	6.7E-19
Benzo[g,h,i]perylene (6)	3.2E-07	2.6E-15	1.8E-16
Benzo[b]chrysene (6)	1.4E-04	1.2E-12	7.9E-14
Coronene (7)	2.6E-04	2.1E-12	1.5E-13
OctaCDD, 1,2,3,4,6,7,8,9-	2.7E-16	2.2E-24	1.5E-25
OctaCDF, 1,2,3,4,6,7,8,9-	5.2E-17	4.3E-25	2.9E-26
HeptaCDD, 1,2,3,4,6,7,8-	2.5E-16	2.0E-24	1.4E-25
HeptaCDF, 1,2,3,4,6,7,8-	2.5E-15	2.0E-23	1.4E-24
HeptaCDF, 1,2,3,4,7,8,9-	7.4E-16	6.1E-24	4.2E-25
HexaCDD, 1,2,3,4,7,8-	1.1E-14	9.1E-23	6.3E-24
HexaCDF, 1,2,3,4,7,8-	4.7E-15	3.9E-23	2.7E-24
HexaCDD, 1,2,3,6,7,8-	7.2E-16	5.9E-24	4.1E-25
HexaCDF, 1,2,3,6,7,8-	1.8E-14	1.5E-22	1.0E-23
HexaCDD, 1,2,3,7,8,9 -	1.1E-15	9.1E-24	6.3E-25
HexaCDF, 1,2,3,7,8,9-	2.6E-15	2.1E-23	1.5E-24
PentaCDD, 1,2,3,7,8-	2.3E-14	1.9E-22	1.3E-23
PentaCDF, 1,2,3,7,8-	2.8E-14	2.3E-22	1.6E-23
HexaCDF, 2,3,4,6,7,8-	3.4E-15	2.8E-23	1.9E-24
PentaCDF, 2,3,4,7,8-	9.2E-14	7.5E-22	5.2E-23

Chemical (number of rings)	A Chemical Reaching Groundwater Minus Well Intercept (mg/yr)	B Concentration in Small Lake (mg/L)	C Concentration in Large Lake (mg/L)
TetraCDD, 2,3,7,8-	5.3E-15	4.3E-23	3.0E-24
TetraCDF, 2,3,7,8-	6.6E-13	5.4E-21	3.7E-22
Arsenic	2.0E+00	1.6E-08	1.1E-09
Cadmium	1.3E-01	1.1E-09	7.4E-11
Chromium, total	3.2E+02	2.6E-06	1.8E-07
Copper	6.4E-01	5.2E-09	3.6E-10
Iron	1.8E+03	1.5E-05	1.0E-06
Lead	1.4E-01	1.1E-09	7.9E-11
Manganese	1.6E+03	1.3E-05	9.2E-07
Nickel	8.8E+00	7.2E-08	5.0E-09
Mercury	1.6E+00	1.3E-08	8.8E-10
Zinc	1.4E+02	1.2E-06	8.0E-08

Abbreviations: PAH = polycyclic aromatic hydrocarbons.

Appendix J. Aquatic Food Web Modeling

J.1. Approach for Inorganic Chemicals

J.2. We present bioaccumulation factors (BAFs) for metals in fish at trophic levels 3 and 4 (TL3 and TL4), along with the sources for these input values, in Table J1, belowApproach for Organic Chemicals

Fish tissue concentrations of organic chemicals in the on-site lake were modeled with AQUAWEB 1.2 (Arnot and Gobas 2004). The biokinetic model calculates a steady-state solution using algorithms for chemical uptake, transformation, and loss by various biological processes by both benthic invertebrates and benthic and pelagic (i.e., water column) fish. Required inputs, chemical concentrations in both the water column and bottom sediments, are calculated by the HHRAP SSW Screening Model as described in Appendices E and F. In addition, AQUAWEB uses chemical-specific Kow values to calculate partitioning of the chemical between particle-phase and aqueous-phase in the water column compartment and in the sediment compartment.

. For inorganic elements below, bioaccumulation depends on chemical speciation in water (and sediments), the fraction that is bioavailable (i.e., dissolved in water), and the overall number of species in the food "chain" (more accurately a food web) supporting the fish species.

Table J.1. Bioaccumulation Factors for Inorganic Chemicals – Open Burning Option.[a]

Chemical	BAF for TL4 (L/kg)	BAF for TL3 (L/kg)	Reference	Fish in Water Column (Walleye) TL4; µg/kg ww	Bottom fish (Yellow Bullhead) TL3; µg/kg ww
Cadmium	40	40	CA OEHHA 2012	5.8E-03	5.8E-03
Chromium	225	225	Eneji et al. 2011	1.4E+00	1.4E+00
Copper	150	150	Eneji et al. 2011	3.9E-01	3.9E-01
Iron	120	120	Eneji et al. 2011	1.7E+02	1.7E+02
Lead	20	20	CA OEHHA 2012	2.4E-03	2.4E-03
Manganese	30	30	Eneji et al. 2011	1.5E-01	1.5E-01
Nickel	20	20	CA OEHHA 2012	2.9E-02	2.9E-02
Zinc	230	230	Eneji et al. 2011	2.5E+00	2.5E+00
Arsenic	17	17	CA OEHHA 2012	3.9E-03	3.9E-03

Abbreviations: BAF = bioaccumulation factor; TL4 = trophic level four; TL3 = trophic level three; ww = wet weight.
[a] Estimated concentrations in fish for other scenarios are presented in Table 4.5 of the main report.

J.3. The concentration of many inorganics actually decreases with increasing trophic level (e.g., arsenic; Chen and Folt 2000) due to limited absorption of inorganic chemicals via the gastrointestinal tract. Readily available data for the other elementsApproach for Organic Chemicals

Fish tissue concentrations of organic chemicals in the on-site lake were modeled with AQUAWEB 1.2 (Arnot and Gobas 2004). The biokinetic model calculates a steady-state solution using algorithms for chemical uptake, transformation, and loss by various biological processes by both benthic invertebrates and benthic and pelagic (i.e., water column) fish. Required inputs, chemical concentrations in both the water column and bottom sediments, are calculated by the HHRAP SSW Screening Model as described in Appendices E and F. In addition, AQUAWEB uses chemical-specific Kow values to calculate partitioning of the chemical between particle-phase and aqueous-phase in the water column compartment and in the sediment compartment.

, however, did not distinguish metal BAFs by trophic level. We therefore we assume the same BAF for TL3 and TL4 fish feeding primarily in the benthos and in the water column, respectively. Methyl mercury, which does bioaccumulate to higher concentrations at higher trophic levels, is not evaluated because it has been banned from animal feeds for many years, and because it is ubiquitous in the atmosphere globally from many emission sources.

J.4. BAFs for essential nutrients and some trace elements tend to decrease with increasing concentration. This indicates biological regulation of absorption and elimination rates, particularly for fish in freshwater. Empirical equations that would predict BAF values on the basis of water concentration were not found or determined. As a conservative approach, the BAF values for inorganic chemicals in Approach for Organic Chemicals

Fish tissue concentrations of organic chemicals in the on-site lake were modeled with AQUAWEB 1.2 (Arnot and Gobas 2004). The biokinetic model calculates a steady-state solution using algorithms for chemical uptake, transformation, and loss by various biological processes by both benthic invertebrates and benthic and pelagic (i.e., water column) fish. Required inputs, chemical concentrations in both the water column and bottom sediments, are calculated by the HHRAP SSW Screening Model as described in Appendices E and F. In addition, AQUAWEB uses chemical-specific Kow values to calculate partitioning of the chemical between particle-phase and aqueous-phase in the water column compartment and in the sediment compartment.

are multiplied by the total water concentration for the chemical (i.e., dissolved plus particulate phase) instead of by the dissolved concentration for the chemical.

J.5. Approach for Organic Chemicals

Fish tissue concentrations of organic chemicals in the on-site lake were modeled with AQUAWEB 1.2 (Arnot and Gobas 2004). The biokinetic model calculates a steady-state solution using algorithms for chemical uptake, transformation, and loss by various biological processes by both benthic invertebrates and benthic and pelagic (i.e., water column) fish. Required inputs, chemical concentrations in both the water column and bottom sediments, are calculated by the HHRAP SSW Screening Model as described in Appendices E and F. In addition, AQUAWEB uses chemical-specific Kow values to calculate partitioning of the chemical between particle-phase and aqueous-phase in the water column compartment and in the sediment compartment.

AQUAWEB Version 1.2 is used exactly as developed. That is, we did not change the AQUAWEB model framework or equations. The model is well-documented in the peer-reviewed literature. This section is an overview of the model structure and key model inputs (i.e., specification of invertebrate and fish species, their characteristics, and the structure of the food web). The user is encouraged to consult the AQUAWEB website and other sources cited here for additional information.

Given the chemical's concentration in the water column and the sediment and chemical Kow values, AQUAWEB uses a series of submodels to estimate the rate constants representing the fish's processes of chemical uptake through ingestion and respiration, chemical elimination through excretion and respiration, and metabolic transformation. The food webs in the AQUAWEB model include 21 separate biotic compartments (1 algal, 1 zooplankton, 5 other invertebrate, and 14 fish) that can be simulated using separate body sizes, metabolic capabilities, lipid content, dietary preferences, and source of prey (benthic or pelagic). Inputs to AQUAWEB assumed for this project are summarized below.

Chemical source terms. Inputs include the total chemical concentration in the water column (in ng/L) and the total chemical concentration in sediments (in ng/g dry weight). The HHRAP SSW Screening Model automatically provides those inputs to AQUAWEB. The model assumes that the chemical concentration specified for the surface water is total chemical, some of which might

be dissolved or sorbed to suspended particles or dissolved organic carbon in the surface water column and in the sediment compartment.

Physical parameters. The HRAP SSW Screening Model loads the required water-body inputs into AQUAWEB. The model default parameter values used for the exposure assessment are shown in Table J.2.

Table J.2. Input Parameter Values Assumed for the Farm Pond (see Appendix F).

Fate and Transport Parameter	Value	Units
Sediment organic carbon content (fraction)	0.04	unitless
Water body temperature	287.65	°C
Dissolved organic carbon content	1.20E-05	kg/L
Particulate organic carbon content	3.20E-06	kg/L
Total suspended solids	13	kg/L

Abbreviations: L = liters.

As noted above, AQUAWEB requires values for log Kow for organic chemicals, and these values are specified along with other chemical inputs within the HHRAP SSW Screening Model. Default values for metabolic transformation rate constants are included in the chemical-specific input tables in the model.

Aquatic food web. The options for building food webs using AQUAWEB include 21 types of biotic compartments; however, to keep the food webs relatively simple, not all of these compartments were used. The default food web (in the online AQUAWEB model) based on the Great Lakes was not used because food chains are longer in the Great Lakes than in other lakes in the United States. A 40 hectare lake approximates a size at which TL4 fish populations in the water column might be readily sustainable without stocking. For each species and size or age class of animal included in the food web, input values for the diet, body size, fraction lipid, and fraction of pore water ventilated are drawn from previously compiled data representing small lakes in southern Minnesota, for which a digitized database for all lakes larger than 10 acres is available. We present assumptions and input values for the aquatic food web in Table J.3 through Table J.5 We model a feasible food “web” rather than simple and separate benthic and pelagic “straight food chains,” because even as adults, most fish species in relatively shallow lakes (e.g., < 10 meters deep) obtain some fraction of their diet from benthic invertebrates.

Fish diets vary substantially with species, age, size, season, lake size (surface area and depth profile), land uses (e.g., agricultural or not), contributions from and connections with other water bodies, latitude, and other factors. We based the food web depicted in Table J.5 on the citations in the table endnotes; however, other scientists might specify different food webs based on the same data sets. For a previous project, we developed food webs for six different ecoregions in Minnesota and discovered that the resulting bioaccumulation estimates were relatively insensitive to the food web structure. Parameters for which the outputs of AQUAWEB are more sensitive included dissolved and particulate organic matter content and total suspended solids.

Table J.3. Input Parameter Specific to Phytoplankton.

Type	Species Name	Lipid Content	Non lipid Organic Carbon Content	Water Content	Phytoplankton Growth Rate Constant
Phytoplankton	Phytoplankton	0.5%	6.5%	93.0%	8.00E-02

Table J.4. Farm Pond Food Web Composition and Properties.

Model Compartment	Taxon	Filter Feeder?	Organism Wet Weight (kg)	Lipid Content	Fraction Sediment Pore Water Ventilated
Zooplankton	Zooplankton	TRUE	5.70E-08	1.2%	0.00E+00
Invertebrate 1	Bivalves	TRUE	1.10E-04	1.3%	5.00E-02
Invertebrate 2	Caddisfly larvae	TRUE	4.00E-05	1.7%	5.00E-02
Invertebrate 3	Mayfly larvae	FALSE	1.00E-04	2.0%	5.00E-02
Invertebrate 4	*Gammarus* (isopod)	FALSE	1.00E-05	2.1%	5.00E-02
Invertebrate 5	Midge larvae	FALSE	4.00E-05	2.0%	5.00E-02
Fish 1	Fish fry	na	4.00E-04	2.0%	0.00E+00
Fish 2	Fingerling fish	na	5.00E-02	2.5%	0.00E+00
Fish 3	N. pike and walleye fingerlings	na	1.20E-01	1.5%	0.00E+00
Fish 4	Black crappie 5-7"	na	1.00E-01	5.0%	0.00E+00
Fish 5	Yellow perch 5-6"	na	1.00E-01	3.5%	0.00E+00
Fish 6	White sucker 6-12"	na	2.28E-01	3.9%	0.00E+00
Fish 7	White sucker 12-16"	na	5.00E-01	5.1%	0.00E+00
Fish 8	N. pike 15-30"	na	1.09E+00	2.9%	0.00E+00
Fish 9	Bluegill 5-8"	na	1.60E-01	5.5%	0.00E+00
Fish 10	Walleye 12-20"	na	7.25E-01	7.9%	0.00E+00

Abbreviations: na = not applicable; N. = northern; " = inches in length.

Table J.5. On-site Lake Food Web by Animal Group or Species.

Species (b)	Phyto plank ton	Sedi ment / Detrius	Zoo plank ton	Bi valves	Caddisfly larvae	Mayfly larvae	Iso pod	Midge larvae	Fish fry	Finger lings	N. pike & walleye fingerlings	Black crappie 5 7	Yellow perch 5 6	White sucker 6 12	White sucker 12 16	N. pike 15 30	Bluegill 5 8
Zooplankton	100%																
Bivalves	50%	40%	10%														
Caddisfly larvae	40%	50%	10%	0%													
Mayfly	0%	100%	0%	0%	0%												
Gammarus	10%	50%	40%	0%	0%	0%											
Midge larvae	40%	60%	0%	0%	0%	0%	0%										
Fish fry	30%	0%	70%	0%	0%	0%	0%	0%									
Minnows/ fingerlings	0%	0%	60%	0%	10%	10%	10%	10%	0%								
Pike & walleye fingerlings	0%	0%	0%	0%	0%	0%	0%	0%	20%	80%							
Black crappie 5-7"	0%	0%	10%	0%	10%	20%	20%	20%	20%	0%	0%						
Yellow perch 5-6"	0%	0%	0%	0%	20%	20%	20%	20%	20%	0%	0%	0%					
White sucker 6-12"	0%	40%	0%	0%	20%	20%	20%	0%	0%	0%	0%	0%	0%				
White sucker 12-16"	0%	40%	0%	0%	20%	20%	20%	0%	0%	0%	0%	0%	0%	0%			
N. pike 15-30"	0%	0%	0%	0%	0%	0%	0%	0%	0%	40%	20%	0%	20%	20%	0%		
Bluegill 5-8"	0%	0%	0%	0%	30%	20%	30%	10%	10%	0%	0%	0%	0%	0%	0%	0%	
Walleye 12-20"	0%	0%	0%	0%	0%	5%	0%	0%	10%	60%	5%	0%	20%	0%	0%	0%	0%

Table J.5 (continued). Endnotes.

[a] Consumer organisms listed as row headers (i.e., listed in first column of table). Diet components listed across the top as column headers. Small fish species include bluegill, crappie, perch, and sucker. Walleye and northern pike fingerlings feed more on smaller fish than on benthic invertebrates.

[b] Sources include AQUAWEB defaults for invertebrates, fish fry, and fingerlings other than walleye and pike. For remaining fish species, data reviewed included compilation of diet by species and size by Leidy and Jenkings 1977 (data from Great Lakes excluded): northern pike—Seaburg and Moyle 1964, Pearse 1921, Hunt and Carbine 1950; white sucker—Scidmore and Woods 1960, Pearse 1921; bluegill—Applegate et al. 1967, Seaburg and Moyle 1964, Scidmore and Woods 1960; black crappie—Seaburg and Moyle 1964, Keast 1968; yellow perch—Pearse 1921, Scidmore and Woods 1960; walleye—Scidmore and Woods 1960.

J.6. References

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Appendix K. Documentation of the Multimedia Ingestion Risk Calculator

K.1. Introduction

This document provides a detailed description of the Multimedia Ingestion Risk Calculator (MIRC), a modeling tool and database designed to assist in estimating risks via multiple ingestion pathways, particularly for food products grown or raised at home or on a farm.[25] MIRC estimates risks to humans from ingestion of produce or animal products, fish, and water in the vicinity of a source of chemical emissions to air. The user can evaluate either generalized (e.g., health protective default) or more site-specific scenarios using the same tool. MIRC includes a database of exposure parameter values, offering the user the option of selecting mean, median, and upper percentile values for many parameters, data permitting. Generally health protective default values are assigned to each parameter in the tool, and the default configuration is used for initial risk screening efforts by USEPA's Office of Air Quality Planning and Standards' (OAQPS) for Risk and Technology Review multimedia risk assessments. MIRC also allows the user to define the parameter values for crops and livestock grown on-site and characteristics of the farm residents to better represent a site-specific scenario.

With user-input concentrations for one or more chemicals in air and soil and air-to-surface deposition rates, MIRC calculates the chemical's concentrations in home- or farm-grown produce and animal food products using algorithms adapted from USEPA's *Human Health Risk Assessment Protocol for Hazardous Waste Combustion Facilities* (hereafter referred to as HHRAP; USEPA 2005a). MIRC uses those calculated concentrations, along with user-input chemical concentrations for fish and drinking water, to estimate chemical intake rates, as average daily doses (ADDs), for adults, children, and nursing infants. Users can obtain chemical input concentrations and deposition rates from measurements at an actual site or from a transport and fate model. For the exposure assessment of livestock carcass management options, inputs are derived from AERMOD, the SSW model, and other methods described in Section 4 of the main

[25] Fully functional versions of MIRC are in both Access™-based and Excel™-based formats; however, MIRC currently is not publicly available.

report. Although MIRC can provide human health risk estimates, this assessment uses MIRC only to estimate chemical exposure levels.

MIRC was developed to be a flexible, transparent application. The tool includes chemical transfer and ingestion exposure algorithms and a database of parameter values, many with several options, used by these equations. The MIRC database includes values for the relevant physiochemical properties and toxicity reference values for more than 500 chemicals, including approximately 60 inorganics taken primarily from a database developed for HHRAP (USEPA 2005a).

K.1.1. Scope of MIRC

For persistent and bioaccumulative chemicals, including PAHs and dioxins/furans, exposure from direct inhalation of the chemical can be much less than exposure from ingestion of the chemical in water, fish, and food products grown in an area of chemical deposition. Vegetables and fruits in such areas can become contaminated directly by deposition of the airborne chemical to foliage, fruits, and vegetables or indirectly by root uptake of the chemical deposited to soils. Livestock can be exposed to persistent and bioaccumulative chemicals via ingestion of contaminated forage and incidental ingestion of contaminated soils.

For chemicals characterized as persistent and bioaccumulative, evaluation of the inhalation pathway for air pollutants may reveal only a portion of the risk to individuals. Households that consume high quantities of self-caught fish or locally grown produce and animal products may be particularly susceptible to ingestion of chemicals transferred from air in the vicinity of an air emissions source. For persistent and bioaccumulative chemicals in particular, therefore, USEPA developed methods of estimating indirect exposure pathways associated with the deposition of airborne chemicals to gardens and farms, as described in HHRAP (USEPA 2005a).

K.1.2. MIRC Highlights

MIRC is a flexible, stand-alone software application. A user can supply either measured or estimated chemical concentrations for soil, air, water, and fish, and also can provide air deposition rates likely for the location(s) of interest based on local meteorology. The user can accept the default values for many exposure parameters and screen for small possibilities of risk,

or the user can select other options or overwrite parameter values to tailor the estimates to a specific scenario or location.

MIRC complies with EPA's latest guidelines for exposure and risk assessment, including HHRAP; the Agency's 2005 *Guidelines for Carcinogen Risk Assessment* (Cancer Guidelines), *Supplemental Guidance for Assessing Susceptibility from Early-Life Exposure to Carcinogens* (Supplemental Guidance), and *Guidance on Selecting Age Groups for Monitoring and Assessing Childhood Exposures to Environmental Contaminants* (USEPA 2005b,c,d); and its *Child-Specific Exposure Factors Handbook* (USEPA 2008a). In particular, MIRC provides several important capabilities:

- When provided air and soil concentrations, the MIRC software package allows rapid calculation of screening-level exposures and risks associated with household consumption of locally grown/raised foods.
- MIRC can calculate exposures and risks associated with incidental ingestion of surface soils, fish consumption, and drinking water.
- The tool calculates ADDs (i.e., chemical intake rates) for six "built-in" age groups to allow use of age-group-specific body weights, ingestion rates, food preferences, and susceptibility to toxic effects.
- Its database of chemical information covers plant- and animal-specific transfer factors and other inputs that determine concentrations in farm food stuffs.
- Value options for receptor characteristics in the database include the mean and 50th, 90th, 95th, and 99th percentile values where data permit. For assessment of carcass management options, mean values are used.
- For carcinogens with a mutagenic mode of action, MIRC estimates a lifetime (LADD) using the three lifestages and potency adjustment factors recommended in USEPA's (2005c,d) cancer guidelines and supplemental guidance.
- The data for children issued September 30, 2008, in the Agency's *Child-Specific Exposure Factors Handbook* (CSEFH) (USEPA 2008a) are included in MIRC.

K.2. MIRC Overview

The MIRC software package allows rapid calculation of screening-level exposures and risks associated with subsistence and recreational farmer/fisher populations in the vicinity of a source of chemical emissions to air. The tool allows a user to assess human exposures via ingestion

pathways, including drinking water consumption, incidental soil ingestion, fish ingestion, and ingestion of ten types of farm-grown food products: exposed fruits, protected fruits, exposed vegetables, protected vegetables, root vegetables, beef, total dairy, pork, poultry, and eggs. The tool also includes a breast milk ingestion and risk module for nursing infants, though we do not use this module in this exposure assessment of livestock carcass management options. For fruits and vegetables, the terms "exposed" and "protected" refer to whether the edible portion of the plant is exposed to the atmosphere.

K.2.1. Exposure Pathways

MIRC estimates the concentrations of chemicals in the farm food categories grown in an area of airborne chemical deposition using algorithms and parameter values provided in HHRAP (USEPA 2005a). Further details about the HHRAP algorithms and default assumptions are available in the HHRAP documentation (USEPA 2005a).

MIRC includes ten categories of food: exposed fruit, protected fruit, exposed

vegetables, protected vegetables, root vegetables, beef, total dairy, pork, poultry, and eggs. Table K.1 summarizes the pathways by which chemicals are transferred to these foods.

Plant produce included in MIRC can accumulate a chemical directly from air and/or soil. For exposed produce, chemical mass is assumed to be transferred to plants from the air in two ways. First, particle-bound chemical can deposit directly on the plant surface. Second, the uptake of vapor-phase chemicals by plants through their foliage can occur. For both exposed and protected produce, the concentration in the plant derived from exposure to the chemical in soil is estimated using an empirical bioconcentration factor that relates the concentration in the plant to the concentration present in the soil. For belowground root vegetables, a root concentration factor is applied. We list the algorithms used to estimate produce concentrations in Section K.3.1 of this appendix.

Chemical concentrations in animal products are estimated based on the amount of chemical consumed through the diet, including incidental ingestion of soil while grazing. The diet options for farm animals in MIRC include forage (plants grown on-site for animal grazing, such as grass), silage (wet forage grasses, fresh-cut hay, or other fresh plant material that has been stored

and fermented), and feed grain products grown on the farm (e.g., corn, soybeans). All three animal feed products are assumed to accumulate chemical via root uptake from the soil. Forage and silage also can accumulate chemical via direct deposition of particle-bound chemical and vapor transfer.

The algorithms in MIRC rely on the assumptions that beef and dairy cattle consume all three feed products, while pigs consume only silage and grain, and chickens consume only grain from the ground, and incidentally ingest contaminated surface soils. The incidental ingestion of the chemical in soils during grazing or consumption of foods placed on the ground is estimated using empirical soil ingestion values. For secondary animal products (dairy products and eggs), MIRC estimates chemical concentrations by applying a biotransfer factor to the estimated concentration in the "source" animal (cows and chickens, respectively). Section K.3.1 lists algorithms for estimating animal product concentrations.

Table K.1. Transfer Pathways for the Modeled Farm-grown Foods.

Farm Food Media	Chemical Transfer Pathways
Exposed fruit and vegetables	• Direct deposition from air of particle-bound chemical • Air-to-plant transfer of vapor phase chemical • Root uptake from soil
Protected fruit and vegetables (including root vegetables)	• Root uptake from soil
Beef and total dairy (including milk)	• Ingestion of forage, silage, and grain[a] • Soil ingestion
Pork	• Ingestion of silage and grain[a] • Soil ingestion
Poultry and eggs	• Ingestion of grain[a] • Soil ingestion

[a] Chemical concentrations in forage, silage, and grain are estimated via intermediate calculations analogous to those used for aboveground produce.

K.2.2. Receptor Groups

As noted in USEPA risk assessment guidelines (USEPA 2005b,c,d, 2008a), exposures of children differ from exposures of adults due to differences in body weights, ingestion rates, dietary preferences, and other factors. It is important, therefore, to evaluate the contribution of exposures during childhood to total lifetime risk using appropriate exposure factor values.

USEPA's HHRAP (Chapter 4, USEPA 2005a) recommends assessing exposures for children and adults separately, but considers all non-infant children in one category. Specifically, HHRAP

recommends eight categories of receptor: farmer, child farmer, resident, child resident, fisher, child fisher, acute receptor, and nursing infant. Over time, different USEPA programs have used different child age groupings to evaluate body weights, ingestion rates, and other parameter values needed to estimate chemical exposures and risks to children.

To improve the match between age groups used to estimate values across exposure parameters, in 2005, USEPA recommended a standard set of child age categories for exposure and risk assessments (USEPA 2005b). USEPA recommended four age groups for infants: birth to < 1 month; 1 to < 3 months; 3 to < 6 months; and 6 to < 12 months. For young children, USEPA recommended an additional four age groups: 1 to < 2 years; 2 to < 3 years; 3 to < 6 years; and 6 to < 11 years. Two age groupings are recommended for teenagers and young adults: 11 to < 16 years; and 16 to < 21 years. These age groupings correspond to different developmental stages, and reflect different food ingestion rates per unit body weight, with the highest ingestion rates occurring for the youngest, most rapidly growing, age groups.

Although the age groupings in MIRC do not precisely match the groupings USEPA recommended in 2005 for Agency exposure assessments (USEPA 2005b), they are the only age-groupings supported by available data. The 1987-1988 *Nationwide Food Consumption Survey* (USDA 1992, 1993, 1994a) remains the most recent survey of ingestion rates for home-grown foods, and USEPA's analysis of that data, published in its 2011 *Exposure Factors Handbook*, remains the most recently published major analysis of the data. Because ingestion of home-grown produce and animal products are the primary exposure pathways used to develop MIRC, those are the age groupings we use for all child parameter values to estimate exposure and risk.

In this assessment, values for each exposure parameter are estimated for adults (20 to 70 years), and five children's age groups:

- Infants under 1 year (i.e., 0 to < 1 year)
- Children ages 1 through 2 years (i.e., 1 to < 3 years)
- Children ages 3 through 5 years (i.e., 3 to < 6 years)
- Children ages 6 through 11 years (i.e., 6 to < 12 years)
- Children ages 12 through 19 years (i.e., 12 to < 20 years)

For assessment of cancer risks from early-life exposure, USEPA recognizes infants and children may be more sensitive to a carcinogenic chemical than adults, with cancers appearing earlier in life or with lower doses experienced during childhood (USEPA 2005c,d). For this reason, the "potency" of a carcinogen might be higher for infants and children than for adults. To date, however, data evaluating the relative sensitivity of children and adults to the same daily dose of a carcinogen remains limited. Based on analyses of radioactive and other carcinogenic chemicals, USEPA recommends evaluating two lifestages for children separately from adults for chemicals that cause cancer by a mutagenic mode of action (MOA): from birth to < 2 years and from 2 to < 16 years (USEPA 2005c,d). USEPA also suggests that, as data become available regarding carcinogens with a mutagenic MOA, further refinements of these age groupings may be considered.

For assessing risks from exposures to carcinogenic chemicals that act via a mutagenic MOA, USEPA recommends two early lifestages (USEPA 2005c,d) which are included in MIRC:

- Children under the age of 2 years (i.e., 0 to < 2 years)
- Children from 2 through 15 years (i.e., 2 to < 16 years)

Different age groupings are needed for the assessment of risks from carcinogenic chemicals with a mutagenic MOA and other carcinogens with other or unknown MOAs. Currently in MIRC, the only persistent and bioaccumulative chemicals with a mutagenic mode of carcinogenesis would be the carcinogenic PAHs. Arsenic also is persistent and carcinogenic via oral exposures.

K.3. Exposure Algorithms

The exposure algorithms in MIRC are described below in four sections. Section K.3.1 presents the algorithms used to estimate chemical concentrations in farm-grown foods from chemical concentrations in soil and air. We include both pathway-specific algorithms for estimating chemical intake by adults and non-infant children. As noted previously, MIRC's exposure algorithms are based on HHRAP modeling (USEPA 2005b). The explicit form of each algorithm is in the HHRAP documentation. This section explains differences between MIRC and HHRAP.

K.3.1. Farm-Raised Foods – Algorithms to Calculate Chemical Concentrations

MIRC's algorithms separately evaluate the chemical concentrations that accrue in produce from those in animal products. The following subsections describe the algorithms and parameters used for each of these estimation processes. The applicable modeled pathways correspond to specific features exhibited by the growth of produce and animals.

Estimating Chemical Concentrations in Produce

Produce (vegetables and fruits) can be contaminated either directly by deposition of airborne chemicals to foliage and fruits, or indirectly by uptake of chemicals deposited to the soil that dissolve in the water that the plant absorbs for growth. Given these two contamination processes, produce is divided into two main groups: aboveground and belowground produce. Aboveground produce is divided into fruits and vegetables. These groups are further subdivided into "exposed" and "protected" depending on whether the edible portion of the plant is exposed to the atmosphere or is protected by a husk, hull, or other outer covering.

Table K.2 lists the transfer pathways for chemicals to the farm produce categories. The subsections below describe the transfer pathways and algorithms for aboveground and belowground produce, respectively.

Table K.2. Chemical Transfer Pathways for Produce.

Farm Food Media		Chemical Transfer Pathways
Aboveground Produce	Exposed fruits and vegetables	Direct deposition from air of particle-bound chemical Air-to-plant transfer of vapor phase chemical Root uptake
	Protected fruits and vegetables	Root uptake
Belowground Produce	Root vegetables	Root uptake

Aboveground produce.

For aboveground *exposed* produce, MIRC assumes chemical mass can be transferred to plants from the air in three ways, as illustrated in Figure K.1. First, particle-bound chemical can deposit directly on the plant surface via deposition (*Pd*). The amount of chemical accumulated is estimated based on the areal fraction of chemical deposition intercepted by the plant surface, minus a loss factor that is intended to account for removal of deposited chemical by wind and rain and changes in concentration due to growth dilution. Second, for chemical present in air in the vapor phase, the concentration of chemical accumulated by the plant's foliage is estimated using an empirical air-to-plant vapor biotransfer factor (*Pv*). Third, estimations of the chemical concentration in the plant due to uptake by roots (*PrAG-produce*) uses an empirical bioconcentration factor (*BrAG-produce*) that relates the chemical concentration in the plant to the average chemical concentration in the soil at the root-zone depth in the produce-growing area (*Csroot-zone_produce*).

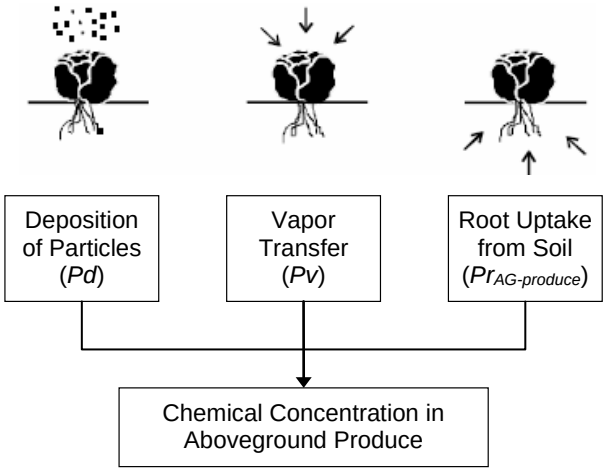

Figure K.1. Estimating chemical concentration in aboveground produce.

The edible portions of aboveground protected produce are not subject to contamination via particle deposition (*Pd*) or vapor transfer (*Pv*). Therefore, root uptake of chemicals is the primary mechanism through which aboveground protected produce becomes contaminated. As shown below, the estimations of chemical concentration in the aboveground plant due to root uptake (*PrAG-produce-DW*) use an empirical bioconcentration factor (*BrAG-produce-DW*) that relates the chemical concentration in the plant to the average chemical concentration in the soil at the root-zone depth in the produce-growing area (*Csroot-zone_produce*). All of these equations are based on dry-weight (dw or DW) measurements.

Equation for Chemical Concentration in Aboveground Produce Due to Deposition of Particle-phase Chemical. The equation in MIRC for chemical concentration in above ground produce

due to deposition of particle phase chemicals (Equation K.1) differs from Equation 5-14 in HHRAP. In HHRAP, Equation 5-14 includes the term Q x (1 – Fv) to indicate the emissions rate, in g/sec, of chemicals from the source and the proportion of the chemical that remains in, or partitions to, the particle-phase in the air. Also in HHRAP, the dry and wet particle phase deposition rates, *Dydp* and *Dywp*, respectively, are normalized to the emission rate and are expressed in units of sec/m^2-yr.

In contrast, with MIRC, the user inputs both the dry and wet particle-phase deposition rates, *Drdp* and *Drwp*, respectively, in units of g/m^2-yr for a specific location relative to an emissions source. Those deposition rates might be values measured near that location or estimated using a fate and transport model, such as AERMOD, in conjunction with local meteorological information and emissions rate data. The chemical emissions term used in HHRAP, *Q*, therefore, is not used in MIRC's Equation K.1. In addition, in MIRC, *Drdp* and *Drwp*, the average annual dry- and wet-particle-phase deposition rates, respectively, are in units of g/m^2-yr whereas air deposition from combustion-based carcass management scenarios occurs only over 48 hours, requiring a conversion to a fraction of a year (i.e., 2/365 days = 0.00548 years). Moreover, the wet deposition terms have limited effect, because we selected meteorological data on days with negligible precipitation, assuming that open burning could not be conducted during periods of rain.

$$Pd_{(i)} = \frac{1{,}000 \times (Drdp + (Fw \times Drwp)) \times Rp_{(i)} \times (1 - e^{(-kp(i) * Tp(i))})}{Yp_{(i)} \times kp_{(i)}} \qquad \textbf{(Eqn. K.1)}$$

where:

$Pd_{(i)}$ = Chemical concentration in aboveground produce type *i* on a dry-weight (dw) basis due to particle deposition (mg/kg produce dw); set equal to zero for *protected* aboveground produce

$Drdp$ = Average annual dry deposition of particle-phase chemical (g/m^2-yr)

Fw = Fraction of wet deposition that adheres to plant surfaces; 0.2 for anions, 0.6 for cations and most organics (unitless)

$Drwp$ = Average annual wet deposition of particle-phase chemical (g/m^2-yr)

$Rp_{(i)}$ = Interception fraction of the edible portion of plant type *i* (unitless)

$kp_{(i)}$ = Plant surface loss coefficient for plant type *i* (yr^{-1})

$Tp_{(i)}$ = Length of exposure to deposition in the field per harvest of the edible portion of plant type *i* (yr)

$Yp_{(i)}$ = Yield or standing crop biomass of the edible portion of plant type i (kg produce dw/m^2)

Chemical Concentration in Aboveground Produce Due to Air-to-Plant Transfer of Vapor-phase Chemical. Equation K.2 presents the equation used to estimate the transfer of vapor-phase chemical to aboveground produce.

$$Pv_{(i)} = \frac{Ca \times Fv \times Bv_{AG(i)} \times VG_{AG(i)}}{\rho_a} \qquad \textbf{(Eqn. K.2)}$$

where:

$Pv_{(i)}$ = Concentration of chemical in edible portion of aboveground produce type *i* from air-to-plant transfer of vapor-phase chemical on a dry-weight (DW) basis (µg/g produce DW); set equal to zero for *protected* aboveground produce

Ca = Average annual *total* chemical concentration in air (g/m^3)

Fv = Fraction of airborne chemical in vapor phase (unitless)

$Bv_{AG(i)}$ = Air-to-plant biotransfer factor for aboveground produce type *i* for vapor-phase chemical in air ([mg/g produce DW] / [mg/g air], i.e., g air/ g produce DW)

$VG_{AG(i)}$ = Empirical correction factor for aboveground *exposed* produce type *i* to address possible overestimate of the diffusive transfer of chemical from the outside to the inside of bulky produce, such as fruit (unitless)

ρ_a = Density of air (g/m^3)

Belowground produce. The equations by which MIRC estimates chemical concentrations in belowground produce are different for nonionic organic chemicals than for inorganic chemicals and ionic organic chemicals.

Nonionic organic chemicals. Soil covers belowground produce, such as tubers or root vegetables, providing protection from chemical deposition and vapor transfer from air. Chemical uptake through the roots is the primary mechanism for chemical contamination of belowground produce. MIRC derives the nonionic organic chemical concentration in the tuber or root vegetable from exposure to the chemical in soil. The algorithm uses an empirical root concentration factor (RCF) and the average chemical concentration in the soil at the root-zone

depth in the produce-growing area (*Csroot-zone_produce*). The RCF relates the chemical concentration in the plant on a wet-weight basis to the average chemical concentration in the root-zone soil (*Csroot-zone_produce*) on a dry-weight basis.

The RCF, as developed by Briggs et al. (1982), is the ratio of the chemical concentration in the edible root on a wet-weight (ww) basis to its concentration in the soil pore water. RCFs are based on experiments with growth solutions (hydroponic) instead of soils making it necessary to divide the soil concentration by the chemical-specific soil/water partition coefficient (Kds) to accurately model a soil-based crop production system. There is no conversion of chemical concentrations in belowground produce from dw to ww because the values are already on a ww basis.

For nonionic organic chemicals, it is possible to predict RCF values and Kds values (for a specified soil organic carbon content) from an estimate of the chemical's Kow from empirically derived regression models. Those models are shown in HHRAP Appendix A-2, Equations A-2-14 and A-2-15 (RCF) and in Equations A-29 and A-2-10 (Kds). The RCF and Kd values calculated for many of the chemicals in HHRAP already are included in the MIRC database (including the values for PAHs and dioxins).

Inorganic and ionic organic chemicals. For inorganic chemicals and ionized organic chemicals, it is not possible to predict RCF or Kds values from Kow. Instead, inorganic chemical calculations use chemical-specific empirical values for the root/soil bioconcentration factor. The root/soil bioconcentration factor, now specified as *BrBG-produce-DW*, must be obtained from the literature for each inorganic chemical on a dw basis.

Estimating Chemical Concentrations in Animal Products

MIRC estimates chemical concentrations in animal products from the amount of chemical consumed by each animal group (designated *m*) through each plant feed type (designated *i*) or (*PlantCh-Intake*(*i*,*m*)) combined with the incidental ingestion of soil for ground-foraging animals (*SoilCh-Intake*(*m*)). Table K.3 summarizes the transfer pathways for chemicals to these home- or farm-raised animal food products. Note that for a general screening-level assessment, all of the pathways can be modeled, as is done for USEPA's *Risk and Technology Review* calculation of screening threshold emission rates for persistent and bioaccumulative chemicals that are also listed as hazardous air pollutants (USEPA 2008b).

The feed options for farm animals in MIRC include forage (plants grown on-site for animal grazing, such as grass), silage (wet forage grasses, fresh-cut hay, or other fresh plant material that has been stored and fermented), and grain products grown on the farm. The algorithms for chemical intake with plant feeds (*PlantCh-Intake*(*i*,*m*)) are based on the assumptions that beef and dairy cattle consume all three plant feed products, while pigs consume only silage and grain, and chickens consume only grain.

Table K.3. Chemical Transfer Pathways for Animal Products.

Farm Food Media		Chemical Transfer Pathways
Animal Products	Beef and total dairy (including milk)	• Ingestion of forage, silage, and grain[a] • Incidental soil ingestion
	Pork	• Ingestion of silage and grain[a] • Incidental soil ingestion
	Poultry and eggs	• Ingestion of grain[a] • Incidental soil ingestion

[a] Chemical concentrations in plant feed (i.e., forage, silage, and grain) are estimated via intermediate calculations.

MIRC assumes three types of plant tissue exposures ultimately can affect animals. As the plants grow, all three types of animal feed accumulate chemicals via root uptake. In addition, there is exposure of forage and silage plant tissues to the air, so those animal foods can accumulate chemicals via direct deposition of particle-bound chemicals and transfer of vapor-phase chemicals. The plants that produce animal feed grains are protected from the air by a husk or pod (e.g., corn, soybeans), so the model does not include direct deposition and vapor-phase transfers from air to these feeds.

Estimation of chemical concentrations in animal feeds uses algorithms analogous to those for aboveground farm produce, as described above. To account for endogenous degradation of a chemical within an animal, MIRC adjusts the chemical concentration in mammalian farm animals (i.e., beef and pigs) using a metabolism factor (MF). The MF is set to 1.0 for chemicals that are not metabolized (e.g., metals) and for chemicals with an unknown metabolic degradation rate (e.g., PAHs). Although other vertebrates, including birds, are likely to use similar metabolic pathways for most chemicals, MIRC adopts a health protective assumption that birds do not metabolize any chemicals and omits an MF from the calculations for poultry and eggs.

MIRC estimates incidental ingestion of soil containing chemicals by livestock during grazing or consumption of feed placed on the ground (*SoilCh-Intake*(*m*)) using empirical soil ingestion rates

(*Qs*) and a soil bioavailability factor for livestock (*Bs*). The default value for Bs for all chemicals is 1.0, which means there is 100% bioavailability of the chemical to the animal. This assumption might be reasonably accurate for the soil surfaces receiving deposition of an airborne chemical. MIRC allows the user to enter a surface soil concentration for areas where livestock forage as *CsS-livestock.*

MIRC calculates animal ingestion of chemicals in feed for each type of livestock (designated *m* in the modeling) based on the composition of foodstuff in their diet. The type of feed is designated *i* in the modeling. For beef and dairy cattle, estimates of chemical intake use all three feed types forage, silage, and grain. For pork, estimates of the chemical intake use only silage and grain. For poultry, estimates of the chemical intake are based on grain consumption. The intake of chemical with each feed type, *PlantCh-Intake*(*i,m*), is calculated separately. Note that the animal feed ingestion rates are on a dry-weight (dw) basis; consequently, there are no dw to wet weight (ww) conversions. In addition, incidental ingestion of contaminated soils is included for consumption of forage by cattle and of grains by chickens.

The concentrations of chemicals in the three different types of plant feeds for livestock are calculated in the same way as aboveground produce with two exceptions. The concentrations are for plants used as animal feeds (not produce consumed by humans), and all types of plant feed (i.e., forage, silage, and grain) are aboveground.

MIRC calculates the chemical concentration in animal feed from uptake through the roots in the same way as it does for uptake of chemicals from plants for human consumption with two exceptions. First, the modeling uses a *Br* value appropriate to grasses. Secondly, MIRC allows different soil concentrations for the chemical in the area growing the animal feed than in the area growing produce for human consumption, if appropriate (e.g., in spatially explicit models). Note that for grains, the *Pd* and *Pv* terms do not apply, and the values are set to zero, because the feed products (i.e., corn kernels, soy beans) are protected from the air by husks or pods.

The algorithms used to calculate *Pd* and *Pv* for forage and silage are identical to those used to calculate the same parameters for aboveground exposed produce.

K.3.2. Chemical Intake Calculations for Adults and Non-Infant Children

MIRC calculates human chemical intake rates from the ingestion of home-grown foods as average daily doses (ADDs) normalized to body weight. MIRC separately calculates ADDs for each chemical, home-grown food type, and consumer age group. ADDs are expressed in milligrams of chemical per kilogram of receptor body weight per day (mg/kg-day). Calculation of ADDs takes into account six major factors. They are: (1) the chemical concentration in each food type i (or in water), (2) the quantity of food brought into the home for consumption, (3) the loss of some of the mass of the foods due to preparation and cooking, (4) how much of the food is consumed per year, (5) the amount of the food obtained from contaminated areas, and (6) the consumer's body weight (USEPA 2011, 2003a).

MIRC evaluates only one exposure scenario at a time. For screening-level assessments, it assumes all components of this equation remain constant for consumers in a given age group over time (e.g., seasonal and annual variations in diet are not explicitly taken into account). To calculate an *ADD*(*y,i*) from the contaminated area for food group i over an entire lifetime of exposure, age-group-specific ingestion rates and body weights are used for the age groups described in the main section. In MIRC, the averaging time used to calculate the daily dose for an age group (*ATy*) equals the exposure duration for that group (*EDy*); therefore these variables cancel out and therefore do not affect the calculations.

For each chemical included in a screening scenario, MIRC estimates the total average daily exposure for age group *y* (*ADD*(*y*)) as the sum of chemical intake from all ingestion pathways:

- Incidental soil ingestion
- Ingestion of fish
- Ingestion of homegrown fruits (exposed and protected)
- Ingestion of homegrown vegetables (exposed, protected, and root)
- Ingestion of animal products from home-raised animals:
  - milk and other dairy products from cows
  - beef products
  - pork products
  - poultry and eggs
- Ingestion of drinking water as formula from a farm source (infants only)

HHRAP documentation describes the algorithms for the six exposure pathways listed above. This assessment briefly describes pertinent features for five of these exposure pathways.

First, a possible exposure pathway in MIRC is ingestion of locally caught fish that are potentially contaminated with chemicals from the carcass management option. USEPA estimates the proportion of the weight of whole fish that tends to be lost during preparation and cooking across a variety of fish species (USEPA 2011), and includes those losses in its HHRAP algorithms for chemical intake from fish. Preparation of whole fish for cooking usually involves removal of the viscera, head, and fins, particularly for larger fish. Many persons also remove (or do not eat) the skin, bones, and belly fat. There are two types of fish included in the exposure algorithm: trophic level 3.5 (abbreviated as TL3) fish, equivalent to benthic carnivores such as catfish, and trophic level 4 (TL4) fish in the water column, equivalent to game fish such as lake trout and walleye. The equations for each trophic level includes corrections for the relative loss during preparation and cooking.

Second, a possible exposure pathway in MIRC is the ingestion of fruit potentially contaminated with chemicals from the carcass management option. MIRC separately calculates ADDs of a chemical from homegrown exposed and protected fruit. MIRC bases fruit ingestion rates on weights of unprepared fruits (e.g., one apple; one pear) or the weight of a can of fruit (e.g., 8 ounce can). The weight of ingested fruit often is less than the initial weight owing to common preparation actions, such as coring or peeling apples and pears or pitting cherries (*L1ExpFruit* and *L1ProFrui*t). Cooking of exposed fruit (e.g., berries, apples, peaches) reduces the liquid content so the weight of the cooked fruit is less than the initial weight (*L2ExpFruit*). USEPA assumes cooking of protected fruit does not reduce the weight of the fruit.

Third, MIRC includes three separate algorithms for homegrown vegetables (exposed, protected, and root). Examples of exposed vegetables are asparagus, broccoli, lettuce, and tomatoes (although they are actually a fruit). Protected vegetables include corn, cabbage, soybeans, and peas. Root vegetables are carrots, beets, and potatoes.

Fourth, the effect of cooking on animal products may alter the concentration of chemicals in the food product as consumed. The reduction in the weight of beef, pork, and poultry during and

after cooking (so called "shrinkage") might cause an increase or decrease in the concentration of the chemical in the consumed food depending on the chemical and the cooking method.

Last, MIRC models the potential for chemical ingestion by infants through contaminated drinking water used to dilute formula. MIRC allows users to specify a chemical concentration in g/L (equivalent to mg/mL) pertinent to their particular scenario. The chemical concentration could represent water from groundwater wells, community water, nearby surface waters, or other source. For this exposure pathway, ingestion rates are in units of milliliters of water per day (mL/day).

K.3.3. Calculation of Total Chemical Intake

To estimate the total ADD, or intake of a chemical from all of the exposures that a single individual in each age group might contact (e.g., soil, local fish, five types of home-grown produce, and five types of home-raised animals or animal products), the media-specific chemical intakes are summed for each age group. MIRC estimates the total average daily exposure for a particular age group *y* (ADD(*y*)) as the sum of chemical intake from all ingestion pathways.

K.4. Model Input Options

This section describes the MIRC input options. Section K.4.1 describes the required user inputs for environmental media concentrations and air deposition rates. Section K.4.2 discusses parameter values for specific types of produce and animal products. Next, section K.4.3 describes options for parameterizing receptor characteristics including age-group-specific values for body weight, water ingestion, and food ingestion by food type. Finally, section K.4.4 discusses options for other exposure parameter values in MIRC, such as exposure frequency and loss of chemical during food preparation and cooking.

The MIRC database contains chemical-specific parameter values for more than 500 chemicals derived from all of the chemical-specific input data compiled by USEPA for use in HHRAP. This assessment considers only those chemicals that are persistent and/or bioaccumulative and toxic (e.g., 2,3,7,8 dioxins/furans, medium and heavier weight PAHs, heavy metals) that are evaluated for USEPA's *Risk and Technology Review*. The HHRAP inputs provided for other chemicals were not reviewed or verified.

K.4.1. Environmental Concentrations

As noted in Section K.2 of these appendices, MIRC estimates exposures and risks to self-sufficient farming and fishing families from ingestion of farm-grown produce in an area receiving airborne chemical deposition. The tool analyzes one exposure scenario at a time, such as an adult farmer exposed to dioxin from ingestion of beef. For this reason, MIRC's analysis is the most robust when evaluating a maximally exposed individual (MEI) or family when screening for possible risks.

The following values specific to the air pollutant of concern are required inputs to MIRC:

- A single air concentration (in g/m^3)
- The fraction of chemical in the air that is in the vapor phase
- Air-to-surface deposition rates for both vapor- and particle-phase chemical in the air (in g/m^2-yr)
- Two fish tissue concentrations, one each for forage and game fish (i.e., fish in TL3 and TL4) (in mg/kg wet weight)
- Concentrations in drinking water (in g/L)
- Four chemical concentrations in soil (in µg/g dry weight), one each for:
  - surface soil in produce growing area
  - surface soil where livestock feed
  - root-zone soil in produce growing area
  - root-zone soil in livestock feed growing

The MIRC software configuration estimates ingestion exposures via drinking water for a specified chemical concentration in the drinking water source (e.g., groundwater well).

The user must provide the inputs listed above; there are no default values for these parameters in MIRC. For this livestock carcass exposure assessment, we computed these inputs using AERMOD (for air concentrations and deposition rates), the SSW model, AQUAWEB (for fish concentrations), and other calculation methods described in Section 4 of the main report. A Microsoft® Excel™ routine in Visual Basic facilitated the aggregation of these inputs from the various tools, and organized them for use by MIRC.

K.4.2. Chemical Uptake into Farm Food Products

Using the above identified chemical information as inputs, MIRC calculates chemical concentrations in foods that are commonly grown or raised on family farms using algorithms

from HHRAP (USEPA 2005a). Parameter values required for these HHRAP algorithms, including chemical-specific media transfer factors (e.g., soil-to-plant transfer coefficients) and plant- and animal-specific properties (e.g., plant interception fraction, quantity of forage consumed by cattle), are in tables in MIRC. The HHRAP-recommended parameter values are the default values in MIRC; however, these and other inputs in MIRC can be revised or overwritten as needed. Table K.4 describes the parameters that are included in the algorithms used to estimate chemical concentrations in the farm food categories. The parameter names and symbols are referenced in this section for plants/produce and animal products.

Table K.4. MIRC Parameters Used to Estimate Chemical Concentrations in Farm Foods.

Parameter	Description	Units
Plants/Produce		
Br_AG-produce-DW(*i*)	Chemical-specific plant/soil chemical bioconcentration factor for edible portion of aboveground produce type *i*, exposed or protected	Unitless (g soil dw / g produce dw)
Bv_AG(*i*)	Chemical-specific air-to-plant biotransfer factor for aboveground produce type *i* for vapor-phase chemical in air	Unitless ([mg chemical / g plant dw] / [mg chemical / g air])
Fw	Fraction of wet deposition that adheres to plant surfaces; 0.2 for anions, 0.6 for cations and most organics	Unitless
Kds	Chemical-specific soil/water partition coefficient	L soil pore water / kg soil dw
*kp_*(*i*)	Plant-specific surface loss coefficient for aboveground exposed produce and animal forage and silage	yr^{-1}
*MAF_*(*i*)	Moisture adjustment factor for aboveground produce type *i* to convert the chemical concentration estimated for dry-weight produce to the corresponding chemical concentration for full-weight fresh produce	Percent water
RCF	Chemical-specific root concentration factor for tubers and root produce on a wet-weight (ww) basis	L soil pore water/ kg root ww
*Rp_*(*i*)	Plant-specific interception fraction for the edible portion of aboveground exposed produce or animal forage and silage	Unitless
*Tp_*(*i*)	Length of plant exposure to deposition per harvest of the edible portion of aboveground exposed produce or animal forage and silage	Year
VG_AG(*i*)	Empirical correction factor for aboveground exposed produce type *i* to address possible overestimate of the diffusive transfer of chemical from the outside to the inside of bulky produce, such as fruit	Unitless
VG_rootveg	Empirical correction factor for belowground produce (i.e., tuber or root vegetable) to account for possible overestimate of the diffusive transfer of chemicals from the outside to the inside of bulky tubers or roots (based on carrots and potatoes)	Unitless
*Yp_*(*i*)	Plant-specific yield or standing crop biomass of the edible portion of produce or animal feed	kg produce dw/m^2
Animal Products		
Bs	Soil bioavailability factor for livestock	Unitless

Parameter	Description	Units
MF	Chemical-specific mammalian metabolism factor that accounts for endogenous degradation of the chemical	Unitless
*Ba_*(*beef*)	Chemical-specific biotransfer factor for chemical in diet of cow to chemical in beef on a fresh-wet (fw; equivalent to ww) basis	mg chemical/kg tissue fw/mg chemical/day or day/kg fw tissue
*Ba_*(*dairy*)	Biotransfer factor in dairy	day/kg tissue fw
*Ba_*(*pork*)	Biotransfer factor in pork	day/kg tissue fw
*Ba_*(*poultry*)	Biotransfer factor in poultry	day/kg tissue fw
*Ba_*(*eggs*)	Biotransfer factor in eggs	day/kg tissue fw
*Qs_*(*m*)	Quantity of soil eaten by animal type m each day	kg/day
*Qp_*(*i,m*)	Quantity of plant feed type i consumed per animal type m each day	kg/day

Abbreviations: dw = dry weight; fw = fresh weight = ww = wet weight; L = liter; yr = years.

Note: Underline ("_") means that the following text should be subscripted; however, subscripting in this table would be too small to be legible.

Source: USEPA 2005a.

Table K.5 and Table K.6 provide the chemical-specific input values that are the current defaults for produce FFC food types in MIRC.

Table K.5. Chemical-Specific Inputs for Produce Parameters for Chemicals Included in MIRC.

Chemical	Fraction of Wet Deposition (*Fw*) (unitless)[a]	Root Concentration Factor (RCF) (belowground) (L/kg)[b]	Soil Water Partition Coefficient (Kds) (L/kg)[c]	Chemical Air to Plant Biotransfer Factor ($Bv_{AG(i)}$) (unitless)[d]
Inorganics				
Cadmium compounds	0.6	na	7.5E+01	na[e]
Mercury (elemental)	0.6	na	1.0E+03	0[f]
Mercuric chloride	0.6	na	5.8E+04	1.8E+03
Methyl mercury	0.6	na	7.0E+03	0[f]
PAHs				
2-Methylnaphthalene	0.6	2.2E+02	5.0E+01	1.4E+00
7,12-Dimethylbenz[a]anthracene	0.6	6.8E+03	4.0E+03	4.2E+04
Acenaphthene	0.6	2.4E+02	3.9E+01	4.6E+00
Acenaphthylene	0.6	2.8E+02	6.8E+01	8.1E+00
Benz[a]anthracene	0.6	6.7E+03	2.9E+03	6.8E+03
Benzo[a]pyrene	0.6	9.2E+03	7.8E+03	1.7E+05
Benzo[b]fluoranthene	0.6	6.6E+03	3.8E+03	1.7E+05
Benzo[g,h,i]perylene	0.6	3.0E+04	2.6E+04	2.3E+06
Benzo[k]fluoranthene	0.6	8.7E+03	5.5E+03	2.8E+05
Chrysene	0.6	6.0E+03	3.4E+03	1.4E+04
Dibenz[a,h]anthracene	0.6	2.3E+04	1.4E+04	6.2E+06
Fluoranthene	0.6	2.2E+03	3.9E+02	9.0E+02
Fluorene	0.6	3.8E+02	6.2E+01	1.6E+01
Indeno[1,2,3-cd]pyrene	0.6	3.5E+04	3.2E+04	2.8E+06
Dioxins				
OctaCDD, 1,2,3,4,6,7,8,9-	0.6	4.8E+05	7.8E+05	2.4E+06
OctaCDF, 1,2,3,4,6,7,8,9-	0.6	3.4E+05	4.9E+05	2.3E+06
HeptaCDD, 1,2,3,4,6,7,8-	0.6	3.4E+05	4.9E+05	9.1E+05
HeptaCDF, 1,2,3,4,6,7,8-	0.6	1.2E+05	1.2E+05	8.3E+05
HeptaCDF, 1,2,3,4,7,8,9-	0.6	4.8E+04	3.9E+04	8.3E+05
HexaCDD, 1,2,3,4,7,8-	0.6	2.4E+05	3.1E+05	5.2E+05
HexaCDF, 1,2,3,4,7,8-	0.6	5.7E+04	4.9E+04	1.6E+05
HexaCDD, 1,2,3,6,7,8-	0.6	4.9E+05	8.0E+05	5.2E+05
HexaCDF, 1,2,3,6,7,8-	0.6	2.9E+05	4.1E+05	1.6E+05
HexaCDD, 1,2,3,7,8,9 -	0.6	4.9E+05	8.0E+05	5.2E+05
HexaCDF, 1,2,3,7,8,9-	0.6	1.6E+05	1.9E+05	1.6E+05

Chemical	Fraction of Wet Deposition (*Fw*) (unitless)[a]	Root Concentration Factor (RCF) (belowground) (L/kg)[b]	Soil Water Partition Coefficient (Kds) (L/kg)[c]	Chemical Air to Plant Biotransfer Factor ($Bv_{AG(i)}$) (unitless)[d]
HexaCDF, 2,3,4,6,7,8-	0.6	2.9E+05	4.1E+05	1.6E+05
PentaCDD, 1,2,3,7,8-	0.6	9.2E+04	9.2E+04	2.4E+05
PentaCDF, 1,2,3,7,8-	0.6	3.9E+04	3.0E+04	9.8E+04
PentaCDF, 2,3,4,7,8-	0.6	2.3E+04	1.6E+04	9.8E+04
TetraCDD, 2,3,7,8-	0.6	4.0E+04	3.1E+04	6.6E+04
TetraCDF, 2,3,7,8-	0.6	1.2E+04	6.2E+03	4.6E+04

Abbreviations: na = not applicable.

Source: USEPA 2005a.

[a] 6E-01 is the value for cations and most organic chemicals. As described in HHRAP (USEPA 2005a), Appendix B (available at http://www.epa.gov/osw/hazard/tsd/td/combust/finalmact/ssra/05hhrapapb.pdf), USEPA estimated this value (USEPA 1994a, 1995a) from a study by Hoffman et al. (1992) in which soluble gamma-emitting radionuclides and insoluble particles tagged with gamma-emitting radionuclides were deposited onto pasture grass via simulated rain. Note that the values developed experimentally for pasture grass may not accurately represent all aboveground produce-specific values. Also note that values based on the behavior of insoluble particles tagged with radionuclides may not accurately represent the behavior of organic compounds under site-specific conditions.

[b] For nonionic organic chemicals, as described in HHRAP (USEPA 2005a), Appendix A (available at http://www.epa.gov/osw/hazard/tsd/td/combust/finalmact/ssra/05hhrapapa.pdf), RCF is used to calculate the below-ground transfer of contaminants from soil to a root vegetable on a wet-weight basis. Chemical-specific values for RCF from empirical regression equations developed by Briggs et al. (1982) based on their experiments measuring uptake of compounds into barley roots from growth solution. Briggs' regression equations allow calculation of RCF values from log Kow. For metals and mercuric compounds, empirical values for soil to root vegetable transfer on a dry-weight basis are available in the literature, thus the RCF was not needed.

[c] As discussed in HHRAP (USEPA 2005a), Appendix A, Kds describes the partitioning of a compound between soil pore-water and soil particles and strongly influences the release and movement of a compound into the subsurface soils and underlying aquifer. Kds values for mercuric compounds were obtained from USEPA (1997b). Kds for cadmium compounds were obtained from USEPA 1996. For all PAHs and dioxins, Kds was calculated by multiplying Koc times the screening scenario's fraction organic carbon content (0.008). Empirical information for Koc was available for acenaphthene, benz[a]anthracene, benzo[a]pyrene, dibenz[a,h]anthracene, fluoranthene, and fluorene in USEAP 1996. For all other organic compounds, the Koc was calculated using the correlation equations presented in USEAP 2005a.

[d] As discussed in HHRAP (USEPA 2005a), Appendix A, the value for mercuric chloride was obtained from USEPA 1997b. *Bv_AG*(*i*) values for PAHs were calculated using the correlation equation derived for azalea leaves as cited in Bacci et al. (1992), then reducing this value by a factor of 100, as suggested by Lorber (1995), who concluded that the Bacci factor reduced by a factor of 100 was similar to his own observations in various studies. The values for dioxins were obtained from Lorber and Pinsky (2000).

[e] It is assumed that metals, with the exception of vapor-phase elemental mercury, do not transfer significantly from air into leaves.

[f] Speciation and fate and transport of mercury from emissions suggest that *Bv_AG*(*i*) values for elemental and methyl mercury are likely to be zero (USEPA 2005a).

Table K.6. Chemical-Specific Inputs by Plant Type for Chemicals in MIRC.

Compound Name	Plant Part	Plant Soil Bio Concentration Factor ($Br_{AG\ produce\ DW(i)}$) (unitless)[a]	Empirical Correction Factor Belowground Produce ($VG_{rootveg}$) (unitless)[b]	Empirical Correction Factor Aboveground Produce ($VG_{AG(i)}$) (unitless)[c]
Inorganics				
Cadmium compounds	Exp. Fruit	1.3E-01	-	1.0E+00
	Exp. Veg.	1.3E-01	-	1.0E+00
	Forage	3.6E-01	-	1.0E+00
	Grain	6.2E-02	-	-
	Prot. Fruit	1.3E-01	-	-
	Prot. Veg.	1.3E-01	-	-
	Root	6.4E-02	1.0E+00	-
	Silage	3.6E-01	-	5.0E-01
Mercury (elemental)	Exp. Fruit	-	-	1.0E+00
	Exp. Veg.	-	-	1.0E+00
	Forage	-	-	1.0E+00
	Grain	-	-	-
	Prot. Fruit	-	-	-
	Prot. Veg.	-	-	-
	Root	-	1.0E+00	-
	Silage	-	-	5.0E-01
Mercuric chloride	Exp. Fruit	1.5E-02	-	1.0E+00
	Exp. Veg.	1.5E-02	-	1.0E+00
	Forage	0.0E+00	-	1.0E+00
	Grain	9.3E-03	-	-
	Prot. Fruit	1.5E-02	-	-
	Prot. Veg.	1.5E-02	-	-
	Root	3.6E-02	1.0E+00	-
	Silage	0.0E+00	-	5.0E-01
Methyl mercury	Exp. Fruit	2.9E-02	-	1.0E-02
	Exp. Veg.	2.9E-02	-	1.0E-02
	Forage	0.0E+00	-	1.0E+00
	Grain	1.9E-02	-	-
	Prot. Fruit	2.9E-02	-	-
	Prot. Veg.	2.9E-02	-	-
	Root	9.9E-02	1.0E-02	-
	Silage	0.0E+00	-	5.0E-01

Compound Name	Plant Part	Plant Soil Bio Concentration Factor ($Br_{AG\ produce\ DW(i)}$) (unitless)[a]	Empirical Correction Factor Belowground Produce ($VG_{rootveg}$) (unitless)[b]	Empirical Correction Factor Aboveground Produce ($VG_{AG(i)}$) (unitless)[c]
PAHs				
Acenaphthene	Exp. Fruit	2.1E-01	-	1.0E+00
	Exp. Veg.	2.1E-01	-	1.0E+00
	Forage	2.1E-01	-	1.0E+00
	Grain	2.1E-01	-	-
	Prot. Fruit	2.1E-01	-	-
	Prot. Veg.	2.1E-01	-	-
	Root	6.2E+00	1.0E+00	-
	Silage	2.1E-01	-	5.0E-01
Acenaphthylene	Exp. Fruit	1.9E-01	-	1.0E-02
	Exp. Veg.	1.9E-01	-	1.0E-02
	Forage	1.9E-01	-	1.0E+00
	Grain	1.9E-01	-	-
	Prot. Fruit	1.9E-01	-	-
	Prot. Veg.	1.9E-01	-	-
	Root	4.1E+00	1.0E-02	-
	Silage	1.9E-01	-	5.0E-01
Benz[a]anthracene	Exp. Fruit	1.7E-02	-	1.0E-02
	Exp. Veg.	1.7E-02	-	1.0E-02
	Forage	1.7E-02	-	1.0E+00
	Grain	1.7E-02	-	-
	Prot. Fruit	1.7E-02	-	-
	Prot. Veg.	1.7E-02	-	-
	Root	2.3E+00	1.0E-02	-
	Silage	1.7E-02	-	5.0E-01
Benzo[a]pyrene	Exp. Fruit	1.4E-02	-	1.0E-02
	Exp. Veg.	1.4E-02	-	1.0E-02
	Forage	1.4E-02	-	1.0E+00
	Grain	1.4E-02	-	-
	Prot. Fruit	1.4E-02	-	-
	Prot. Veg.	1.4E-02	-	-
	Root	1.2E+00	1.0E-02	-
	Silage	1.4E-02	-	5.0E-01
Benzo[b]fluoranthene	Exp. Fruit	1.8E-02	-	1.0E-02
	Exp. Veg.	1.8E-02	-	1.0E-02
	Forage	1.8E-02	-	1.0E+00
	Grain	1.8E-02	-	-
	Prot. Fruit	1.8E-02	-	-
	Prot. Veg.	1.8E-02	-	-

Compound Name	Plant Part	Plant Soil Bio Concentration Factor ($Br_{AG\ produce\ DW(i)}$) (unitless)[a]	Empirical Correction Factor Belowground Produce ($VG_{rootveg}$) (unitless)[b]	Empirical Correction Factor Aboveground Produce ($VG_{AG(i)}$) (unitless)[c]
	Root	1.7E+00	1.0E-02	-
	Silage	1.8E-02	-	5.0E-01
Benzo(g,h,i)perylene	Exp. Fruit	5.7E-03	-	1.0E-02
	Exp. Veg.	5.7E-03	-	1.0E-02
	Forage	5.7E-03	-	1.0E+00
	Grain	5.7E-03	-	-
	Prot. Fruit	5.7E-03	-	-
	Prot. Veg.	5.7E-03	-	-
	Root	1.1E+00	1.0E-02	-
	Silage	5.7E-03	-	5.0E-01
Benzo[k]fluoranthene	Exp. Fruit	1.4E-02	-	1.0E-02
	Exp. Veg.	1.4E-02	-	1.0E-02
	Forage	1.4E-02	-	1.0E+00
	Grain	1.4E-02	-	-
	Prot. Fruit	1.4E-02	-	-
	Prot. Veg.	1.4E-02	-	-
	Root	1.6E+00	1.0E-02	-
	Silage	1.4E-02	-	5.0E-01
Chrysene	Exp. Fruit	1.9E-02	-	1.0E-02
	Exp. Veg.	1.9E-02	-	1.0E-02
	Forage	1.9E-02	-	1.0E+00
	Grain	1.9E-02	-	-
	Prot. Fruit	1.9E-02	-	-
	Prot. Veg.	1.9E-02	-	-
	Root	1.7E+00	1.0E-02	-
	Silage	1.9E-02	-	5.0E-01
Dibenz(a,h)anthracene	Exp. Fruit	6.8E-03	-	1.0E-02
	Exp. Veg.	6.8E-03	-	1.0E-02
	Forage	6.8E-03	-	1.0E+00
	Grain	6.8E-03	-	-
	Prot. Fruit	6.8E-03	-	-
	Prot. Veg.	6.8E-03	-	-
	Root	1.6E+00	1.0E-02	-
	Silage	6.8E-03	-	5.0E-01
Fluoranthene	Exp. Fruit	4.0E-02	-	1.0E-02
	Exp. Veg.	4.0E-02	-	1.0E-02
	Forage	4.0E-02	-	1.0E+00
	Grain	4.0E-02	-	-
	Prot. Fruit	4.0E-02	-	-

Compound Name	Plant Part	Plant Soil Bio Concentration Factor ($Br_{AG\ produce\ DW(i)}$) (unitless)[a]	Empirical Correction Factor Belowground Produce ($VG_{rootveg}$) (unitless)[b]	Empirical Correction Factor Aboveground Produce ($VG_{AG(i)}$) (unitless)[c]
	Prot. Veg.	4.0E-02	-	-
	Root	5.6E+00	1.0E-02	-
	Silage	4.0E-02	-	5.0E-01
Fluorene	Exp. Fruit	1.5E-01	-	1.0E-02
	Exp. Veg.	1.5E-01	-	1.0E-02
	Forage	1.5E-01	-	1.0E+00
	Grain	1.5E-01	-	-
	Prot. Fruit	1.5E-01	-	-
	Prot. Veg.	1.5E-01	-	-
	Root	6.2E+00	1.0E-02	-
	Silage	1.5E-01	-	5.0E-01
Indeno(1,2,3-cd)pyrene	Exp. Fruit	5.1E-03	-	1.0E-02
	Exp. Veg.	5.1E-03	-	1.0E-02
	Forage	5.1E-03	-	1.0E+00
	Grain	5.1E-03	-	-
	Prot. Fruit	5.1E-03	-	-
	Prot. Veg.	5.1E-03	-	-
	Root	1.1E+00	1.0E-02	-
	Silage	5.1E-03	-	5.0E-01
Dioxins				
OctaCDD, 1,2,3,4,6,7,8,9-	Exp. Fruit	7.1E-04	-	1.0E-02
	Exp. Veg.	7.1E-04	-	1.0E-02
	Forage	7.1E-04	-	1.0E+00
	Grain	7.1E-04	-	-
	Prot. Fruit	7.1E-04	-	-
	Prot. Veg.	7.1E-04	-	-
	Root	6.1E-01	1.0E-02	-
	Silage	7.1E-04	-	5.0E-01
OctaCDF, 1,2,3,4,6,7,8,9-	Exp. Fruit	9.2E-04	-	1.0E-02
	Exp. Veg.	9.2E-04	-	1.0E-02
	Forage	9.2E-04	-	1.0E+00
	Grain	9.2E-04	-	-
	Prot. Fruit	9.2E-04	-	-
	Prot. Veg.	9.2E-04	-	-
	Root	6.8E-01	1.0E-02	-
	Silage	9.2E-04	-	5.0E-01
HeptaCDD, 1,2,3,4,6,7,8-	Exp. Fruit	9.2E-04	-	1.0E-02
	Exp. Veg.	9.2E-04	-	1.0E-02
	Forage	9.2E-04	-	1.0E+00

Compound Name	Plant Part	Plant Soil Bio Concentration Factor ($Br_{AG\ produce\ DW(i)}$) (unitless)[a]	Empirical Correction Factor Belowground Produce ($VG_{rootveg}$) (unitless)[b]	Empirical Correction Factor Aboveground Produce ($VG_{AG(i)}$) (unitless)[c]
	Grain	9.2E-04	-	-
	Prot. Fruit	9.2E-04	-	-
	Prot. Veg.	9.2E-04	-	-
	Root	6.8E-01	1.0E-02	-
	Silage	9.2E-04	-	5.0E-01
HeptaCDF, 1,2,3,4,6,7,8-	Exp. Fruit	2.0E-03	-	1.0E-02
	Exp. Veg.	2.0E-03	-	1.0E-02
	Forage	2.0E-03	-	1.0E+00
	Grain	2.0E-03	-	-
	Prot. Fruit	2.0E-03	-	-
	Prot. Veg.	2.0E-03	-	-
	Root	9.4E-01	1.0E-02	-
	Silage	2.0E-03	-	5.0E-01
HeptaCDF, 1,2,3,4,7,8,9-	Exp. Fruit	4.0E-03	-	1.0E-02
	Exp. Veg.	4.0E-03	-	1.0E-02
	Forage	4.0E-03	-	1.0E+00
	Grain	4.0E-03	-	-
	Prot. Fruit	4.0E-03	-	-
	Prot. Veg.	4.0E-03	-	-
	Root	1.2E+00	1.0E-02	-
	Silage	4.0E-03	-	5.0E-01
HexaCDD, 1,2,3,4,7,8-	Exp. Fruit	1.2E-03	-	1.0E-02
	Exp. Veg.	1.2E-03	-	1.0E-02
	Forage	1.2E-03	-	1.0E+00
	Grain	1.2E-03	-	-
	Prot. Fruit	1.2E-03	-	-
	Prot. Veg.	1.2E-03	-	-
	Root	7.6E-01	1.0E-02	-
	Silage	1.2E-03	-	5.0E-01
HexaCDF, 1,2,3,4,7,8-	Exp. Fruit	3.5E-03	-	1.0E-02
	Exp. Veg.	3.5E-03	-	1.0E-02
	Forage	3.5E-03	-	1.0E+00
	Grain	3.5E-03	-	-
	Prot. Fruit	3.5E-03	-	-
	Prot. Veg.	3.5E-03	-	-
	Root	1.2E+00	1.0E-02	-
	Silage	3.5E-03	-	5.0E-01

Compound Name	Plant Part	Plant Soil Bio Concentration Factor ($Br_{AG\ produce\ DW(i)}$) (unitless)[a]	Empirical Correction Factor Belowground Produce ($VG_{rootveg}$) (unitless)[b]	Empirical Correction Factor Aboveground Produce ($VG_{AG(i)}$) (unitless)[c]
HexaCDD, 1,2,3,6,7,8-	Exp. Fruit	7.0E-04	-	1.0E-02
	Exp. Veg.	7.0E-04	-	1.0E-02
	Forage	7.0E-04	-	1.0E+00
	Grain	7.0E-04	-	-
	Prot. Fruit	7.0E-04	-	-
	Prot. Veg.	7.0E-04	-	-
	Root	6.1E-01	1.0E-02	-
	Silage	7.0E-04	-	5.0E-01
HexaCDF, 1,2,3,6,7,8-	Exp. Fruit	1.0E-03	-	1.0E-02
	Exp. Veg.	1.0E-03	-	1.0E-02
	Forage	1.0E-03	-	1.0E+00
	Grain	1.0E-03	-	-
	Prot. Fruit	1.0E-03	-	-
	Prot. Veg.	1.0E-03	-	-
	Root	7.1E-01	1.0E-02	-
	Silage	1.0E-03	-	5.0E-01
HexaCDD, 1,2,3,7,8,9-	Exp. Fruit	7.0E-04	-	1.0E-02
	Exp. Veg.	7.0E-04	-	1.0E-02
	Forage	7.0E-04	-	1.0E+00
	Grain	7.0E-04	-	-
	Prot. Fruit	7.0E-04	-	-
	Prot. Veg.	7.0E-04	-	-
	Root	6.1E-01	1.0E-02	-
	Silage	7.0E-04	-	5.0E-01
HexaCDF, 1,2,3,7,8,9-	Exp. Fruit	1.6E-03	-	1.0E-02
	Exp. Veg.	1.6E-03	-	1.0E-02
	Forage	1.6E-03	-	1.0E+00
	Grain	1.6E-03	-	-
	Prot. Fruit	1.6E-03	-	-
	Prot. Veg.	1.6E-03	-	-
	Root	8.5E-01	1.0E-02	-
	Silage	1.6E-03	-	5.0E-01
HexaCDF, 2,3,4,6,7,8-	Exp. Fruit	1.0E-03	-	1.0E-02
	Exp. Veg.	1.0E-03	-	1.0E-02
	Forage	1.0E-03	-	1.0E+00
	Grain	1.0E-03	-	-
	Prot. Fruit	1.0E-03	-	-
	Prot. Veg.	1.0E-03	-	-
	Root	7.1E-01	1.0E-02	-

Compound Name	Plant Part	Plant Soil Bio Concentration Factor ($Br_{AG\ produce\ DW(i)}$) (unitless)[a]	Empirical Correction Factor Belowground Produce ($VG_{rootveg}$) (unitless)[b]	Empirical Correction Factor Aboveground Produce ($VG_{AG(i)}$) (unitless)[c]
	Silage	1.0E-03	-	5.0E-01
PentaCDD, 1,2,3,7,8-	Exp. Fruit	2.4E-03	-	1.0E-02
	Exp. Veg.	2.4E-03	-	1.0E-02
	Forage	2.4E-03	-	1.0E+00
	Grain	2.4E-03	-	-
	Prot. Fruit	2.4E-03	-	-
	Prot. Veg.	2.4E-03	-	-
	Root	1.0E+00	1.0E-02	-
	Silage	2.4E-03	-	5.0E-01
PentaCDF, 1,2,3,7,8-	Exp. Fruit	4.6E-03	-	1.0E-02
	Exp. Veg.	4.6E-03	-	1.0E-02
	Forage	4.6E-03	-	1.0E+00
	Grain	4.6E-03	-	-
	Prot. Fruit	4.6E-03	-	-
	Prot. Veg.	4.6E-03	-	-
	Root	1.3E+00	1.0E-02	-
	Silage	4.6E-03	-	5.0E-01
PentaCDF, 2,3,4,7,8-	Exp. Fruit	6.8E-03	-	1.0E-02
	Exp. Veg.	6.8E-03	-	1.0E-02
	Forage	6.8E-03	-	1.0E+00
	Grain	6.8E-03	-	-
	Prot. Fruit	6.8E-03	-	-
	Prot. Veg.	6.8E-03	-	-
	Root	1.5E+00	1.0E-02	-
	Silage	6.8E-03	-	5.0E-01
TetraCDD, 2,3,7,8-	Exp. Fruit	4.5E-03	-	1.0E-02
	Exp. Veg.	4.5E-03	-	1.0E-02
	Forage	4.5E-03	-	1.0E+00
	Grain	4.5E-03	-	-
	Prot. Fruit	4.5E-03	-	-
	Prot. Veg.	4.5E-03	-	-
	Root	1.3E+00	1.0E-02	-
	Silage	4.5E-03	-	5.0E-01
TetraCDF, 2,3,7,8-	Exp. Fruit	1.2E-02	-	1.0E-02
	Exp. Veg.	1.2E-02	-	1.0E-02
	Forage	1.2E-02	-	1.0E+00
	Grain	1.2E-02	-	-
	Prot. Fruit	1.2E-02	-	-
	Prot. Veg.	1.2E-02	-	-

Compound Name	Plant Part	Plant Soil Bio Concentration Factor ($Br_{AG\ produce\ DW(i)}$) (unitless)[a]	Empirical Correction Factor Belowground Produce ($VG_{rootveg}$) (unitless)[b]	Empirical Correction Factor Aboveground Produce ($VG_{AG(i)}$) (unitless)[c]
	Root	1.9E+00	1.0E-02	-
	Silage	1.2E-02	-	5.0E-01

Abbreviations: "-" = not required; prot. = protected; exp. = exposed.

[a] As discussed in HHRAP (USEPA 2005a), the *Br_AG-produce-DW(i)* for aboveground produce and forage accounts for the uptake from soil and the subsequent transport of contaminants through the roots to the aboveground plant parts. For organics, correlation equations to calculate values for *Br* on a dry weight basis were obtained from Travis and Arms (1988). For cadmium, *Br* values were derived from uptake slope factors provided in USEPA 1992. Uptake slope is the ratio of contaminant concentration in dry weight plant tissue to the mass of contaminant applied per hectare soil. *Br* aboveground values for mercuric chloride and methyl mercury were calculated using methodology and data from Baes et al. (1984). *Br* forage values for mercuric chloride and methyl mercury (on a dry weight basis) were obtained from USEPA 1997b. The HHRAP methodology assumes that elemental mercury doesn't deposit onto soils. Therefore, it's assumed that there is no plant uptake through the soil.

[b] As discussed in HHRAP (USEPA 2005a), Appendix B, *VG_rootveg* represents an empirical correction factor that reduces produce concentration. Because of the protective outer skin, size, and shape of bulky produce, transfer of lipophilic chemicals (i.e., log Kow greater than 4) to the center of the produce is not likely. In addition, typical preparation techniques, such as washing, peeling, and cooking, further reduce the concentration of the chemical in the vegetable as consumed by removing the high concentration of chemical on and in the outer skin, leaving the flesh with a lower concentration than would be the case if the entire vegetable were pureed without washing. For belowground produce, HHRAP (USEPA 2005a) recommends using a *VG_rootveg* value of 0.01 for PB-HAP with a log Kow greater than 4 and a value of 1.0 for PB-HAP with a log Kow less than 4 based on information provided in USEPA 1994b. In developing these values, USEPA (1994b) assumed that the density of the skin and the whole vegetable are equal (potentially overestimating the concentration of PB-HAP in belowground produce due to root uptake).

[c] As discussed in HHRAP (USEPA 2005a), Appendix B, *VG_ag* represents an empirical correction factor that reduces aboveground produce concentration and was developed to estimate the transfer of PB-HAP into leafy vegetation versus bulkier aboveground produce (e.g., apples). Because of the protective outer skin, size, and shape of bulky produce, transfer of lipophilic PB-HAP (log Kow greater than 4) to the center of the produce is not likely. In addition, typical preparation techniques, such as washing, peeling, and cooking, further reduces residues. For aboveground produce, HHRAP (USEPA 2005a) recommends using a *VG_ag* value of 0.01 for PB-HAP with a log Kow greater than 4 and a value of 1.0 for PB-HAP with a log Kow less than 4 based on information provided in USEPA 1994b. In developing these values, USEPA (1994b) assumed the following: (1) translocation of compounds deposited on the surface of aboveground vegetation to inner parts of aboveground produce would be insignificant (potentially underestimating the concentration of PB-HAP in aboveground produce due to air-to-plant transfer); (2) the density of the skin and the whole vegetable are equal (potentially overestimating the concentration of PB-HAP in aboveground produce due to air-to-plant transfer); and (3) the thickness of vegetable skin and broadleaf tree skin are equal (effects on the concentration of PB-HAP in aboveground produce due to air-to plant transfer unknown).

For forage, HHRAP recommends a *VG_ag* value of 1.0, also based on information provided in USEPA 1994b.

USEPA (1994b) does not provide a *VG_ag* value for silage; the *VG_ag* value for silage of 0.5 was obtained from NC DEHNR (1997); however, NC DEHNR does not present a specific rationale for this recommendation. Depending on the composition of the site-specific silage, this value may under- or overestimate the actual value.

Table K.7 lists additional non-chemical-specific input values for parameters used in the algorithms that calculate chemical concentrations in produce. Unless otherwise noted, the default parameter values were obtained from HHRAP. Refer to HHRAP (USEPA 2005a, Chapter 5 and associated appendices) for detailed descriptions of these parameters and documentation of input values.

Table K.7. Non-Chemical-Specific Produce Inputs.

Plant Part	Interception Fraction ($Rp_{(i)}$) (unitless)[a]	Plant Surface Loss Coefficient ($kp_{(i)}$) (1/year)[b]	Length of Plant Exposure to Deposition ($Tp_{(i)}$) (year)[c]	Yield or Standing Crop Biomass ($Yp_{(i)}$) (kg/m^2)[d]	Plant Tissue Specific Moisture Adjustment Factor ($MAF_{(i)}$) (percent)[e]
Exposed Vegetable	0.982	18	0.16	5.66	92
Protected Fruit	na	na	na	na	90
Protected Vegetable	na	na	na	na	80
Forage (animal feed)	0.5	18	0.12	0.24	92
Exposed Fruit	0.053	18	0.16	0.25	85
Root Vegetables	na	na	na	na	87
Silage (animal feed)	0.46	18	0.16	0.8	92
Grain (animal feed)	na	na	na	na	90

Abbreviations: na = not applicable.

Source: USEPA 2005a.

[a] Baes et al. (1984) used an empirical relationship developed by Chamberlain (1970) to identify a correlation between initial *Rp* values and pasture grass productivity (standing crop biomass [*Yp*]) to calculate *Rp* values for exposed vegetables, exposed fruits, forage, and silage. Two key uncertainties are associated with using these values for *Rp*: (1) Chamberlain's (1970) empirical relationship developed for pasture grass may not accurately represent aboveground produce. (2) The empirical constants developed by Baes et al. (1984) for use in the empirical relationship developed by Chamberlain (1970) may not accurately represent the site-specific mixes of aboveground produce consumed by humans or the site-specific mixes of forage or silage consumed by livestock.

[b] The term *kp* is a measure of the amount of chemical that is lost to natural physical processes (e.g., wind, water) over time. The HHRAP-recommended value of 18 yr^{-1} (also recommended by USEPA 1994a and 1998) represents the midpoint of a range of values reported by Miller and Hoffman (1983). There are two key uncertainties associated with using these values for *kp*: (1) The recommended equation for calculating *kp* includes a health protective bias in that it does not consider chemical degradation processes. (2) Given the reported range of *kp* values from 7.44 to 90.36 yr^{-1}, plant concentrations could range from about 1.8 times higher to about 5 times lower than the plant concentrations estimated in FFC media using the midpoint *kp* value of 18.

[c] HHRAP (USEPA 2005a) recommends using a *Tp* value of 0.16 years for aboveground produce and cattle silage. This is consistent with earlier reports by USEPA (1994a, 1998) and NC DEHNR (1997), which recommended treating *Tp* as a constant based on the average period between successive hay harvests. Belcher and Travis (1989) estimated this period at 60 days. *Tp* is calculated as 60 days ÷ 365 days/year = 0.16 years. For forage, the average of the average period between successive hay harvests (60 days) and the average period between successive grazing (30 days) is used (that is, 45 days), and *Tp* is calculated as (60 days + 30 days)/ 2 ÷ 365 days/yr = 0.12 yr. Two key uncertainties are associated with use of these values for *Tp*: (1) The average period between successive hay harvests (60 days) may not reflect the length of the growing season or the length between successive harvests for site-specific aboveground produce crops. The concentration of chemical in aboveground produce due to direct (wet and dry) deposition (*Pd*) will be underestimated if the site-specific value of *Tp* is less than 60 days, or overestimated if the site-specific value of *Tp* is more than 60 days.

[d] *Yp* values for aboveground produce and forage were calculated using an equation presented in Baes *et al*. (1984) and Shor *et al*. (1982): $Yp = Y_{hi} / A_{hi}$, where Y_{hi} = Harvest yield of i^{th} crop (kg DW) and A_{hi} = Area planted to i^{th} crop (m^2), and using values for Y_h and A_h from USDA (1994b and 1994c). A production-weighted U.S. average *Yp* of 0.8 kg dw/m^2 for silage was obtained from Shor *et al*. 1982.

[e] *MAF* represents the plant tissue-specific moisture adjustment factor to convert dry-weight concentrations into wet-weight concentrations (which are lower owing to the dilution by water compared with dry-weight concentrations). Values obtained from Chapter 10 of USEPA's 2003 SAB Review materials for *3MRA Modeling System, Volume II*, "Farm Food Chain and Terrestrial Food Web Data" (USEPA 2003a), which references USEPA 1997c. Note that the value for grain used as animal feed is based on corn and soybeans, not seed grains such as barley, oats, or wheat.

Animal-Product Parameter Values

MIRC also requires chemical-specific inputs for many of the animal product algorithms. Table K.8 lists the relevant values for the chemicals in MIRC considered in this assessment. The HHRAP algorithms require additional inputs for the animal products calculations. These are not specific to persistent and bioaccumulative hazardous air pollutants, but are specific to the animal and animal product type. Table K.9 lists the soil and plant ingestion rates recommended in HHRAP for beef cattle, dairy cattle, swine, and chicken.

Table K.8. Animal Product Chemical-specific Inputs for Chemicals Included in MIRC.

Compound Name	Soil Bio Availability Factor (*Bs*) (unitless)	Biotransfer Factors (Ba_m) (day/kg FW tissue)[a] and Metabolism Factors (*MF*) (unitless)[b]						
		Mammal				Non mammal		
		Beef (Ba_{beef})	Dairy (Ba_{dairy})	Pork (Ba_{pork})	*MF*	Eggs (Ba_{eggs})	Poultry ($Ba_{poultry}$)	*MF*
Inorganics								
Cadmium compounds	1	1.2E-04	6.5E-06	1.9E-04	1	2.5E-03	1.1E-01	na
Mercury (elemental)	1	0	0	0	1	0	0	na
Mercuric chloride	1	1.1E-04	1.4E-06	3.4E-05	1	2.4E-02	2.4E-02	na
Methyl mercury	1	1.2E-03	1.7E-05	5.1E-06	1	3.6E-03	3.6E-03	na
PAHs								
Acenaphthene	1	2.5E-02	5.2E-03	3.0E-02	0.01	1.0E-02	1.8E-02	na
Acenaphthylene	1	2.6E-02	5.5E-03	3.1E-02	0.01	1.1E-02	1.9E-02	na
Benz[a]anthracene	1	3.9E-02	8.3E-03	4.8E-02	0.01	1.7E-02	2.9E-02	na
Benzo[a]pyrene	1	3.8E-02	8.0E-03	4.6E-02	0.01	1.6E-02	2.8E-02	na
Benzo[b]fluoranthene	1	3.9E-02	8.3E-03	4.8E-02	0.01	1.7E-02	2.9E-02	na
Benzo(g,h,i)perylene	1	2.9E-02	6.1E-03	3.5E-02	0.01	1.2E-02	2.1E-02	na
Benzo[k]fluoranthene	1	3.8E-02	8.0E-03	4.6E-02	0.01	1.6E-02	2.8E-02	na
Chrysene	1	4.0E-02	8.4E-03	4.8E-02	0.01	1.7E-02	2.9E-02	na
Dibenz[a,h]anthracene	1	3.1E-02	6.5E-03	3.8E-02	0.01	1.3E-02	2.3E-02	na
Fluoranthene	1	4.0E-02	8.5E-03	4.9E-02	0.01	1.7E-02	3.0E-02	na
Fluorene	1	2.9E-02	6.1E-03	3.5E-02	0.01	1.2E-02	2.1E-02	na
Indeno[1,2,3-c,d]pyrene	1	2.7E-02	5.8E-03	3.3E-02	0.01	1.2E-02	2.0E-02	na
Dioxins								
OctaCDD, 1,2,3,4,6,7,8,9-	1	6.9E-03	1.4E-03	8.3E-03	1	2.9E-03	5.1E-03	na
OctaCDF, 1,2,3,4,6,7,8,9-	1	8.8E-03	1.8E-03	1.1E-02	1	3.7E-03	6.5E-03	na
HeptaCDD, 1,2,3,4,6,7,8-	1	8.8E-03	1.8E-03	1.1E-02	1	3.7E-03	6.5E-03	na
HeptaCDF, 1,2,3,4,6,7,8-	1	1.6E-02	3.5E-03	2.0E-02	1	6.9E-03	1.2E-02	na
HeptaCDF, 1,2,3,4,7,8,9-	1	2.4E-02	5.1E-03	3.0E-02	1	1.0E-02	1.8E-02	na
HexaCDD, 1,2,3,4,7,8-	1	1.1E-02	2.3E-03	1.3E-02	1	4.6E-03	8.1E-03	na
HexaCDF, 1,2,3,4,7,8-	1	2.3E-02	4.8E-03	2.8E-02	1	9.6E-03	1.7E-02	na

Compound Name	Soil Bio Availability Factor (*Bs*) (unitless)	Biotransfer Factors (Ba_m) (day/kg FW tissue)[a] and Metabolism Factors (*MF*) (unitless)[b]						
		Mammal				Non mammal		
		Beef (Ba_{beef})	Dairy (Ba_{dairy})	Pork (Ba_{pork})	*MF*	Eggs (Ba_{eggs})	Poultry ($Ba_{poultry}$)	*MF*
HexaCDD, 1,2,3,6,7,8-	1	6.8E-03	1.4E-03	8.2E-03	1	2.9E-03	5.0E-03	na
HexaCDF, 1,2,3,6,7,8-	1	9.7E-03	2.0E-03	1.2E-02	1	4.1E-03	7.1E-03	na
HexaCDD, 1,2,3,7,8,9 -	1	6.8E-03	1.4E-03	8.2E-03	1	2.9E-03	5.0E-03	na
HexaCDF, 1,2,3,7,8,9-	1	1.4E-02	2.9E-03	1.7E-02	1	5.8E-03	1.0E-02	na
HexaCDF, 2,3,4,6,7,8-	1	9.6E-03	2.0E-03	1.2E-02	1	4.1E-03	7.1E-03	na
PentaCDD, 1,2,3,7,8-	1	1.8E-02	3.9E-03	2.2E-02	1	7.8E-03	1.4E-02	na
PentaCDF, 1,2,3,7,8-	1	2.6E-02	5.5E-03	3.2E-02	1	1.1E-02	1.9E-02	na
PentaCDF, 2,3,4,7,8-	1	3.1E-02	6.5E-03	3.8E-02	1	1.3E-02	2.3E-02	na
TetraCDD, 2,3,7,8-	1	2.6E-02	5.5E-03	3.2E-02	1	1.1E-02	1.9E-02	na
TetraCDF, 2,3,7,8-	1	3.6E-02	7.7E-03	4.4E-02	1	1.5E-02	2.7E-02	na

Abbreviations: MF = metabolism factors; na = not applicable.

Source: USEPA 2005a, unless otherwise indicated.

[a] As discussed in HHRAP (USEPA 2005a), Appendix A, biotransfer factors for mercury compounds were obtained from USEPA 1997b. Considering speciation, fate, and transport of mercury from emission sources, elemental mercury is assumed to be vapor-phase and hence is assumed not to deposit to soil or transfer into aboveground plant parts. As a consequence, there is no transfer of elemental mercury into animal tissues. Biotransfer factors for cadmium compounds were obtained from USEPA 1995b. Biotransfer factors for dioxins and PAHs were calculated from chemical octanol-water partitioning coefficients (Kow values) using the correlation equation from RTI (2005) and assuming the following fat contents: milk - 4%; beef - 19%; pork - 23%; poultry -14%; and eggs - 8%.

[b] As discussed in HHRAP (USEPA 2005a), USEPA (1995c) recommends using a metabolism factor (*MF*) to account for metabolism of PAHs by mammals to offset the amount of bioaccumulation suggested by biotransfer factors. USEPA has recommended an MF of 0.01 for bis(2-ethylhexyl)phthalate (BEHP) and 1.0 for all other chemicals (USEPA 1995d). For MIRC, an *MF* of 0.01 is also used to calculate concentrations of PAHs in food products from mammalian species based on the work of Hofelt et al. (2001). This factor takes into account the P450-mediated metabolism of PAHs in mammals; applying this factor in the approach used in this analysis reduced the concentrations of chemicals in beef, pork, and dairy by two orders of magnitude.

Table K.9. Soil and Plant Ingestion Rates for Animals.

Animal	Soil Ingestion Rate $Qs_{(m)}$ (kg dw/day)[a]	Plant Part Consumed by Animal	Plant Ingestion Rate $Qp_{(I,m)}$ (kg dw/day)
Beef cattle[b]	0.5	Silage	2.5
		Forage	8.8
		Grain	0.47
Dairy cattle[c]	0.4	Silage	4.1
		Forage	13.2
		Grain	3.0
Swine[d]	0.37	Silage	1.4
		Grain	3.3
Chicken (eggs)[e]	0.022	Grain	0.2

Abbreviations: dw = dry weight;

Source: USEPA 2005a HHRAP (Chapter 5).

[a] Beef cattle: NC DEHNR (1997) and USEPA (1994b) recommended a soil ingestion rate for subsistence beef cattle of 0.5 kg/day based on Fries (1994) and NRC (1987). As discussed in HHRAP, Fries (1994) reported soil ingestion to be 4% of the total dry matter intake. NRC (1987) cited an average beef cattle weight of 590 kg, and a daily dry matter intake rate (non-lactating cows) of 2% of body weight. This results in a daily dry matter intake rate of 11.8 kg dw/day and a daily soil ingestion rate of about 0.5 kg/day.

Dairy cattle: NC DEHNR (1997) and USEPA (1994b) recommended a soil ingestion rate for dairy cattle of 0.4 kg/day based on Fries (1994) and NRC (1987). As discussed in HHRAP, Fries (1994) reported soil ingestion to be 2% of the total dry matter intake. NRC (1987) cited an average beef cattle weight of 630 kg and a daily dry matter intake rate (non-lactating cows) of 3.2% of body weight. This resulted in a daily dry matter intake rate of 20 kg/day dw, and a daily soil ingestion rate of approximately 0.4 kg/day. Uncertainties associated with Qs include the lack of current empirical data to support soil ingestion rates for dairy cattle and the assumption of uniform contamination of soil ingested by cattle.

Swine: NC DEHNR (1997) recommended a soil ingestion rate for swine of 0.37, estimated by assuming a soil intake that is 8% of the plant ingestion rate of 4.3 kg dw/day. Uncertainties include the lack of current empirical data to support soil ingestion rates and the assumption of uniform contamination of the soil ingested by swine.

Chicken: HHRAP (USEPA 2005a) assumes that chickens consume 10% of their total diet (which is approximately 0.2 kg/day grain) as soil, a percentage that is consistent with the study from Stephens *et al*. (1995). Uncertainties include the lack of current empirical data to support soil ingestion rates for chicken and the assumption of uniform contamination of soil ingested by chicken.

[b] The beef cattle ingestion rates of forage, silage, and grain are based on the total daily intake rate of about 12 kg dw/day (based on NRC [1987] reporting a daily dry matter intake that is 2% of an average beef cattle body weight of 590 kg) and are supported by NC DEHNR (1997), USEPA (1994b and 1990), and Boone *et al.* (1981). The principal uncertainty associated with these *Qp* values is the variability between forage, silage, and grain ingestion rates for cattle.

[c] The dairy cattle ingestion rates of forage, silage, and grain are based on the total daily intake rate of about 20 kg dw/day (NRC 1987; USEPA 1992) as recommended by NC DEHNR (1997). Uncertainties include the proportion of each food type in the diet, which varies with location. Assuming uniform contamination of plant materials consumed by cattle also introduces uncertainty.

[d] Swine are not grazing animals and are assumed not to eat forage (USEPA 1998). USEPA (1994b and 1998) and NC DEHNR (1997) recommended including only silage and grains in the diet of swine. USEPA (1995c) recommended an ingestion rate of 4.7 kg dw/day for a swine, referencing NRC (1987). Assuming a diet of 70% grain and 30% silage (USEPA 1990), HHRAP estimated ingestion rates of 3.3 kg[grain dw]/day and 1.4 kg [silage dw]/day. Uncertainties associated with *Qp* include variability of the proportion of grain and silage in the diet, which varies from location to location.

[e] Chickens consume grain provided by the farmer. The daily quantity of grain feed consumed by chicken is assumed to be 0.2 kg dw/day (Ensminger (1980), Fries (1982), and NRC (1987)). Uncertainties associated with this variable include the variability of actual grain ingestion rates from site to site. In addition, assuming uniform contamination of plant materials consumed by chicken introduces some uncertainty.

K.4.3. Adult and Non-Infant Exposure Parameter Values

This section summarizes the MIRC default exposure parameters and other value options for adults and non-infants. The selected default values result in a highly health protective screening scenario. This assessment uses parameter value options from EPA's *Exposure Factors Handbook* (EFH; USEPA 2011) and *Child-Specific Exposure Factors Handbook* (CSEFH; USEPA 2008a). We use time-weighted average values for age groupings other than those used in MIRC (see Section K.2.2 above for MIRC age groups).

To evaluate ingestion rates for home-produced farm food items, MIRC categorizes food as: exposed and protected fruit, exposed and protected vegetables, root vegetables, beef, total dairy products, pork, poultry, and eggs. Within MIRC, those ingestion rates are already normalized to body weight (i.e., g wet weight/kg-day) (USEPA 2011). The body weight parameter values presented in Table K.10, therefore, are not applied in the chemical intake (ADD) equations for these food types.

MIRC also includes ingestion rates for drinking water (mL/day), soil (mg/day), and fish (g/day). These ingestion rates, however, are calculated on a per person basis, that is, they are not normalized for body weight. The body weight parameter values presented in Table K.10, therefore, are applied in the chemical intake (ADD) equations for these media.

Body Weights

Body weight (BW) options included in MIRC include mean, 5th, 10th, 50th, 90th, and 95th percentile values for adults and the five children's age groups: <1 year; 1–2 years; 3–5 years; 6–11 years; and 12–19 years. For its default screening assessment and this assessment of livestock carcass management options from deaths during a natural disaster, USEPA uses the mean BW for each age group. Table K.10 lists the BWs currently in the MIRC database.

In general, BW values for the five children's age groups are calculated from the summary data provided in Table 8-3 of USEPA's 2008 CSEFH. For comparison, we estimated alternative BW values for children ages 12 through 19 years using data from Portier et al. (2007). Those values (see last row of Table K.10), are not included in MIRC. However, the 64 kg calculated mean is the same from either of the two methods for children ages 12 through 19 years. The other

percentile values for this age group differed by approximately 10% or less using the two methods.

Table K.10. Mean and Percentile Body Weight Estimates for Adults and Children.

Lifestage (years)	Duration (years)	Body Weight (kg)					
		Mean	5th	10th	50th	90th	95th
Adult[a] (20-70)	50	80.0[a]	52.9	56	69.3	89.7	97.6
Child < 1[b]	1	7.83	6.03	6.38	7.76	9.24	9.66
Child 1-2[c]	2	12.6	9.9	10.4	12.5	14.9	15.6
Child 3-5[d]	3	18.6	13.5	14.4	17.8	23.6	26.2
Child 6-11[e]	6	36.0	22.1	24.0	33.5	51.2	58.6
Child 12-19[f]	8	64.2	39.5	45	64.2	83.5	89
[Child 12-19][g]	*8*	*64.3*	*41.1*	*44.6*	*60.9*	*88.5*	*98.4*

Abbreviations: BW = body weight.

[a] BW represents the recommended body weight from USEPA's (2011) EFH. Although the 18 to 74 year age category in USEPA's EFH does not match exactly the age 20 to 70 year categorization of adults in MIRC, the magnitude of error in the mean and percentile body weights is likely to be very small (i.e., less than 1%).

[b] Each BW represents a time-weighted average of body weights for age groups birth to <1 month, 1 to <3 months, 3 to <6 months, and 6 to <12 months from Table 8-3 of USEPA's (2008a) CSEFH. Original sample sizes for each of these age groups can also be found in Table 8-3.

[c] Each BW represents a time-weighted average of body weights for age groups 1 to <2 years and 2 to <3 years from Table 8-3 of the 2008 CSEFH. Original sample sizes for each of these age groups can also be found in Table 8-3.

[d] BWs obtained directly from Table 8-3 of the 2008 CSEFH (age group 3 to <6 years).

[e] Each BW represents a time-weighted average of body weights for age groups 6 to <11 years and 11 to <16 years from Table 8-3 of the 2008 CSEFH. Original sample sizes for each of these age groups can also be found in Table 8-3.

[f] Mean BW estimated using Table 8-22 of the 2008 CSEFH, which is based on NHANES IV data as presented in Portier et al. (2007). This estimate was calculated as the average of the 8 single-year age groups from 12 to 13 years through 19 to 20 years. Values for the other percentiles were estimated using Portier et al. (2007).

[g] Each BW represents a time-weighted average of body weights for age groups 11 to <16 years and 16 to <21 years from Table 8-3 of the 2008 CSEFH. Estimated values include 11-year-olds and individuals through age 20, which contributes to uncertainty in the estimates for 12 to 19 years. Those values are provided for comparison purposes only and are not included in MIRC.

Water Ingestion Rates

MIRC options allow calculation of chemical ingestion via drinking water obtained from surface-water sources or from groundwater wells in the contaminated area. Users can set drinking water ingestion rates to zero or revise the drinking water ingestion rates to better reflect site-specific water uses. USEPA's (2008a) CSEFH recommends values for drinking water ingestion rates for children based on a study reported by Kahn and Stralka (2008). Table 3-4 of the 2008 CSEFH provides per capita estimates of community water ingestion rates by age categories. Community water ingestion includes both direct and indirect ingestion of water from the tap. Direct ingestion is defined as the direct consumption of water as a beverage, while indirect ingestion includes

water added during food or beverage preparation. The source of these data is the 1994-1996 and 1998 USDA's *Continuing Survey of Food Intakes by Individuals (CSFII)* (USDA 2000). Table K.11 includes the drinking water ingestion rates for children that are included in MIRC.

This assessment obtained mean and percentile adult drinking water ingestion rates from USEPA (2004), which presents estimated per capita water ingestion rates for various age categories based on data collected by the USDA's 1994–1996 and 1998 CSFII (USDA 2000). Adult ingestion rates, presented in Table K.11, represent community water ingestion, both direct and indirect as defined above, for males and females combined, ages 20 years and older.

Table K.11. Estimated Daily Per Capita Mean and Percentile Water Ingestion Rates.[a]

Lifestage (years)	Ingestion Rates, Community Water (mL/day)				
	Mean	50th	90th	95th	99th
Child <1[b]	504	482	969	1113	1,440
Child 1-2[c]	332	255	687	903	1,318
Child 3-5[d]	382	316	778	999	1,592
Child 6-11[e]	532	417	1,149	1,499	2,274
Child 12-19[f]	698	473	1,641	2,163	3,467
Adult[g]	1,219	981	2,534	3,087	4,567

Abbreviations: IR = ingestion rate.

Sources: USEPA 2004, 2008a

*The sample size does not meet minimum reporting requirements as described in USEPA 2008a. For some of these MIRC age groupings, the values are based on the time-weighted average value for 2 or more age ranges from CSEFH Table 3-4. One or more age ranges within the group may not meet the minimum reporting requirements, but not necessarily all of them fall within this category.

[a] Source is Kahn and Stralka 2008, also presented in the CSEFH (USEPA 2008a).

[b] Each IR represents a time-weighted average of ingestion rates for age groups birth to <1 month, 1 to <3 months, 3 to <6 months, and 6 to <12 months from Table 3-4 of the 2008 CSEFH.

[c] Each IR represents a time-weighted average of ingestion rates for age groups 1 to <2 years and 2 to <3 years from Table 3-4 of the 2008 CSEFH.

[d] Each IR represents the ingestion rate for age group 3 to <6 years from Table 3-4 of the 2008 CSEFH.

[e] Each IR represents the ingestion rate for age group 6 to <11 years from Table 3-4 of the 2008 CSEFH. This value represents a health protective (i.e., slightly low) estimate of IR for ages 6 through 11 years since 11-year olds are not included in this CSEFH age group.

[f] Each IR represents a time-weighted average of ingestion rates for age groups 11 to <16 years, 16 to <18, and 18 to <21 years from Table 3-4 of the 2008 CSEFH. Note that estimated values include 11-year-olds and individuals through age 20, which contributes to uncertainty in the estimates for 12 to 19 years.

[g] Adult drinking water ingestion rates were obtained from USEPA (2004), Appendix E, Part I, Table A1 for community water, both sexes (ages 20+), direct plus indirect water ingestion.

Local Food Ingestion Rates

MIRC includes mean, median, 90th, 95th, and 99th percentile food-specific ingestion rates (IRs) for adult and child consumers of the ten categories of farm-raised produce and animal products. This assessment uses mean values from USEPA's analysis of data from the USDA's 1987 to 1988 *Nationwide Food Consumption Survey (NFCS)* (USDA 1993), as presented in Chapter 13 of the Agency's *Exposure Factors Handbook* (i.e., Intake Rates for Various Home Produced Food Items) (USEPA 2011). "Consumers only" include only individuals who reported eating a specified type of food during the three-day period covered by the survey. "*Per capita*" IRs include all persons surveyed whether they consumed the food type or not; those data are not included in MIRC. The NFCS questionnaire included five options for a household to self-identify: gardens, raises animals, hunts, fishes, or farms. As of September 2008, that survey provided the most recent NFCS data available (USEPA 2008a, CSEFH).[26] As of April 2016, online Google searches did not identify more recent USDA NFCS surveys.

Following USEPA's analysis, we compiled data for two types of households to consider adult IRs: (1) households that farm (F), and (2) households that garden or raise animals (HG for homegrown). This division reflects the Survey's "Response to Questionnaire" (USEPA 2011, Chapter 13) and how USEPA tabulated the results. The first type of household, F, represents farmers who might both grow crops and raise animals and who are likely to consume more homegrown/raised foods than the second type of household. The second type of household, HG, represents the non-farming households that may consume lower amounts of homegrown or raised foods (i.e., HG encompasses both households that garden and households that raise animals).

The food-specific ingestion rates reflect the amount of each food type that F and HG households produce and bring into their homes for consumption. USEPA averaged the reported consumption rate for homegrown foods over the 1-week survey period.

Table K.12 lists the mean food-specific ingestion rates for adults in F households. In MIRC, users can specify the use of HG ingestion rates if they are more appropriate for the user's

[26] Note that EPA's 2008 CSEFH does not distinguish between exposed and protected fruits and vegetables when recommending food ingestion rates based on the same data set for the same age categories. USEPA's 1997 analysis for its EFH therefore remains the most appropriate data source for use in MIRC.

exposure scenario. Table K.12 reflects consumers only. Those who did not report consumption of a given food type during the survey are not included (USEPA 2011, Chapter 13).

For children, USEPA estimated food-specific IRs for four age categories (USEPA 2011): 1–2 years, 3–5 years, 6–11 years, and 12–19 years. Sample sizes are insufficient to distinguish IRs for children in different types of households. Consequently, MIRC uses a single IR value in both F and HG households for a given food type and age category (Table K.12). When there were fewer than 20 observations representing a subpopulation for a food type and age category, USEPA had insufficient data to develop consumer-only intake rates.

Table K.12. Summary of Consumer-only, Age-Group-Specific Mean Food Ingestion Rates for Farm-Grown Foods

Product	Child (age in yr)					Adult (20 70 yr)
	<1	1 2	3 5	6 11	12 19	
Mean ingestion rates (g/kg-day)						
Beef[a]	na	4.14	4.00	3.77	1.72	1.93
Dairy[b]	na	91.6	50.9	27.4	13.6	2.96
Eggs[a]	na	2.46	1.42	0.86	0.588	0.606
Exposed Fruit[a]	na	6.14	2.60	2.52	1.33	1.19
Exposed Vegetable[a]	na	3.48	1.74	1.39	1.07	1.38
Pork[a]	na	2.23	2.15	1.50	1.28	1.10
Poultry[a]	na	3.57	3.35	2.14	1.50	1.37
Protected Fruit[a]	na	16.6	12.4	8.50	2.96	5.19
Protected Vegetable[a]	na	2.46	1.30	1.10	0.78	0.862
Root Vegetable[a]	na	2.52	1.28	1.32	0.94	1.03
Water (mL/day)[c]	na	332	382	532	698	1218
Median ingestion rates (g/kg-day)						
Beef[a]	na	2.51	2.49	2.11	1.51	1.55
Dairy[b]	na	125	66.0	34.4	15.5	2.58
Eggs[a]	na	1.51	0.83	0.561	0.435	0.474
Exposed Fruit[a]	na	1.82	1.11	0.61	0.62	0.593
Exposed Vegetable[a]	na	1.89	1.16	0.64	0.66	0.812
Pork[a]	na	1.80	1.49	1.04	0.89	0.802
Poultry[a]	na	3.01	2.90	1.48	1.30	0.922
Protected Fruit[a]	na	7.59	5.94	3.63	1.23	2.08
Protected Vegetable[a]	na	1.94	1.04	0.79	0.58	0.564
Root Vegetable[a]	na	0.46	0.52	0.57	0.56	0.59
Water (mL/day)[c]	na	255	316	417	473	981
90th percentile ingestion rates (g/kg-day)						
Beef[a]	na	9.49	8.83	11.4	3.53	4.41

Product	Child (age in yr)					Adult (20 70 yr)
	<1	1 2	3 5	6 11	12 19	
Dairy[b]	na	185	92.5	57.4	30.9	6.16
Eggs[a]	na	4.90	3.06	1.90	1.30	1.31
Exposed Fruit[a]	na	12.7	5.41	6.98	3.41	2.37
Exposed Vegetable[a]	na	10.7	3.47	3.22	2.35	3.09
Pork[a]	na	4.90	4.83	3.72	3.69	2.23
Poultry[a]	na	7.17	6.52	4.51	3.13	2.69
Protected Fruit[a]	na	44.8	32.0	23.3	7.44	15.1
Protected Vegetable[a]	na	3.88	2.51	2.14	1.85	1.81
Root Vegetable[a]	na	7.25	4.26	3.83	2.26	2.49
Water (mL/day)[c]	na	687	778	1149	1640	2534
95th percentile ingestion rates (g/kg-day)						
Beef[a]	na	12.9	12.5	12.5	3.57	5.83
Dairy[b]	na	167	89.9	56.0	32.3	7.80
Eggs[a]	na	5.38	3.62	2.37	1.43	1.59
Exposed Fruit[a]	na	14.6	6.07	11.7	4.78	3.38
Exposed Vegetable[a]	na	11.9	6.29	5.47	3.78	4.46
Pork[a]	na	6.52	6.12	4.73	6.39	2.60
Poultry[a]	na	8.10	7.06	5.07	3.51	3.93
Protected Fruit[a]	na	48.3	35.1	26.9	11.4	19.2
Protected Vegetable[a]	na	9.42	5.10	3.12	2.20	2.83
Root Vegetable[a]	na	10.4	4.73	5.59	3.32	3.37
Water (mL/day)[c]	na	903	999	1499	2163	3087
99th percentile ingestion rates (g/kg-day)						
Beef[a]	na	20.9	19.8	13.3	4.28	6.84
Dairy[b]	na	180	87.2	54.8	34.7	9.20
Eggs[a]	na	16.2	11.2	8.19	4.77	1.83
Exposed Fruit[a]	na	25.2	32.5	15.7	5.9	13.0
Exposed Vegetable[a]	na	12.1	7.36	13.3	5.67	8.42
Pork[a]	na	8.71	9.74	6.61	4.29	3.87
Poultry[a]	na	9.63	10.24	6.12	4.60	4.93
Protected Fruit[a]	na	109	71.2	58.2	19.1	34.4
Protected Vegetable[a]	na	9.42	5.31	5.40	2.69	5.56

Product	Child (age in yr)					Adult (20 70 yr)
	<1	1 2	3 5	6 11	12 19	
Root Vegetable[a]	na	10.4	4.73	7.47	5.13	7.57
Water (mL/day)[c]	na	1318	1592	2274	3467	4567

Abbreviations: na = not applicable; yr = year(s).

[a] Primary source for values was the 1987–1988 NFCS survey; compiled results are presented in Chapter 13 of USEPA's (2011) *Exposure Factors Handbook*. When data were unavailable for a particular age group, intake rate for all age groups was used multiplied by the age-specific ratio of intake based on national population intake rates from CSFII.

[b] Primary source for values was 1987–1988 NFCS survey, compiled results presented in Chapter 13 of 2011 *Exposure Factors Handbook* (USEPA 2011). When data were unavailable for a particular age group, intake rate for all age groups was used multiplied by the age-specific ratio of intake based on national population intake rates from an NHANES 2003–2006 analysis in Chapter 11 of the 2011 *Exposure Factors Handbook.*

[c] Primary source for children less than 3 years of age was a Kahn and Stralka (2008) analysis of CSFII data, and from EPA's analysis of NHANES 2003–2006 data for children and adults greater than three. All data tables that were used and justifications for data sources are presented in Chapter 3 of the 2011 *Exposure Factors Handbook.*

As referenced in Section 6.2.2.2, HHRAP recommends a method for calculating age-specific consumer ingestion rates. In general, refer to the HHRAP documentation for calculations used in the case of "missing" age-specific consumer-only IRs. In this assessment, food-specific intake rates for those child age groups and food items not included in Chapter 13 of the 2011 EFH ((*IRage_group_x*) are derived using the following information:

- Mean consumer-only intake of the farm food item, as brought into the home, for the total NFCS survey population (from EFH Chapter 13)—*IRCO_total*
- Mean *per capita* intake of the food type from all sources, as consumed, for the specific child age group, from Chapter 3 of the *CSFII Analysis of Food Intake Distributions* (USEPA 2003b)—*IRPC, age_group_x*
- Mean *per capita* intake of the farm food item for the total CSFII survey population (from Chapter 3 of USEPA 2003b)—*IRPC_total*

The ratio of IRPC, age_group_x to IRPC_total from the CSFII data shows the consumption rate of a particular food type by a specific age group, relative to the consumption rate for that food type for the population as a whole. The ratio of IRCO, age_group_x to IRCO_total, that is the consumption rate of a particular food type by a specific age group (consumers only) relative to the consumption rate for that food type for the NFCS survey population as a whole (consumers only), should be approximately the same.

Local Fish Ingestion Rates

MIRC uses the USEPA's (2002) analysis of freshwater and estuarine fish consumption from the USDA's *Continuing Survey of Food Intake by Individuals (CSFII) for 1994-96 and 1998* to provide fish ingestion rate options by age category. Although the fish consumption rates reported in the CSFII include all sources, commercial and self-caught, for purposes of screening level risk assessments, this assessment assumes that all freshwater and estuarine fish consumed are self-caught. The inclusion of commercially obtained and estuarine fish will overestimate locally caught freshwater fish ingestion rates for most populations in the United States; however, it also might underestimate locally caught fish ingestion rates for some populations (e.g., Native Americans, Asian and Pacific Island communities, rural African American communities). Because consumption of locally caught fish varies substantially from region to region in the United States and from one population or ethnic group to the next, users of MIRC are encouraged to use more locally relevant data whenever available. This assessment did not use fish ingestion data representative of an Iowa farm to avoid limiting the applicability of the assessment's results to that specific part of the country.

MIRC also includes values for the mean and the 90th, 95th, and 99th percentile fish *per capita* ingestion rates (freshwater and estuarine fish only) for children based on the USEPA's analysis of 1994-96 and 1998 CSFII data (USEPA 2002, 2008a). Those rates include both children who eat fish and those who do not. As shown in USEPA's 2008 CSEFH, Table 10-7, the *per capita* ingestion rates for some child-age groups often are zero. While this may reflect the relatively short-term of the survey, it also can represent relatively infrequent consumption of fish. In general, children appear to eat fish on the order of once a week to once a month or less compared with the near daily ingestion of other types of food products (e.g., dairy, produce, meat). In a quantitative model such as MIRC, zero fish ingestion rates are not useful so this assessment developed an alternative method to estimate fish ingestion rates for children and adults that could provide reasonable, non-zero values likely to approximate a mean value for all age groups.

In the alternative method, the assessment derives age-group-specific fish ingestion rates by using values for each age group, *y* that meet two criteria:

- Mean consumer-only fish ingestion rates for age group *y*, *IRCO,y*, from EPA's *Estimated Per Capita Fish Consumption in the United States* (USEPA 2002, Section 5.2.1.1, Table 5, for freshwater/estuarine habitat)[27]
- Fraction of the population consuming freshwater/estuarine fish, *FPC,y*, calculated as consumer-only sample size / U.S. population sample for age group *y*. The data to calculate those fractions are available in the 2008 CSEFH and USEPA 2002

Calculation of Alternative Age-Group-Specific Fish Ingestion Rates. Equation K.3 calculates the alternative, per capita fish ingestion rates by age group (*IRPC,y*):

$$IR_{PC_y} = IR_{CO_y} * F_{PC_y} \qquad \textbf{(Eqn. K.3)}$$

where:

$IR_{PC,y}$ = *Per capita* fish ingestion rate for age group *y* (g/day)

$IR_{CO,y}$ = Consumer-only fish ingestion rates for age group *y* (g/day) (USEPA 2002, Section 5.2.1.1, Table 5, for freshwater/estuarine habitat)

$F_{PC,y}$ = Fraction of the population consuming freshwater/estuarine fish, calculated as consumer-only sample size / total U.S. population sample size for age group *y* (unitless) (2008 CSEFH, USEPA 2002)

In the above, *per capita* (as opposed to consumer-only) indicates intake rates for the entire population rather than the subset of the population that ingests the particular food category. Here, the HHRAP methodology recommends using *per capita* ingestions, because there are no consumer percentile specific intakes provided for the different age groups.

[27] Table 10-9 of the CSEFH provides mean and upper percentile values, but does not include median values, because USEPA prefers use of mean to median values for exposure assessment (USEPA 2008).

Table K.13 shows the mean and percentile consumer fish ingestion rates for children and adults and the fraction of the population consuming freshwater/estuarine fish used to calculate long-term *per capita* fish ingestion rates by age group. Table K.15 summarizes the mean and percentile per capita fish ingestion rates estimated using the above approach. The fish ingestion rates provided in Table K.15 and included in MIRC are intended to represent the harvest and consumption of fish in surface waters in a hypothetical depositional area. Among the ingestion rates presented in Table K.16, the mean values for adults and children aged 1–2 are used for the exposure assessment of livestock carcass management options.

Table K.13. Daily Mean and Percentile Consumer-Only Fish Ingestion Rates for Children and Adults (*IRCO,y*).[a]

Lifestage (years)	Ingestion Rates, All Fish (g/day)				
	Mean	50th	90th	95th	99th
Child <1	na	na	na	na	na
Child 1-2[b]	27.31	15.61	64.46	87.60	138.76*
Child 3-5[c]	40.31	23.04	95.16	129.31	204.84*
Child 6-11[d]	61.49	28.46	156.86*	247.69*	385.64*
Child 12-19[e]	79.07	43.18	181.40*	211.15*	423.38*
Adult[f]	81.08	47.39	199.62*	278.91	505.65*

Abbreviations: na = not applicable, we assume that children < 1 year of age do not consume fish.

Sources: USEPA 2002, 2008a

*Indicates that the sample size does not meet minimum reporting requirements as described in USEPA 2002. Owing to the small sample sizes, these upper percentiles values are highly uncertain.

[a] Per capita fish ingestion rates (IR) for children by age group are available from Chapter 10 of the CSEFH (USEPA 2008a); however, all 50th and some 90th percentile ingestion rates are zero. Per capita fish IRs were therefore estimated as described in Equation J.1 to provide reasonable, non-zero values for all age groups and percentiles.

[b] A fish IR for ages 1-2 years was not available. The value represents the consumer-only fish IR for ages 3 to 5 from USEPA (2002) (Section 5.2.1.1 Table 5 [freshwater/estuarine habitat]), scaled down by the ratio of the mean Child 1-2 body weight to the mean Child 3-5 body weight.

[c] These values represent the consumer-only fish IR for ages 3 to 5 from USEPA (2002), Section 5.2.1.1 Table 5 (freshwater/ estuarine habitat). Sample size = 442.

[d] These values represent the consumer-only fish IR for ages 6 to 10 from USEPA (2002), Section 5.2.1.1 Table 5 (freshwater/ estuarine habitat). Sample size = 147.

[e] These values represent the time-weighted average per capita fish IR for ages 11 to 15 and 16 to 17 years from USEPA (2002), Section 5.1.1.1 Table 5 (freshwater/estuarine habitat); the value may underestimate ingestion rate for ages 12 to 19 years. Sample size = 135.

[f] These values represent the consumer-only fish IR for individuals 18 years and older from USEPA (2002), Section 5.2.1.1 Table 4 (freshwater/estuarine habitat). Sample size = 1,633.

Table K.14. Fraction of Population Consuming Freshwater/Estuarine Fish on a Single Day (*FPC,y*).

Lifestage (years)	Fraction Consuming Fish
Child 3-5	0.0503[a]
Child 6-11	0.0440[b]
Child 12-19	0.0493[c]
Adult	0.08509[d]

Sources: USEPA 2002, 2008a

[a] This value was calculated using the ages 3 to 5 sample size for consumers only divided by the sample size for the U.S. population divided by 2 to represent the proportion consuming fish on a single day (the consumers-only group includes individuals who consumed fish on at least one of two survey days) to match the one-day ingestion rate.

[b] As in endnote "a," the value was calculated using the ages 6–10 sample size for consumers only divided by the sample size for U.S. population divided by 2.

[c] The value was calculated by summing the ages 11–15 and 16–17 sample sizes for consumers only and dividing by both by the sum of the sample sizes for U.S. population and by a factor of 2.

[d] The value was calculated using the ages 18 and older sample size for consumers only divided by the sample size for U.S. population. The result was divided by 2 to represent a one-day sampling period in order to match the one-day ingestion rate.

Table K.15. Calculated Long-term Mean and Percentile per capita Fish Ingestion Rates for Children and Adults (*IRPC,y*).

Lifestage (years)	Ingestion Rates (IR), All Fish (g/day)				
	Mean	50th	90th	95th	99th
Child <1	na	na	na	na	na
Child 1-2[a]	1.37	0.79	3.24	4.41	6.98
Child 3-5[b]	2.03	1.16	4.79	6.51	10.3
Child 6-11[c]	2.71	1.25	6.90	10.9	17.0
Child 12-19[d]	3.90	2.13	8.95	10.4	20.9
Adult[e]	6.90	4.03	16.99	23.73	43.02

Abbreviations: na = not applicable assuming that children < 1 year of age do not consume fish; IR = ingestion rates.

Sources: USEPA 2002, 2008a

[a] Values were calculated as (consumer-only IR for Child 1–2) x (fraction of population consuming fish for Child 1–2).

[b] Values were calculated as (consumer-only IR for Child 3–5) x (fraction of population consuming fish for Child 3–5).

[c] Values were calculated as (consumer-only IR for Child 6–11) x (fraction of population consuming fish for Child 6–11).

[d] Values were calculated as (consumer-only IR estimated for Child 12–19) x (fraction of population estimated to consume fish for Child 12–19).

[e] Values were calculated as (consumer-only IR for Adults) x (fraction of population consuming fish for Adults).

Soil Ingestion Rates

Adults might accidentally ingest soil during gardening activities, and individuals might ingest soil particles that adhere to exposed fruit, as well as exposed and belowground vegetables. Soil that is re-suspended in the air by wind can resettle on exposed fruits and vegetables. Children can ingest soils in those ways, but children playing outdoors also ingest soils directly or by hand-to-mouth activities during play. MIRC includes soil ingestion rate options by age group for these types of exposures. MIRC does not include geophagy options for children who may exhibit pica, or the recurrent ingestion of unusually high amounts of soil (i.e., on the order of 1,000–5,000 mg/day or more) (USEPA 2008a).

Data on soil ingestion rates are sparse; the MIRC soil ingestion rates listed in Table K.16 are based on very limited data. The studies evaluated by USEPA for children generally focused on children aged 1–2 and 3–5 years old and are not specific to families that garden or farm. The default ingestion rates in MIRC are the 90th percentile values, as for other ingestion rate parameters. For the exposure assessment for cattle management options, MIRC values are set instead to mean values.

Table K.16. Daily Mean and Percentile Soil Ingestion Rates for Children and Adults.

Age Group (years)	Soil Ingestion Rate (mg/day)				
	Mean[a]	50th [a]	90th	95th	99th
Child 1-2	50	50	200[b]	200[b]	200[b]
Child 3-5	50	50	200[b]	200[b]	200[b]
Child 6-11	50	50	201[c]	331[d]	331[d]
Child 12-19	50	50	201[c]	331[d]	331[d]
Adult 20-70	20	20	201[c]	331[d]	331[d]

Sources: USEPA 2008a, USEPA 2011

[a] For mean and 50th percentile soil ingestion rates for children, value represents a "central tendency" estimate from USEPA's (2008a) CSEFH, Table 5-1. For adults, value is the recommended mean value for adults from USEPA's (2011) EFH, Chapter 5, Table 5-1.

[b] Values are the recommended "upper percentile" value for children from USEPA's 2011 EFH, Chapter 4, Table 4-23. The 2008 CSEFH and 2011 EFH included a high-end value associated with pica only, but this value has not been used.

[c] Values are 90th percentile adult ingestion rates calculated in Stanek et al. (1997); used to represent older children and adults.

[d] Values are 95th percentile adult ingestion rates calculated in Stanek et al. (1997); used to represent older children and adults.

Total Food Ingestion Rates

This assessment uses the mean total food ingestion rates presented in Table K.17 to normalize or truncate the sum of food-specific ingestion rates to reasonable values.

Table K.17. Daily Mean and Percentile Per Capita Total Food Intake for Children and Adults.

Lifestage (years)	Percent of Group Consuming Food	Mean	50th	90th	95th	99th
Total Food Intake (g/day, as consumed)						
Child < 1[a]	67.0% - 99.7% [h]	322	270	599	779	1152
Child 1-2[b]	100%	1,032	996	1537	1703	2143
Child 3-5[c]	100%	1,066	1,020	1,548	1,746	2,168
Child 6-11[d]	100%	1,118	1,052	1,642	1,825	2,218
Child 12-19[e]	100%	1,197	1,093	1,872	2,231	2,975
Adult[f]	100%	1,100	1,034	1,738	2,002	2,736
Total Food Intake (g/kg-day, as consumed)						
Child < 1[a]	67.0% - 99.7% [h]	39	34	72	95	147
Child 1-2[b]	100%	82	79	125	144	177
Child 3-5[c]	100%	61	57	91	102	132
Child 6-11[d]	100%	40	38	61	70	88
Child 12-19[e]	100%	21	19	34	40	51
Adult[g]	100%	14.8	13.9	23.7	27.6	35.5

Abbreviations: in endnotes, N = sample size.

Sources: USEPA (2005e) analysis of CSFII data and USEPA (2008a) CSEFH.

[a] These values represent a time-weighted average for age groups birth to <1 month (N=88), 1 to <3 months (N=245), 3 to <6 months (N=411), and 6 to <12 months (N=678) from Table 14-3 of the 2008 CSEFH.

These values represent a time-weighted average for age groups 1 to <2 years (N=1,002) and 2 to <3 years (N=994) from Table 14-3 of the 2008 CSEFH.

[c] These values were obtained from Table 14-3 of the 2008 CSEFH (age group 3 to <6 years, N=4,112).

[d] These values were obtained from Table 14-3 of the 2008 CSEFH (age group 6 to <11 years, N=1,553). These values represents a health protective (i.e., slightly low) estimate for ages 6 through 11 years since 11-year olds are not included in this CSEFH age group.

[e] These values represent a time-weighted average for age groups 11 to <16 years (N=975) and 16 to <21 (N=743) years from Table 14-3 of the 2008 CSEFH. Note that estimated values include 11-year-olds and individuals through age 20, which contributes to uncertainty in the estimates.

[f] These values represent a time-weighted average for age groups 20 to 39 years (N=2,950) and 40 to 69 years (N=4,818) from Table 5B of the 2005 USEPA analysis of CSFII.

[g] These values represent a time-weighted average for age groups 20 to 39 years (N=2,950) and 40 to 69 years (N=4,818) from Table 5A of the 2005 USEPA analysis of CSFII.

[h] Percents consuming foods from Table 14-3 of the 2008 CSEFH include: 67.0% (birth to <1 month); 74.7% (1 to <3 months); 93.7% (3 to <6 months); and 99.7% (6 to <12 months). Infants under the age of 1 that consume breast milk are classified as "non-consumers" of food.

This procedure would be particularly important if one estimated chemical intake from multiple upper-percentile food ingestion rates for different types of food were added together. Percentiles (including medians) are not additive, and adding multiple upper percentiles can yield unrealistically high values that exceed the maximum observed (or likely possible) long-term ingestion rate (see Section 5.2.3 of main report). Individuals representing the upper percentile ingestion rate for one food category might not be the same individuals who reported high percentile ingestion rates for one or any of the other food categories.

K.4.4. Other Exposure Factor Values

The other exposure parameters included in the MIRC algorithms are exposure frequency, the fraction of the food type obtained from the contaminated area, and the reduction in the weight of the food types during preparation and cooking. The following subsections briefly discuss each of these topics.

Exposure Frequency

The exposure frequency (EF) represents the number of days per year that an individual consumes home-produced food items contaminated with the chemical being evaluated. In MIRC, the default value for EF is 365 days/year for all exposure sources and all potential receptors. This assumption is consistent with the food ingestion rates used in MIRC (i.e., average daily intake rates equivalent to annual totals divided by 365 days), but does not imply that residents necessarily consume home-produced food products every day of the year. MIRC users can specify lower EF values for various food types when residents obtain some of their diet from commercial sources or when consumption of homegrown produce is seasonal. To evaluate daily intake rates based on shorter averaging times, MIRC users can overwrite both the food-specific ingestion rates and the EF for each homegrown food product.

Fraction Contaminated

The fraction contaminated (FC) represents the portion of each food product consumed that contains the chemical at a level consistent with environmental concentrations in the area of concern (e.g., area with maximum deposition rates). MIRC includes the default FC of 1.0, i.e., assumes 100% of the food consumed is produced by households that farm, garden, or raise animals. Obviously, this is the most health protective assumption because it maximizes the

impact of consuming food from the location represented by the chemical concentrations input into the model. While MIRC users can vary this default FC value for individual food products to tailor the assessment to a particular exposure scenario, this assessment retained the default value.

Preparation and Cooking Losses

The actual food ingested generally is less than the amount brought into a home. Food preparation and cooking losses are included in the FFC exposure calculations to account for amounts of food products that are not ingested due to loss during preparation, cooking, or post-cooking. The ADD equations account for these losses, because the food ingestion rates calculated from the USDA 1987 to 1988 NFCS are based on the weight of products as brought into the house prior to any type of preparation. Not all of the produce or products are eventually ingested. In general, some parts of the produce and products are discarded during preparation while other parts might not be consumed even after cooking (e.g., bones).

MIRC includes three distinct types of preparation and cooking losses in the ingestion exposure algorithms: (1) loss of part of the food (i.e., removal of the skin from vegetables and fruit by paring, removing pits, coring, deboning), (2) loss of weight during cooking (e.g., evaporation of water, fats remaining in a cooking vessel), and (3) post-cooking loss (e.g., non-consumption of bones or draining cooking liquid). MIRC includes mean values for these three types of preparation and cooking losses for all of the categories of food. Nevertheless, because different types of losses apply to different types of foods, MIRC uses two parameters (*L1* and *L2*), to vary the loss according to the food type (see footnotes to Table K.18).

Table K.18. Fraction Weight Losses from Preparation of Various Foods.

Product	Mean Cooking, Paring, or Preparation Loss (Cooking Loss Type 1 [*L1*]) (unitless)[a]	Mean Net Post Cooking (Cooking Loss Type 2 [*L2*]) (unitless)[b]
Exposed Fruit[c]	0.244	0.305
Exposed Vegetable	0.162[d]	na
Protected Fruit	0.29[e]	na
Protected Vegetable	0.088[f]	na
Root Vegetable[g]	0.075	0.22
Beef	0.27	0.24
Pork	0.28	0.36
Poultry	0.32	0.295[h]
Fish[i]	0.0	0.0

Abbreviations: na = not available.

Source: USEPA 1997a and 2011, Chapter 13 (specific tables identified below).

[a] For *fruits*, includes losses from draining cooked forms. For *vegetables*, includes losses due to paring, trimming, flowering the stalk, thawing, draining, scraping, shelling, slicing, husking, chopping, and dicing and gains from the addition of water, fat, or other ingredients. For *meats*, includes dripping and volatile losses during cooking.

[b] For *fruits*, includes losses from removal of skin or peel, core or pit, stems or caps, seeds and defects; may also include losses from removal of drained liquids from canned or frozen forms. For *vegetables*, includes losses from draining or removal of skin. For *meats*, includes losses from cutting, shrinkage, excess fat, bones, scraps, and juices.

[c] These values represent averages of means for all fruits with available data (except oranges) (Table 13-6).

[d] This value represents an average of means for all exposed vegetables with available data (Table 13-7). Exposed vegetables include asparagus, broccoli, cabbage, cucumber, lettuce, okra, peppers, snap beans, and tomatoes.

[e] This value was set equal to the value for oranges (Table 13-6).

[f] This value represents an average of means for all protected vegetables with available data (Table 13-7). Protected vegetables include pumpkin, corn, peas, and lima beans.

[g] These values represent averages of means for all root vegetables with available data (Table 13-7). Root vegetables include beets, carrots, onions, and potatoes.

[h] This value represents an average of means for chicken and turkey (Table 13-5).

[I] If the user changes fish ingestion rates to match a survey of the whole weight of fish brought into the home from the field (divided by the consumers of the fish), an appropriate value for *L1* would be 0.31 and an appropriate *L2* would be 0.11 (USEPA 2011).

All preparation and cooking loss parameter values are estimated as specified in Table K.18's endnotes and the data in Chapter 13 of USEPA's 1997 and 2011 EFH (USEPA 1997a, 2011).

There are substantial uncertainties associated with the *L1* and *L2* parameters, including the wide variation across produce types that were averaged together to create a mean value. For example, the *L2* factor does not distinguish between weight loss during cooking by water evaporation, which could leave most of the chemical in the food, or by pouring the cooking liquid down the drain, which would remove water-soluble chemicals and possibly lipid-soluble chemicals if oils also are poured down the drain. The factor also does not distinguish cooking liquids used to

create sauces, because the sauce is not part of the food type consumed. The concentration of a chemical might be highest in the skin (e.g., of fish, fruits, root vegetables) and lower in the consumed fillet or bulky portion of many fruits and vegetables. Depending on the chemical, discarding the skin can remove more of the chemical from ingestion than suggested by the associated loss in weight. Finally, the data USEPA used to evaluate *L1* included negative losses (i.e., weight gains) due to hydration of dried vegetables (e.g., peas and lima beans). Hydration increases the range of *L1* values across different vegetables.

In contrast, the default *L1* and *L2* values for fish are set to zero. That is because self-caught fish ingestion rates are not the USDA's 1987 to 1988 NFCS (USDA 1993, 1994a) as reported in USEPA's EFH, which reported food as brought into the home. Instead, MIRC includes fish *IR* data based on actually consumed parts (e.g., fillet purchased from store, canned tuna). That means there are no losses associated with fish preparation. A MIRC user can change fish ingestion rates to match a local survey of the whole weight of fish brought into the home (divided by number of persons consuming the fish) and set the *L1* and *L2* parameters to non-zero values. For this assessment of carcass management options, we assume all fish ingested are caught in the on-site lake and set *L1* and *L2* to zero.

Food Preparation/Cooking Adjustment Factor for Fish

Cooking also can induce changes in the concentrations of chemicals in fish. When chemical concentration data comes from uncooked fish, the calculation must adjust for the chemical's concentration in fish after cooking, because the fish consumption rates are "as consumed". To account for this situation, MIRC can apply a food preparation/cooking adjustment factor (*FPCAF*) to the data on concentration in uncooked fish to estimate a concentration in cooked fish. The following subsections discuss *FPCAF*s for the four categories of chemicals in this assessment.

Metals. Metals are assumed to bind to muscle and to be retained during the cooking process. This assessment assumed that 0.33 of the moisture/fat in fish is lost during cooking and therefore used a *FPCAF* of 1.5 for metals.

- ***Dioxins/furans.*** Dioxins are lipophilic and often are lost along with fats during cooking. This assessment used a *FPCAF* of 0.7 to account for these losses during the cooking process. This value is not likely to overestimate

loss of PCDD/PCDFs from fish during cooking (pan frying, broiling, grilling). Reductions in TCDD concentrations could be much higher with skin removal and trimming of fat. The research of Schecter et al. (1998), Reinert et al. (1972), and Zabik and Zabik (1995) support use of that value: Schecter et al. (1998) reported the mass of PCDD and PCDF in fresh catfish fillet (skin on) decreased by about 50% per serving portion during cooking. Given the simultaneous losses of moisture/fats during broiling, the PCDDs and PCDFs concentrations decreased by 33% (i.e., multiply uncooked concentration in fresh fish by a factor of 0.66 = 0.70 to one significant digit).

- Reinert et al. (1972) reported higher losses of another highly lipophilic chemical, DDT, from cooking fish fillets of bloaters, yellow perch, lake trout, and coho salmon. Concentrations of DDT in fish fillet portions for lake trout and coho salmon, top predators, were reduced by 64 to 72% by frying or broiling, primarily through preferential loss of fat (and lipophilic DDT) during cooking. The investigators did not report whether the skin was on or off; however, they used steak cuts instead of flat fillets, which provide a smaller ratio of skin to muscle than is the case for fillets that constitute one side of the fish. Finally, Zabik and Zabik (1995) quantified the reduction in TCDD concentration of skinless cooked fillets compared with uncooked fillets (with skin). Concentrations of TCDD in the skinless cooked fish relative to the raw fillet (with skin) were reduced by approximately 44% for walleye, 80% for white bass, 61% for lake trout. TCDD concentrations were lower by approximately 43% for Chinook Salmon cooked with the skin on versus 57% for chinook salmon cooked with the skin off. They found a 37% reduction of TCDD concentration for carp fillets cooked with the skin on and a 54% reduction with the skin removed.

PAHs. While it is reasonable to assume there might be losses of lipophilic PAHs during the cooking process, there is insufficient information to distinguish whether there is a net loss or gain during cooking, because cooking can create PAHs from proteins in the tissue. The literature acknowledges these competing forces, but does not provide sufficient information to disentangle the gain and loss mechanisms. This assessment adopts a neutral approach by not assuming an adjustment factor for PAHs in the modeling.

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Appendix L. Toxicity Reference Values

Some chemicals are more hazardous than others to humans, livestock, and aquatic and terrestrial ecosystems. Some chemicals are of low toxicity even at high exposure concentrations (e.g., iron) while others are of high toxicity at low doses (e.g., dioxins). Section 2.4.1 of the main report presented the chemicals selected for the exposure assessment as well as those excluded from the assessment and the reasons for their exclusion. For the chemicals included in the assessment, this section summarizes the toxicity reference values (TRVs), human and ecological health and welfare benchmarks, and other criteria that indicate the relative hazards posed by specified chemical environmental concentrations and exposures.

Benchmarks by which to evaluate human exposures should be for the same route and duration of exposure as the anticipated exposures of possible concern. For the livestock carcass management options, two routes of exposure are relevant for humans: oral and inhalation. TRVs for chronic, subchronic, and acute exposure durations were sought; however, benchmarks are not available for some chemical and exposure duration combinations.

L.1. Benchmarks Used in Exposure Assessment (main report, Section 7)

Table L.1.1 lists the TRVs for oral (ingestion) exposure to inorganic chemicals. Table L.1.2 lists oral TRVs for two organic chemicals, BaP, and 2,3,7,8-tetrachlorodibenzodioxin (2,3,7,8-TCDD). BaP is the index chemical for the RPF approach to evaluating polyaromatic hydrocarbons (PAHs, see Appendix A). The compound 2,3,7,8-TCDD serves as the index chemical for the toxicity equivalency factor (TEQ or TEF) for dioxins/furans (see Appendix B). Cells shaded in grey indicate the values used in Section 7 of the main report.

Potentially harmful inhalation exposures could occur during the combustion phase of open-pyre or air-curtain burning of carcasses, which is assumed to last approximately 48 hours. Table L.1.3 lists the TRVs for inhalation exposure to inorganic chemicals, and Table L.1.4 presents TRVs for inhalation of BaP and 2,3,7,8-TCDD. Cells shaded in grey indicate the values used in Section 7 of the main report.

The sections that follow the first four tables (Sections L.2 through L.6) describe the human TRVs and environmental concentration benchmarks in more detail.

Table L.1.1. Toxicity Reference Values for Oral Exposure to Inorganic Chemicals.

Chemical	Chronic Oral RfD (mg/kg day)	Chronic Oral RfD Ref	Sub chronic Oral RfD (mg/kg day)	Sub chronic Oral RfD Ref	Short term Oral RfD (mg/kg day)	Short term Oral RfD Ref	Acute Oral RfD (mg/kg day)	Acute Oral RfD Ref	Oral Slope Factor (mg/kg day) [1]	Oral Slope Factor Ref	Selected Oral Non cancer TRV (mg/kg day)	Oral Risk Specific Dose[a] (mg/kg day)
Arsenic, Inorganic	3.00E-04	IRIS	5.00E-03	PPRTV Archive	-		5.00E-03	ATSDR Final	1.50E+00	IRIS	3.00E-04	6.7E-05
Cadmium (Diet)	1.00E-03	IRIS	5.00E-04	ATSDR Draft	5.00E-04	ATSDR Draft	-		-		1.00E-03	-
Cadmium (Water)	5.00E-04	IRIS	-		-		-		-			
Chromium (VI)	3.00E-03	IRIS	-		-		-		-		3.00E-03	-
Copper	4.00E-02	HEAST	1.00E-02	ATSDR Final	1.00E-02	ATSDR Final	1.00E-02	ATSDR Final	-		1.00E-02	-
Iron	7.00E-01	PPRTV Current	7.00E-01	PPRTV Current	-		-		-		7.00E-01	-
Lead and Compounds	-		-		-		-		8.50E-03	CalEPA	-	1.2E-02
Manganese (Diet)	1.40E-01	IRIS	1.40E-01	HEAST	-		-		-		1.40E-01	-
Manganese (Non-diet)	2.40E-02	IRIS recommends subtracting dietary exposure	-		-		-		-		2.40E-02	-
Nickel Oxide	1.10E-02	CalEPA	-		-		-		-		1.10E-02	-
Zinc and Compounds	3.00E-01	IRIS	3.00E-01	ATSDR Final	3.00E-01	ATSDR Final	-		-		3.00E-01	-

Abbreviations: "-" = not available; ATSDR = Agency for Toxic Substances and Disease Registry; CalEPA = California Environmental Protection Agency; HEAST = USEPA Health Effects Assessment Summary Tables; IRIS = USEPA Integrated Risk Information System; PPRTV = Provisional Peer Reviewed Toxicity Values; Ref = reference; RfD = reference dose.

[a] The risk-specific dose represents the exposure dose corresponding to a target risk level of 10^{-4}. The risk-specific dose is calculated by dividing the target risk level by the oral slope factor.

Table L.1.2. Toxicity Reference Values for Oral Exposure to Organic Chemicals.

Chemical	Chronic Oral RfD (mg/kg day)	Chronic Oral RfD Ref	Sub chronic Oral RfD (mg/kg day)	Sub chronic Oral RfD Ref	Short term Oral RfD (mg/kg day)	Short term Oral RfD Ref	Acute Oral RfD (mg/kg day)	Acute Oral RfD Ref	Oral Slope Factor (mg/kg day) [1]	Oral Slope Factor Ref	Selected Oral Non cancer TRV (mg/kg day)	Oral Risk Specific Dose[a] (mg/kg day)
Benzo[a]pyrene	-		-		-		-		7.30E+00	IRIS	-	1.4E-05
TCDD, 2,3,7,8-	7.00E-10	IRIS	2.00E-08	ATSDR Final	2.00E-08	ATSDR Final	2.00E-07	ATSDR Final	1.30E+05	CalEPA	2.0E-08	7.7E-10

Abbreviations: "-" = not available; ATSDR = Agency for Toxic Substances and Disease Registry; CalEPA = California Environmental Protection Agency; IRIS = USEPA Integrated Risk Information System; PPRTV = Provisional Peer Reviewed Toxicity Values; Ref = reference; RfD = reference dose.

[a] The risk-specific dose represents the exposure dose corresponding to a target risk level of 10^{-4}. The risk-specific dose is calculated by dividing the target risk level by the oral slope factor.

Table L.1.3. Toxicity Reference Values for Inhalation Exposure to Inorganic Chemicals.

Chemical	Chronic Inhal RfC (mg/m^3)	Chronic Inhal RfC Ref	Sub chronic Inhal RfC (mg/m^3)	Sub chronic Inhal RfC Ref	Short term Inhal RfC (mg/m^3)	Short term Inhal RfC Ref	Acute Inhal RfC (mg/m^3)	Acute Inhal RfC Ref	Inhal Unit Risk ($\mu g/m^3$) [1]	Inhal Unit Risk Ref	Selected Inhal Non cancer RfC ($\mu g/m^3$)	Derived Inhal Cancer Risk Specific Conc[a] ($\mu g/m^3$)
Arsenic, Inorganic	1.50E-05	CALEPA	-		-		2.00E-04	CalEPA	4.30E-03	IRIS	1.5E-02	2.3E-02
Cadmium	1.00E-05	ATSDR Final	9.00E-04	PPRTV Archive	-		3.00E-05	ATSDR Final	1.80E-03	IRIS	3.0E-02	5.6E-02
Chromium (VI)	1.00E-04	IRIS; See below	-		-		-		-		1.00E-01	
Copper	-		-		-		1.00E-01	CalEPA	-		1.00E+02	
Iron	-		-		-		-		-		-	
Lead and Compounds	-		-		-		-		1.20E-05	CalEPA	-	8.3E+00
Manganese	5.00E-05	IRIS	-		-		-		-		5.00E-02	
Nickel Oxide	6.00E-05	CALEPA	-		-		2.00E-04	CalEPA	2.60E-04	CalEPA	6.00E-02	3.8E-01
Zinc and Compounds	-		-		-		-		-		-	

Abbreviations: "-" = not available; ATSDR = Agency for Toxic Substances and Disease Registry; CalEPA = California Environmental Protection Agency; Inhal = Inhalation; IRIS = USEPA Integrated Risk Information System; PPRTV = Provisional Peer Reviewed Toxicity Values; Ref = reference; RfC = reference concentration.

[a] The risk-specific concentration represents the exposure concentration in air corresponding to a target risk level of 10^{-4}. The risk-specific air concentration is calculated by dividing the target risk level by the inhalation slope factor.

Table L.1.4. Toxicity Reference Values for Inhalation Exposure to Organic Chemicals.

Chemical	Chronic Inhal RfC (mg/m^3)	Chronic Inhal RfC Ref	Sub chronic Inhal RfC (mg/m^3)	Sub chronic Inhal RfC Ref	Short term Inhal RfC (mg/m^3)	Short term Inhal RfC Ref	Acute Inhal RfC (mg/m^3)	Acute Inhal RfC Ref	Inhal Unit Risk ($\mu g/m^3$) [1]	Inhal Unit Risk Ref	Selected Inhal Non cancer RfC ($\mu g/m^3$)	Derived Inhal Cancer Risk Specific Conc[a] ($\mu g/m^3$)
Benzo[a]-pyrene	-		-		-		-		1.10E-03	CalEPA	-	9.1E-02
TCDD, 2,3,7,8-	4.0E-08	CALEPA	-		-		-		3.80E+01	CalEPA	4.0E-05	2.6E-06

Abbreviations: "-" = not available; "CalEPA" = California Environmental Protection Agency; Inhal = Inhalation; Ref = reference; RfC = reference concentration.

[a] The risk-specific concentration represents the air exposure concentration corresponding to a target risk level of 10^{-4}. The risk-specific dose is calculated by dividing the target risk level by the inhalation slope factor.

Section L.2 describes benchmark selection for such short-term inhalation exposures. Although chronic releases of some gases (e.g., hydrogen sulfide) might continue for years, release rates should be slow (e.g., less than a few cubic meters per day), and ambient air will substantially dilute the gas concentrations; hence, chronic inhalation exposures are not evaluated.

For all livestock carcass management options, chemicals from the carcasses (and from auxiliary materials included in carcass management) will remain onsite for years to decades, possibly allowing chronic ingestion exposures via drinking water or foods grown on-site. Section L.3 describes benchmarks for the protection of human health and welfare that are expressed as chemical concentrations in specific environmental media. Section L.4 describes TRVs for human ingestion exposures expressed as doses for comparison with total chemical ingested from all sources (e.g., drinking water, incidental soil ingestion, and consumption of foods grown on-site).

For environmental hazards that might arise from chemicals remaining from carcass management, ecological benchmarks are described in Section L.5. Benchmarks for other types of effects or hazards are discussed in Section L.6.

L.2. Air Concentrations—Short-term Human Health Benchmarks

The two on-site combustion options burn carcasses and auxiliary fuels over a 48-hr period. Thus, an exposure benchmark expressed as an air concentration averaged over 48 hours would be most suitable for comparison. Shorter limits, such as 1-hr or 8-hr average concentrations, might not be adequately protective, and benchmarks based on longer averaging periods (e.g., annual) might be overly conservative.

Chemical irritants show a strong inverse correlation between the duration of exposure and the concentration of chemical tolerated. For example, for ammonia, USEPA's 1-hr acute exposure guideline level (AEGL) 2 (which might result in long-lasting adverse health effects) is 160 ppm (114 mg/m^3), whereas the 8-hr AEGL 2 is 110 ppm (99 mg/m^3). USEPA's 24-hr Provisional Advisory Level (PALs) is lower, at 22 mg/m^3, and its 30-day PAL is lower still, at 13.6 mg/m^3. Finally, USEPA's chronic reference concentration (RfC) for ammonia in IRIS is 0.1 mg/m^3. In other words, higher air concentrations can only be tolerated for shorter durations. It would not be health protective to use a 1-hr or 8-hr AEGL 2 (i.e., 114 or 99 mg/m^3, respectively) to evaluate a 48-hr exposure for ammonia. In fact a 48-hr exposure at 22 mg/m^3 (the 24-hr PAL) might cause

adverse effects, whereas a 48-hr exposure at 13.6 mg/m^3 ppm (the 30-day PAL) presumably is safe. A 48-hr exposure at 0.1 mg/m^3 (the chronic RfC) also should be safe, and in fact appears to be overly conservative by approximately 2 orders of magnitude.

Non-irritant chemicals tend not to show a strong inverse relationship between inhalation exposure duration and the highest concentration associated with no adverse health effects. California EPA's (CalEPA) inhalation reference exposure level (REL) for repeated 8-hr exposures for systemic effects of arsenic, for example, is the same as its lifetime chronic REL (i.e., both are 1.5E-05 mg/m^3), although its 1-hr REL is higher (i.e., 2.0E-04 mg/m^3) (CalEPA 2014a,b).

Based on the considerations described above and based on USEPA's hierarchy of human health toxicity values recommended for use in risk assessment for Superfund, a hierarchy of sources was used to identify short-term inhalation exposure benchmarks for chemicals for this assessment. USEPA sources were preferred, with CalEPA and ATSDR toxicity profiles consulted in the absence of USEPA values (USEPA 2003). For USEPA sources, 24-hr and 30-day PALs would be preferred over an IRIS chronic RfC or Superfund Provisional Peer-Reviewed Toxicity Value (PPRTV); 10- and 30-minute and 1-, 4-, and 8-hour inhalation AEGLs were not considered, because they might not be adequately protective over a 48-hr exposure duration. USEPA PALs are based on other existing guidelines, however, and currently (May 2, 2016) are not available online. Oak Ridge National Laboratory (ORNL)'s Risk Assessment Information System (RAIS; available online) was used to identify other existing guidelines.

When USEPA values were not available, and CalEPA or ATSDR "acute" inhalation benchmarks were used instead. For these sources, the supporting toxicity studies were reviewed to determine whether the identified benchmark is expected to be protective for a 48-hr exposure. For example, CalEPA's repeated 8-hr REL for some chemicals is based on experiments with more than 60 hours of inhalation exposure, which is likely to be protective for a 48-hr exposure. A CalEPA 8-hr REL for other chemicals might be based on experiments with as few as one or two 8-hr exposures, in which case the REL might not be protective. CalEPA's Acute (1-hr) REL values usually are be based on 30 to 90 minutes of exposure, which might *not* be protective for a 48-hr exposure. ATSDR's "acute" minimal risk levels (MRLs), on the other hand, cover 1- to 14-day exposures and often are derived from experiments ranging from 24 hours continuous exposure to

2 weeks intermittent inhalation exposure (e.g., 6.5 hr/day, 5 days/wk). Thus, an ATSDR acute inhalation MRL is likely to be protective for a 48-hr exposure, but original toxicological profiles were consulted to determine the basis of an acute inhalation MRL.

For chemicals considered carcinogenic via inhalation, air unit risk levels also were obtained and used to calculate an air concentration associated with a lifetime risk of 1.0E-04. USEPA IRIS was the preferred source, and CalEPA values were used where EPA values were not available. A lifetime exposure corresponds to approximately 25,500 days (i.e., 70 years), and 48 hours represents 0.00008% of a lifetime for humans; therefore, chemicals were not assessed for carcinogenic risks from 48-hr inhalation exposures.

Table L.1.1, includes the inhalation benchmarks identified for inorganic chemicals evaluated in this assessment. Several chemicals had only chronic values available (e.g., chromium, manganese), while others had both short and longer-term inhalation benchmarks available (e.g., cadmium, nickel). No inhalation benchmarks were available for some chemicals (e.g., zinc, iron). Table L.1.2 includes the inhalation benchmarks for organic chemicals.

L.3. Benchmark Concentrations – Human Welfare

For chemicals that could migrate from livestock carcasses into soils and then to groundwater and surface waters (e.g., from air deposition, leaching, erosion, runoff), several types of benchmarks are applicable. USEPA Office of Water (OW) has developed two types of water concentration benchmarks protective of human health: one set for ambient surface waters and another set for drinking water.

National Ambient Water Quality Criteria (NAWQC). Under the Clean Water Act (CWA), USEPA's OW develops NAWQC to protect human health (HH), aquatic life (AL), wildlife, and uses of surface waters.[28] One of the criteria to protect human health assumes daily consumption of 2 liters of untreated water along with an average of 17.5 grams of fish caught in the surface water and incidental water ingestion during recreation. That criterion is presented for the NAWQC-HH in Table L.3.1.

[28] http://water.epa.gov/scitech/swguidance/standards/criteria/current/index.cfm

Table L.3.1. Concentrations in Water to Protect Human Health and Welfare.[a]

Chemical Agent	EPA Benchmark	Water Concentration (µg/L)
Metals		
Arsenic	NAWQC-HH MCL	**0.018** **10**
Chromium (total)	MCL	**100**
Iron	NSDWR (to limit rusting/discoloration porcelain/laundry)	**300**
Lead	Drinking Water Maximum Contaminant Action Level[b]	15,000
Mercury	MCL	**0.002**
Zinc	NAWQC-HH	7,400
PAHs		
Benzo[a]pyrene	MCL	**0.2**
Benzo[a]anthracene **Benzo[b]fluoranthene** **Benzo[k]fluoranthene** **Chrysene**	NAWQC-HH	**0.0038**
Dibenzo[a,h]Anthracene **Ideno[1,2,3-cd]Pyrene**	NAWQC-HH	**0.018**
Fluoranthene	NAWQC-HH	**130**
Fluorene		1,100
Dioxins/Furans		
2,3,7,8-TCDD	NAWQC-HH	**0.000000005 (5.0 10^{-9})**
Other Chemicals and Measures		
Nitrate (as N) Nitrite (as N)	MCL MCL	10,000 1,000
Sulfate	NSDWR (taste)	250,000
Chloride		250,000

Abbreviations: NAWQC = national ambient water quality criterion; HH = for the protection of human health; MCL = maximum contaminant level; NSDWR = national secondary drinking water regulation.

[a] Values in bold are concentrations at or below 1 ppm (1 mg/L or 1,000 µg/L).

[b] Lead in drinking water is regulated by a treatment technique that requires systems to control the corrosiveness of the water. If more than 10 % of tap water samples exceed the action level, water systems must take additional steps.

The other criterion is established for ingestion of fish only (assumes drinking water from a different source), and is not included in Table L.3.1 because it generally is a less stringent value. Both are based on USEPA's Reference Dose (RfD) or cancer slope (potency) factor (CSF) and an associated risk of 1.0E-06. Thus, the NAWQC-HH for arsenic is lower than is needed to target a risk of 1.0E-04 (see Section 7 of the main report).

Maximum Contaminant Levels (MCLs). Under the Safe Drinking Water Act (SDWA), USEPA OW develops MCLs and MCL Goals (MCLGs).[29] The MCLs are National Primary Drinking Water Regulations; they are legally enforceable standards that apply to public water systems developed with both health (e.g., RfDs) and technological feasibility considered. The MCLGs are not enforceable (for carcinogenic chemicals, MCLGs are zero). The MCL for arsenic is listed in Table L.3.1 because the NAWQC-HH for arsenic is based on a 1.0E-06 risk, which is more conservative than needed for the 1.0E-04 risk targeted in this assessment.

***National Secondary Drinking Water Regulations* (*NSDWRs*).** USEPA OW also develops NSDWR, which are non-enforceable guidelines based on aesthetic effects including taste, odor, and color.

USEPA OW accounts for likely dietary exposures to a given chemical somewhat differently when calculating MCLs and NAWQC-HH; therefore, MCLs and NAWQC-HH are not necessarily the same. For chemicals with both an MCL and NAWQC-HH, the lower of the two is presented in Table L.3.1 (except for arsenic for which both are listed).

L.4. Ingestion Reference Doses

A hierarchy of sources was reviewed for chronic and subchronic oral RfDs, with EPA sources (i.e., IRIS and PPRTV) preferred and ATSDR and CalEPA values checked for chemicals for which USEPA RfDs could not be identified. Table L.4.1 presents the chronic RfDs and oral CSFs for the chemicals that might deposit to soils, contaminate crops, livestock (and dairy products), poultry (and eggs), or accumulate in fish. The relative oral toxicity of the chemicals can be assessed with RfD values and oral CSFs without assuming specific exposure scenarios.

For PAHs, most of which are categorized as B2 carcinogens, meaning that evidence of carcinogenicity in animals is adequate to conclude that they are likely human carcinogens, EPA is developing a RPF approach to toxicity assessments. The approach facilitates estimating the combined toxicity of mixtures of PAHs based on the relative concentrations of different congeners (USEPA SAB 2011). BaP serves as the index chemical, and the carcinogenic potency

[29] http://water.epa.gov/drink/contaminants/index.cfm#List

of other PAHs is estimated as a factor by which to multiply the BaP oral cancer slope factor. RPFs for PAHs are listed in the last table in Appendix A.

For dioxins and furans, EPA has published its recommended toxicity equivalence factors (TEFs or TEQs) with 2,3,7,8-tetrachlorodibenzo-p-dioxin (TCDD) as the index chemical. All TEFs for dioxins and furans are less than 1.0, meaning that 2,3,7,8-TCDD is the most toxic of the group (USEPA 2010). The TEFs for the dioxin congeners are presented in the last table in Appendix B.

For an exposure duration to be considered chronic, it must cover more than 10% of the animal's lifespan. USEPA defines subchronic exposures for humans as lasting between two weeks to six years. For the carcass management options, the highest exposure concentrations that might be associated with leaching from buried carcasses or ash, for example, is likely to occur over the first few months, with lower concentrations occurring over subsequent months and years. Thus, it might be overly conservative to compare chronic RfDs with the average first month or first year of exposure. Similar to the case for inhalation exposure (Section L.2), higher exposure concentrations or doses might be acceptable over shorter time periods. However, all subchronic RfDs identified for the chemicals evaluated were equal to the chronic RfD values

Table L.4.1. Chronic Oral Reference Doses (RfDs).[a]

Chemical Agent	Chronic Oral Reference Dose (mg/kg day)	Source	Oral Slope Factor (1/(mg/kg day))	Carcinogenic Weight of Evidence[b]	Source
Arsenic (inorganic)	0.0003	IRIS	1.5	A	IRIS
Cadmium (diet)	0.001	IRIS	7 studies indicate not carcinogenic via oral exposure	not assessed	IRIS
Cadmium (water)	0.0005	IRIS		not assessed	IRIS
Chromium (VI)	0.003	IRIS	–	D	IRIS
Copper	0.04	HEAST	–	D	HEAST
Iron	0.7	PPRTV Current	–	Information inadequate to assess	PPRTV
Lead	no threshold	IRIS	0.0085	B2	CalEPA
Manganese	0.14	IRIS	–	D	
Divalent Mercury	0.0003	IRIS	–	not assessed	IRIS
Nitrates	1.6	IRIS	–	not available	IRIS
Nitrites	0.1	IRIS	–	not available	IRIS
Nickel Soluble Salts	0.02	IRIS	–	not assessed	IRIS
Nickel Oxide	0.011	CalEPA	not evaluated for oral carcinogenicity		
Zinc	0.3	IRIS	–	D	
PAHs					
Benzo[a]pyrene (index chemical for PAHs)	not assessed		7.3	B2	IRIS
Other PAHs	not assessed		use RPFs	B2	EPA xxxx
Dioxins/furans					
2,3,7,8-TCDD (index chemical for dioxins/furans)	0.0000000007 ($7x10^{-10}$)		cancer assessment currently underway		
Other Dioxins/Furans[c]	use TEFs (=TEQs)				

[a] IRIS is USEPA's Integrated Risk Information System. Values in bold are concentrations at or below 1 ppm.

[b] Weight-of-evidence (WOE) categories for carcinogens: A: Human carcinogen. B2: Probable human carcinogen – based on sufficient evidence of carcinogenicity in animals. D: Not classifiable as to human carcinogenicity.

[c] TEFs are toxicity equivalency factors (USEPA 2010).

L.5. Ecological Benchmarks

Ecological benchmarks expressed as concentrations in surface water (Section L.5.1) and as concentrations in surface soils (Section L.5.2) were sought for the chemicals and secondary characteristics associated with carcass management options.

L.5.1. Surface Water

Under the CWA, EPA OW also develops national ambient water quality criteria for the protection of aquatic life (NAWQC-AL) and their uses. Criteria for many metals depend on water characteristics such as hardness or pH. Criteria for chemicals that are major plant nutrients vary by region of the country and sometimes by surrounding land uses. Measures of other water characteristics important to sustaining aquatic life (e.g., dissolved oxygen) can vary by temperature and region. Table L.5.1 presents NAWQC-AL organized in three categories. The first group of chemicals includes the metals and other toxic chemicals. The second group includes measures of water quality that represent the aggregate effect of the chemicals in water. The last group includes the major nutrients that affect plant growth in surface waters (and on land). Chemicals for which the benchmark is less than 1 mg/L (1,000 µg/L) are highlighted in bold. Table 5.4.5 in the main document presents numeric aquatic life criteria in the first data column.

Table L.5.1. Concentrations in Ambient Surface Waters to Protect Aquatic Life.[a]

Chemical Agent	USEPA Benchmark	Water Concentration (µg/L)
Non-nutrient Chemicals		
Arsenic	NAWQC-AL, criterion continuous concentration (CCC) (i.e., for chronic exposures)	**150**
Chromium (III)		**74**
Chromium (VI)		**11**
Chloride		230,000
Copper		**9.0**
Iron		1,000
Lead		**2.5**
Nickel		**52**
Zinc		**120**
Mercury		**770**
H_2S (tends not to partition to water)		**2.0**
Secondary Characteristics [b]		
Biological Oxygen Demand (BOD)	NAWQC-AL for Dissolved Oxygen	There are no federal criteria related directly to BOD or COD, only oxygen
Chemical Oxygen Demand (COD)		

Chemical Agent	USEPA Benchmark	Water Concentration (µg/L)
Total Dissolved Solids (TDS)	No federal criteria	Contributing ions: anions – carbonates, chlorides, sulfates, nitrates; cations – sodium, potassium, calcium, magnesium
Dissolved Oxygen (four separate criteria) 30-day mean 7-day mean 7-day minimum 1-day minimum	NAWQC-AL cold water or warm water and early or other life stages (LS)	cold water: early LS / other LS; warm water: early LS / other LS na / 6,500 / na / 5,500 6,500 / na / 6,000 / na na / 5,000 / na / 4,000 5,000 / 4,000 / 5,000 / 3,000
pH	NAWQC-AL CCC	6.5-9.0
Soluble Nutrients[c]		
Ammonia-nitrogen (NH_4-N)	NAWQC- AL-CCC varies by ecoregion and environmental conditions (e.g., pH, temperature, season). See also state-specific criteria.	1,900 µg /L total ammonia-nitrogen (TAN), pH = 7.0, 20°C (30-day rolling average)
Ammonium		
Phosphorus (avg of 6 regions) USEPA Region 4 USEPA Region 5 USEPA Region 8 USEPA Region 9 USEPA Region 12 USEPA Region 14		19 20 33 8 20 10 8
Total Nitrogen (avg of 6 regions) USEPA Region 4 USEPA Region 5 USEPA Region 8 USEPA Region 9 USEPA Region 12 USEPA Region 14		474 440 560 240 360 520 320

Abbreviations: avg = average: BOD = biological oxygen demand ; CCC = criterion continuous concentration (i.e., chronic criterion); COD = chemical oxygen demand; d = day; LS = lifestage na = not applicable; NAWQC-AL = national ambient water quality criteria for the protection of aquatic life and their uses; TDS = total dissolved solids.

[a] Values in bold are sufficiently low to be of concern.

[b] Secondary characteristics (also known as water quality indicators) can be affected by decomposition products; they are not specific chemicals that are released.

[c] For state and ecoregional adoption of EPA-approved nitrogen and phosphorus criteria, refer to http://cfpub.epa.gov/wqsits/nnc-development/

L.5.2. Soils

For soils, this assessment uses USEPA's Superfund *Ecological Soil Screening Levels* (Eco-SSLs) as described in Section 5.4.2 of the main report. The Eco-SSLs are intended to screen chemical concentrations in surface soils for potential impacts on wildlife, vegetation, and soil biota (e.g., earthworms, other soil invertebrates important to soil aeration and nutrient recycling). The Eco-SSLs for soil invertebrates are primarily based on direct soil toxicity to earthworms, but other soil-dwelling invertebrates (e.g., insect larvae) are sometimes tested. The mammalian Eco-SSLs are based on indirect exposures of ground-feeding mammals ingesting soil invertebrates. They

usually are backcalculated on the basis of shrews consuming earthworms and larval insects. The avail Eco-SSLs also are based on indirect ingestion exposures and usually are back calculated on the basis of woodcock consuming 100% earthworms. The Eco-SSLs for plants are based on direct toxicity of soils to plants.

Table L.5.2. Ecological Soil Screening Levels.

Chemical	Ecological Soil Screening Levels (mg/kg) [a]			
	Invertebrates	Mammalian	Avian	Plants
Arsenic	-	4.6	43	18
Cadmium	-	-	-	-
Chromium	-	130	-	-
Copper	-	230	120	13
Iron	-	-	-	-
Lead	1700	56	11	120
Manganese	450	4000	4300	220
Nickel	280	130	210	38
Zinc	120	79	46	160
PAHs	-	-	-	-
Dioxin/ Furans	-	-	-	-

[a] Chemical-specific Eco-SSL reports can be found https://rais.ornl.gov/documents/eco-ssl_[chemical].pdf. For example, the Eco-SSL document for nickel can be found at https://rais.ornl.gov/documents/eco-ssl_nickel.pdf. Also theoretically at http://www.epa.gov/ecotox/ecossl/; however, that link seems to lead to ECOTOX only.

L.6. Other Adverse Effects

Methane Explosion. A highly flammable gas, methane becomes explosive in mixtures with oxygen between a lower explosive limit (LEL) of 5% volume of methane/volume of air (v/v) and an upper explosive limit (UEL) of 15% v/v. Methane concentrations above the UEL (> 15%/v) are too rich (O_2 levels are too low) to support combustion (USEPA 2005).

Odor Detection. Hydrogen sulfide (H_2S) is one of the most odorous of the chemicals produced by decaying carcasses, with concentrations as low as 0.008 ppm (0.01 mg/m^3) producing a detectably noxious odor (ATSDR 2014). It originates from *anaerobic* decomposition of carcasses, and smells like rotten eggs. Ammonia, on the other hand, must reach approximately 50 ppm before humans can smell it (ATSDR 2004).

Eutrophication of Surface Waters. Excessive nutrient loading to surface waters over a relatively short period of time (e.g., days, weeks) can cause serious algal blooms and growth of noxious

weeds, which can limit recreational uses of water and restrict areas suitable for fish. When algal blooms die off, decomposition of the algal cells by bacteria often consumes sufficient oxygen to cause fish kills. Thus, excessive nutrient loading can have adverse consequences for both humans and aquatic organisms.

No single benchmark concentration for nutrient chemicals is applicable to all waters in all parts of the country. In some locations, phosphorus might be the limiting nutrient while in other areas, nitrogen might be. Additions of the limiting nutrient will foster plant growth, whereas addition of the non-limiting nutrient might not cause an obvious effect. Regions with heavy agricultural land use tend to develop problems when there is nutrient loading to surface waters from fertilizer runoff. For livestock operations, runoff from manure also loads receiving waters with nutrients, which can result in surface waters failing to attain some state-designated uses. Nutrient loading from livestock carcass management could be compared with the nutrient loading from normal livestock management operations to determine if it could be considered excessive.

L.7. References

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