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3 Economics of Invasive Species Damage and Damage Management

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INTRODUCTION

Annually, the estimated damage caused by invasive species in the United States has exceeded $100 billion, becoming one of the leading causes of environmental change and global biodiversity loss (Wilcove et al. 1998; Mack et al. 2000; Sala et al. 2000; Pimentel et al. 2005). Invasions by nonnative species highlight the undeniable link and feedback loops between ecological and economic systems (Perrings et al. 2002; Julia et al. 2007).

Ecological systems determine if the conditions are suitable for invasion by nonnative species; however, economic systems help fuel the introduction of nonnative species and are themselves affected by invasive species when the ecosystem's ability to provide services is diminished or when livestock or crops are made unmarketable (Julia et al. 2007).

Invasive species have played an important role in U.S. agriculture. While some of the goods cultivated by the U.S. agricultural sector are indigenous plant and animal species, many are introduced; a minimum of 4542 species currently existing in the United States originated from outside its borders (Office of Technology Assessment 1993). Introduced species, such as corn, wheat, rice, as well as cattle, poultry, and other livestock, are all important commodities produced by the U.S. agricultural sector. Some introduced species have potential conservation values as well, providing food and shelter for native species, acting as catalysts for restoration, serving as substitutes for extinct species, and augmenting ecosystem services (Schlaepfer et al. 2011). A distinction can be drawn, then, between introduced species and invasive species. Like introduced species, invasive species are nonnative to that ecosystem; however, invasive species have the potential to cause harm, whether measured economically, environmentally, or as a human health hazard (The White House 1999).

Vertebrate invasive species (VIS) are a subset of nonnative invasive species that can include bony fish, sharks, rays, amphibians, reptiles, mammals, and birds. They are exemplified by such species as the Burmese python (*Python molurus bivittatus*), brown tree snake (*Boiga irregularis*), European starling (*Sturnus vulgaris*), and wild boar (*Sus scrofa*).

Wild boar (*Sus scrofa*) is actually just one species among several categorized more broadly as "feral swine"; other species that fall within this category include feral domestic pigs (*Sus scrofa domestica*), Eurasian wild boar (*Sus scrofa linnaeus*), and hybrids between the two. Feral swine are the most abundant free-ranging, exotic ungulate in North America, so a significant amount of literature has been published regarding their impacts. Given the substantial amount of attention paid to feral swine, as well as their unique ability to create damage, we will examine separately the impacts of feral swine from other VIS in this chapter.

Earlier chapters have provided evidence that suggests that the frequency of VIS invasions may be increasing and creating significant environmental, ecological, and agricultural damages. Estimating the total economic impact and potential future economic impact of VIS is crucial to targeted prevention, management, and control efforts (McNeely 2001; National Invasive Species Council 2001). Commonly, to generate funding to fight an established VIS or to prevent the expansion of a VIS, it is necessary first to understand the full range of potential economic impacts.

Studies examining the full scope of economic impacts of VIS are relatively recent. Most of the early studies simply examined the direct economic impact, typically to agricultural production, associated with a specific VIS already established in a limited geographical region (Engeman et al. 2010). Very few studies have used these direct economic impacts to examine or forecast the broader macroeconomic (indirect and induced) impacts. Even fewer studies have combined biology and economics into a bioeconomic model to predict impacts before a VIS actually becomes established and estimate the value of preemptive versus reactive management strategies (Kolar and Lodge 2002). The challenge facing policy makers, of course, is to determine biologically effective and economically feasible methods of prevention, control, and damage mitigation of invasive species (Burnett et al. 2008).

In this chapter, we provide a general overview of the economic impact of both the presence and management of VIS in the United States. We begin by framing the general role of economics in determining the overall impact of VIS. We then examine current published estimates of damage and management costs. Finally, we discuss ways to improve economic estimation of VIS impacts.

Framing the Economic Impacts of Vertebrate Invasive Species (VIS) within an Ecological Context

Although published estimates of impacts exist, the contextual roadmap that links economic impact and the ecology of VIS is not described extensively in the literature. One example of a methodology for determining the ecological impact of invasive species is provided by Parker et al. (1999) who derived the simple equation $I = R \times A \times E$, where I = impact, R = range size, A = abundance, and E = effect per individual. While R and A are a function of a suite of biological factors, E is a function of the ability of a VIS to create economic damage.

The direct economic damage or harm created by a VIS typically falls into three broad categories: destruction, depredation, and disease transmission. Total economic damage (D) of a VIS is the sum across these three categories and across time.

Destruction refers to destroyed property (e.g., statues, golf courses, buildings, bridges, power lines), equipment (e.g., vehicles, farm equipment, cables, irrigation equipment), crops (e.g., nonconsumptive impacts associated with rooting behavior), habitat, and associated recreational opportunities (e.g., lost tourism or hunting) (Daszak et al. 2000; Kaller and Kelso 2006; Hartin et al. 2007; Engeman et al. 2008; Jones et al. 2008; Campbell and Long 2009; Shwiff et al. 2010; Depenbusch et al. 2011; Loss et al. 2013; Bevins et al. 2014; Doody et al. 2014; Yang et al. 2014). Depredation refers to the consumption of crops, livestock, wildlife species, or companion animals by a VIS. Disease refers to mortality or morbidity in humans, companion animals, livestock, or wildlife caused by a VIS-associated pathogen (Witmer and Sanders 2003; Campbell et al. 2008; Hall et al. 2008).

In general, most invasive species impose damages that fall within two of the three categories. Reptiles (e.g., Burmese pythons and Brown tree snakes) and other aquatic nonnatives typically cause economic impact through depredation and environmental destruction but rarely through disease transmission (Greene et al. 2007; Snow et al. 2007). Some avian species, such as starlings, can create impacts in all three categories through depredation of crops, destruction of property (e.g., statues, bridges, buildings), and disease transmission (e.g., fecal contamination of livestock feed) (Shwiff et al. 2012). A substantial portion of the overall impact of avian VIS tends to be through depredation of crops, while the other two categories of damage tend to contribute significantly less to the overall impact. Many rodent VIS are similar to avian VIS in that the majority of the impact comes from depredation on crops and significantly less from destruction and disease transmission. These latter impacts are still important, but often dwarfed by the impact of depredation to crops. Feral swine, in contrast, can create significant impact in all three categories. Research has focused largely on the impact of feral swine to crop depredation (Seward et al. 2004; Pimentel et al. 2005; Ober et al. 2011; Mengak 2012); however, it has provided substantial estimates of other damage categories as well (Frederick 1998; Engeman et al. 2003; Mayer and Johns 2011; Higginbotham 2013). Valuing the damages caused by a VIS in each of these three categories requires an understanding of the implications of a biological impact for different sectors of the economy. To do this, both the primary and secondary impacts must be quantified.

METHODS OF VALUATION

Primary Impacts

Valuation of the primary damage caused by VIS—through destruction, depredation, and disease transmission—is usually accomplished by estimating the market, loss, repair, or restoration values associated with the affected resource. Market values are commonly used when monetizing impacts to livestock or crops (Cumming et al. 2005; Engeman et al. 2010; Gebhardt et al. 2011). Loss values are often used in the case of death related to disease transmission, or predation of things not actively bought and sold in markets, including humans, companion animals, and sometimes wildlife. Repair costs and restoration costs are typically used as the valuation method for damages categorized as destruction (Engeman et al. 2008). Finally, restoration costs, rehabilitation costs, lost recreational opportunities, or nonmarket values are often used to quantify economic damages to ecosystems and wildlife (Engeman et al. 2004a,b, 2005).

Nonmarket valuation of wildlife can occur through survey methods such as the contingent valuation method (CVM) and travel cost method (TCM), as well as non-survey methods, such as benefit transfer. CVM is a survey-based, stated preference approach that solicits responses from individuals regarding their willingness to pay (WTP) for various use and nonuse values associated with wildlife (Loomis 1990; Kotchen and Reiling 1998). Several factors can affect WTP for wildlife, including the species' usefulness and likeability, information level of respondents, level of economic damage created by the species, and questionnaire design (Brown 1994; Brown et al. 1996; Nunes and van den Bergh 2001; Bateman et al. 2002; Tisdell and Wilson 2006; Martín-López et al. 2007, 2008). Criticisms of CVM include the hypothetical nature of the questionnaire and the inability to validate responses, causing some to question its usefulness for determining value (Eberle and Hayden 1991; Boyle 2003). Additionally, this type of valuation typically understates the true nonmarket value (Pearce and Moran 1994; Balmford et al. 2002).

TCM is another survey approach which uses costs incurred for travel to quantify demand for recreational activities that are sometimes linked to a species of interest (Kotchen and Reiling 1998). TCM is based on the idea that as some environmental amenity changes (e.g., the size of a wildlife population), the amount people are willing to pay to use it will change, which is revealed by a change in travel costs (see Loomis and Walsh 1997 for an extensive discussion and examples of this method). Criticisms of this method include concerns about the assumption that visitors' values equal or exceed their travel costs. Critics argue that travel costs are simply costs, not an accurate representation of value. Another concern is that this method requires values to be assigned to the time individuals spend traveling to a site. It is difficult to assign accurate values to the opportunity cost of travelers' time because people value their time differently, depending on their occupation or the activity they gave up in order to travel to the site.

The benefit-transfer method relies on benefit values derived from CVM and TCM studies in one geographical location and species, which are then transferred to another location and similar species. Adjustments to these values can be made by factoring in differences in incomes or prices from one area to an other. Typical criticisms of this method focus on the reliability of the original value estimates derived from CVM or TCM (Brouwer 2000; Smith et al. 2002).

Primary damages can generate secondary impacts due to economic factors that create linkages to established economic sectors. For example, primary damages arising from the destruction of an ecosystem may be measured by multiplying the number of acres damaged by the restoration price per acre. However, if the ecosystem destruction also reduces economic activity that would have been generated from tourist expenditures in a nearby town, this would represent the secondary impact (Shwiff et al. 2010).

Secondary Impacts

Regional economic analysis (REA) is an accepted methodology for estimating the secondary impacts in an economy based on the most current economic and demographic data available (BEA 2008). Regional economic models attempt to quantify the impacts on output as a result of input changes in a regional economy. These models are developed by constructing a mathematical replica of a regional economy (city, county, state, etc.) that contains all the linkages between existing economic sectors (e.g., agricultural, manufacturing, and industrial). The model then uses existing estimates of primary impacts to quantify secondary impacts, thereby calculating the total effect on jobs and revenue in a specified regional economy.

REA allows for the estimation of secondary (indirect and induced) impacts associated with primary VIS damages in units of measure that are important to the general public (e.g., revenue, income, and jobs). These secondary impacts are also known as upstream and downstream impacts. For example, when a VIS depredates crops, the reduction in yield per acre translates into less yield delivered to the processor and eventually to retail; these are downstream impacts. Additionally, the producer may buy fewer inputs (e.g., fuel and parts for equipment) because there are fewer acres to harvest; these are upstream impacts. These upstream and downstream impacts can be measured through the use of regional economic models, also known as input-output (IO) models, such as Impact Analysis for Planning (IMPLAN, Minnesota IMPLAN Group) and Regional Economic Modeling (REMI Inc.).

IO models are the most widely used tool for modeling the linkages and leakages of a regional economy. These models use transaction tables to illustrate how outputs from one industry may be sold to other industries as intermediate inputs or as final goods to consumers, and how households can use wages from their labor to purchase final goods (Richards 1972). This allows for the tracking of annual monetary transactions between industry sectors (processing), payments to factors of production (value added), and consumers of final goods (final demand). This complex network of transactions is summarized in the form of "multipliers" which measure how changes in economic activity relate to changes in final demand for a particular good. Many regional economic models are static; that is, they estimate economic impacts only within a single time period.

Arguably, economic impacts generated by VIS are dynamic, and therefore require a regional economic model that can account for complex interactions among economic sectors over multiple time periods. A dynamic regional economic model has been developed to generate annual forecasts and simulate behavioral responses to compensation, price, and other economic factors (REMI: Model Documentation – Version 9.5). The REMI model incorporates interindustry transactions, endogenous final-demand feedbacks, substitution among factors of production in response to changes in the relative factor prices, wage responses to changes in labor-market conditions, and changes in the share of local and export markets in response to changes in regional profitability and production costs (Treyz et al. 1991). The dynamic nature of REMI enables it to create a control (baseline) forecast that projects economic conditions within a region on the basis of trends in historical data. Economic impacts are then examined by comparing the control forecast to simulations that account for changes in variables such as industry-specific income, value added, and employment. Modeling impacts in this way can translate the primary impacts of a VIS into regional impacts on revenue and jobs, expanding the general public's perception of the potential benefits of preventing or combatting a VIS. These secondary impacts not only help estimate the total impact of a VIS, but also help engage a broader audience by highlighting the implications of a VIS for local communities and economies.

CURRENT PUBLISHED ESTIMATES OF PRIMARY DAMAGE

Below, we summarize current published estimates of damage. Many damage estimates are aggregated across the three damage categories; a related tendency is to report destruction and depredation impacts as a single number. Studies that do this are often not replicable and difficult to extend or extrapolate to other areas. In the case of studies that simply list damage as an aggregated estimate, we listed those impacts under the destruction category.

Examining published estimates of economic damage created by invasive species excluding feral swine, it is clear there is a paucity of research in this area. This explains why the most widely cited estimate of total damage from bird, mammal, reptile, and amphibian invasive species is $39.4 billion annually (Pimentel et al. 2000, 2005). Additionally, Pimentel et al. (2005) estimate the annual control costs are $11.5 million, although this only includes feral pig and brown tree snake control costs. Below, we dig deeper into the published literature, beyond Pimentel et al. (2000, 2005), to determine what other damage estimates exist.

VIS Except Feral Swine

Destruction

Marbuah et al. (2014) estimated damage costs from 79 harmful species to be $185 billion in the United States in 1993, including a cost of $46 billion per year for invasive mammals and birds. During the federal fiscal years from 1990 to 1997, damages reported to U.S. Department of Agriculture (USDA) Animal and Plant Health

TABLE 3.1
Estimated Annual VIS Damage

VIS	Annual Damage Estimate (in Millions USD)
Wild horses	$5
Mongooses	$50
Rats	$19,000
Cats	$17,000
Dogs	$250
Pigeons	$1100
Starlings	$800
Brown tree snakes	$1

Source: Office of Technology Assessment. 1993. *Harmful Non-Indigenous Species in the United States, OTA-F-565*. U.S. Government Printing Office, Washington, DC, USA.

Inspection Service (APHIS) Wildlife Services (WS) included $1,226,717 from invasive reptiles, $14 million from invasive mammals, and $28 million from invasive birds (Bergman et al. 2002). The annual cost of introduced rats alone was estimated at $21.2 million (Cusack et al. 2009).

In 1993, the Office of Technology Assessment estimated that terrestrial VIS caused $39.4 billion in damages annually in the United States; however, feral swine estimates are included in that amount. Specific estimates of damage from that report are detailed in Table 3.1.

The brown tree snake (*Boiga irregularis*) is capable of causing significant damages to property and productivity in the north Pacific through its tendency to create power outages (Fritts 2002) and impact tourism. Shwiff et al. (2012) used data from the snake's invasion on Guam, along with survey information from Hawaii, to estimate the cost of a potential invasion into Hawaii. Results suggested that total annual damage from such an invasion would be between $593 million and $2.14 billion.

Depredation

One of the most common forms of damage by VIS is agricultural loss due to depredation. We refer to depredation as both crop and livestock losses attributable to VIS activities, excluding losses associated with diseases transmitted by VIS. Invasive bird species are common culprits of agricultural depredation because they frequently forage in crop-intensive areas. Pimentel et al. (2005) estimate that the European starling (*Sturnus vulgaris*) is responsible for $800 million in crop losses annually. This figure reflects both the starling's large population in the United States as well as their ability as individuals to inflict crop losses. This estimate is based on losses not only from grain fields, but also in fruit production, such as cherries.

Bergman et al. (2002) calculate that, from fiscal years 1990 to 1997, the most frequent requests for assistance with invasive mammals in the United States were related to livestock predation by invasive canines. Invasive dogs (*Canis* spp.) were responsible for 20% of the total damage reported to the USDA WS during that time frame. Invasive dogs are introduced species of canines that cause economic, environmental, or human harm. This definition excludes native species like wolves or coyotes. In the case of invasive dogs, the important part of the definition is that the dogs are causing harm. The most frequent occurrence is livestock depredation by dogs that have become feral.

Disease

Published estimates that detail the economic impacts of VIS-associated disease transmission are scant. While it is generally known that VIS can play a substantial role in the transmission of transboundary diseases between humans, wildlife, and domestic animals, it is difficult to translate that impact into dollar terms. It is estimated that wildlife—some but not all of which are VIS—play a role in 79% of the reportable domestic animal diseases and, of those diseases, 40% are zoonotic. For example, the common pigeon and European starling are known carriers of dozens of diseases that pose a threat to human and livestock health and safety (Weber 1979). In another example, across the Gulf Coast in the United States, invasive nutria (*Myocastor coypus*) may carry tuberculosis, septicemia, and a variety of parasites that represent a health hazard to water supplies and recreation (USDA APHIS WS 2010). While there are many examples of diseases that VIS may host, the need for economic estimates of the impact caused by VIS-introduced disease represents an important area of future research.

Control

In 2011 alone, the U.S. Department of the Interior spent $100 million on invasive species prevention, early detection, rapid response, control, management, research, outreach, international cooperation, and habitat restoration. In 2005, the U.S. Fish and Wildlife Services (FWS) and its partners spent $2 million working with 15 trappers to eradicate over 8000 nutria from Maryland's Blackwater National Wildlife Refuge. FWS, in partnership with many organizations, has spent more than $6 million since 2005 on finding and applying solutions to the growing problem of Burmese pythons and other large invasive constrictor snakes in Florida. FWS spent $604,656 over a three-year period (2007–2009) to design python traps, deploy and maintain them, and educate the public in the Florida Keys to prevent the potential extinction of the endangered Key Largo woodrat and other vulnerable endangered species. From 1999 to 2009, federal and state agencies spent $1.4 million on Key Largo woodrat recovery and $101.2 million on wood stork recovery to combat python impacts (U.S. Fish & Wildlife Service 2012a,b,c). The National Park Service has spent $317,000 annually on various programs related to constrictor snake issues, such as researching snake biology for removal purposes in Everglades National Park (U.S. Fish & Wildlife Service 2012a,b). Research and control of brown tree snakes requires nearly $4 million per year; this is in addition to normal operating costs for management of Guam's National Wildlife Refuge and military environmental programs (USGS).

Feral Swine: A Notorious VIS

As noted earlier, feral swine are the most abundant free-ranging, exotic ungulate in North America. Enough literature has been published about their impacts to justify a more in-depth review. Feral swine have existed in pockets of the southeastern United States, California, and Hawaii for nearly five hundred years, and recent trends indicate a general northward expansion of populations. Feral swine have experienced significant range expansion over the past 30 years, in part because a subset of the human population wants to hunt them closer to home (Spencer et al. 2005; Acevedo et al. 2006; Saito et al. 2012; Bevins et al. 2014). This expansion has increased conflicts with agriculture and humans, triggering several assessments of the costs and benefits of feral swine in different locations (e.g., Higginbotham et al. 2008; Campbell and Long 2009; Siemann et al. 2009; Ober et al. 2011; Engeman et al. 2012; Mengak 2012; Campbell et al. 2013; Higginbotham 2013; Bevins et al. 2014). In addition, there has been considerable research on the increasing management conflicts stemming from feral swine expansion (e.g., Weeks and Packard 2009; Honda and Kawauchi 2011; Koichi et al. 2013; Warner and Kinslow 2013).

Destruction

The most commonly cited publication about feral swine damage is Pimentel et al. (2005), which reports an estimated annual impact of $800 million ($941 million 2012 USD) resulting from crop and environmental damage. Environmental damages associated with feral swine include erosion due to rooting, grubbing, and wallowing (Engeman et al. 2004a,b; Seward et al. 2004). Their impact is significant enough that, for example, they were found to “dominate the disturbance regime” of the Northern California Coast Range Preserve (Kotanen 1995). Feral swine have also contributed to the decline of 22 species of plants and four species of amphibians, in addition to the predation of marine turtles and their nests (Seward et al. 2004). Damage to marshes and parks by feral swine has also been noted (Engeman et al. 2003, 2004a; Pimentel et al. 2005), including damage to priceless archaeological sites (Engeman et al. 2012). Another commonly reported form of property damage is vehicle collisions involving feral swine. One study examined 179 vehicle collisions in South Carolina involving feral swine and found an average damage estimate of $1173 per collision (Mayer and Johns 2011).

Table 3.2 summarizes a wide variety of damage estimates found in the feral swine literature, adjusted for inflation to 2012 using BLS (2014). The base year of 2012 was chosen to put these figures on par with the most recent USDA Census of Agriculture. When possible, the data were converted into annualized costs. Given the diverse circumstances underlying each research project, the comparison of costs across different locations and time scales is problematic. For example, Higginbotham et al. (2008) found feral swine cause $58 million/year in damage to the whole of Texas agriculture, an area of 59 million acres. Meanwhile, Mengak (2012) reported a similar $58 million/year for crop damages to 9.7 million acres in Georgia, only part of which was agricultural land. This area is responsible for approximately 1% of U.S. total crop sales (USDA NASS 2014). Jerrolds et al. (2014) conducted a survey of agricultural groups and resource managers in Tennessee and found that 94% of counties had swine populations, and most complaints related to crop and pasture damage. There is also some anecdotal evidence of considerable losses realized in New York. Hall (2012) discusses a farm in Clinton County suffering $25,000 in losses from corn, apple, and strawberry depredation. Westenbroek (2011) discusses a farm in

TABLE 3.2
Estimates of Feral Swine Destruction

Geographical Area	Description	Estimates
	Crops—Single Incidents	
Geographical Area	**Description**	**Estimates**
Texas (7)	Peanuts	$64,803
New York (4)	Corn	$15,157
New York (5)	Corn, apples, and strawberries	$25,000
	Crops—Annual Aggregates	
Geographical Area	**Description**	**Estimates**
Texas (1)	Peanuts	$225,518/yr.
Texas (1)	N/A	$15,492–$464,765/yr.
Texas (17)	Corn, soybeans, wheat, rice, sorghum, peanuts	$89,817,000/yr.
Alabama (17)	Corn, soybeans, wheat, rice, peanuts	$21,322,000/yr.
Arkansas (17)	Corn, soybeans, wheat, rice, peanuts	$19,575,000/yr.
Florida (17)	Corn, soybeans, wheat, rice, peanuts	$5,985,000/yr.
North Florida (3)	Corn, cotton, peanuts, and soybeans	$1,921,224/yr..
Georgia (6)	Reported crops—Mengak (2012, p. 13) SW Extension District	$58,180,000/yr.
Georgia (17)	Corn, soybeans, wheat, rice, peanuts	$5,150,000/yr.
Louisiana (17)	Corn, soybeans, wheat, rice, peanuts	$15,670,000/yr.
Mississippi (17)	Corn, soybeans, wheat, rice, peanuts	$18,518,000/yr.
Missouri (17)	Corn, soybeans, wheat, rice, peanuts	$485,000/yr.
North Carolina (17)	Corn, soybeans, wheat, rice, peanuts	$4,684,000/yr.
South Carolina (17)	Corn, soybeans, wheat, rice, peanuts	$8,747,000/yr.
	Property	
Geographical Area	**Description**	**Estimates**
New York (12)	Two Lawns	$421 each
Georgia (6)	Property damage in SW Extension District	$24,500,000/yr.
California (8)	31 residential properties and 1 golf course	$93,652/yr.
Nationwide (13)	Avg. property damage from feral swine—vehicle collisions	$1,197/per car
	Total Uncategorized	
Geographical Area	**Description**	**Estimates**
Texas (9)	"Economic loss since feral swine appeared on the respondent's property" (Adams, et al. 2005, p. 1316)	$32,25,796
Texas (10)	Cost to Texas agriculture	$57,580,650/yr.
Texas (10)	Repairing damage and control	$7,751,242/yr.
California (8)	Total reported damage to hay, forage, ponds, lawns, drainage, orchards, vineyards, Irrigation, livestock, crops, trees, fruits, and nuts	$2,634,343/yr.

(*Continued*)

TABLE 3.2 (*Continued*)
Estimates of Feral Swine Destruction

Environmental

Geographical Area	Description	Estimates
Florida (14)	Value of damaged area of Savannas Preserve State Park	$1,545,717–$5,036,456
Florida (15)	Damage to 3 Florida state parks at the end of the study period	$6,652–28,384/ha
California (16)	Damage and control	$400,169/yr.

Sources: 1. Tolleson, D.R., et al., 1995, *Great Plains Wildlife Damage Control workshop Proceedings*, June 2–3, Fort Worth, Texas, p. 454.; 3. Ober, H.K., et al., 2014. *Farmer Perceptions of Wildlife Damage to Row Crops in North Florida*. Department of Wildlife Ecology and Conservation, Florida Cooperative Extension Service, Institute of Food and Agricultural Sciences, University of Florida.; 4. Westenbroek, T. Letter to P. Anderson. September 25, 2011. Estimate of Damage due to feral swine. Cornell University Cooperative Extension, Sullivan County; 5. Hall, W. 2012. *Wayne's World: Many Folks Despise them but Feral Hogs are Smart*. The Times Herald Record, Middletown, NY.; 6. Mengak, M.T., 2012, Georgia Wild Pig Survey, Final Report, University of Georgia, Athens, GA; 7. Beach, R., 2013, *Texas Natural Wildlife*, San Angelo, TX; 8. Frederick, J.M., 1998, *18th Vertebrate Pest Conference*, University of California, Davis; 9. Adams, C.E., et al., 2005, *Wildlife Society Bulletin* 33,1312–1320; 10. Higginbotham, B., G. Clary, L. Hysmith, and M. Bodenchuk. 2008. Statewide Feral Hog abatement pilot project, 2006–2007. Texas AgnLife Extension Service. Available online at http://feralhogs.tamu.edu/files/2010/05/06-07-Feral-Hog-Abatement-Pilot-Project.pdf. Accessed December 12, 2016; 12. USDA APHIS VS, 2010, *National Brucellosis Surveillance Strategy*, Riverdale, Maryland, 20737; 13. Mayer, J.J. and P.E. Johns. 2011. *Characterization of Wild Pig-Vehicle Collisions*. Washington Savannah River Company, Aiken, SC and Carolina Wildlife Consultants, New Ellenton, SC. May 23, 2011; 14. Engeman, R.M., et al., 2004b, *Journal for Nature* Conservation 12, 143–147; 15. Engeman, R.M., et al., 2003, *Environmental Conservation* 30, 319–324; 16. Sweitzer, R.A. and B.E. McCann. 2007. Natural areas ecological damage and economic costs survey report. Unpublished report submitted to all interested survey respondents. Prepared by R.A. Sweitzer and B.E. McCann. Department of Biology, University of North Dakota, Grand Forks, North Dakota, USA, 37pp.

Note: All figures have been adjusted to 2012 USD using BLS (2014).

Delaware County that lost $14,850 to feral swine consumption of corn fields. It is difficult to compare in a meaningful way two areas so different in size and context, even though they experienced similar levels of reported damage.

Depredation

There is very little quantitative data published about the predatory behavior of feral swine. However, what is lacking in quantitative data is offset by what is known in qualitative terms. Surveys, reports describing feral swine attacks, and anecdotal evidence are available from several sources. Survey respondents have experienced or are concerned about danger to humans from attack, livestock depredation, and damage or injury to pets (Barrett and Pine 1981; Rollins 1993; Sweitzer and McCann 2007; Mengak 2012). Several popular press articles describe actual attacks on humans (Moore Jr. 2008; Roberts 2011; Sanchez 2011). Love (2013) details the case of an inmate on a work crew who was attacked by a feral swine. Mayer (2013) found that up to 15% of reported attacks on humans by feral swine are fatal.

Feral swine are known to prey on livestock, primarily sheep (*Ovis aries*) and goats (*Capra hircus*), but also cows (*Bos taurus*) and exotic game species (Frederick 1998; Seward et al. 2004; Christie et al. 2014). Barrios-Garcia and Ballari (2012) reported that around 30% of feral swine diets consist of animal matter, depending on the ecosystem and season.

Seward et al. (2004) report that feral swine cause greater than $1.2 million in goat losses annually. Some feral swine kills may be mistakenly reported as coyote kills, leading to under reporting of feral swine depredation (Seward et al. 2004). Anecdotally, though, a rancher in Texas experienced a 15%–20% reduction in goat kid production on property where feral swine resided (Beck 1999). In 1990, Texas authorities documented 1243 head of sheep and goats lost to feral swine, at a value of $110, 669 in 2012 (Rollins 1993). In 1991, Texas and California reported 1473 sheep, goats, and exotic game animals killed by feral swine (Barrett and Birmingham 1994). Feral swine density has actually been found to be a good predictor of ewes losing lambs (Choquenot et al. 1997).

Without a larger body of quantitative work, it is difficult to know the extent of the economic threat that feral swine pose to livestock. However, the available qualitative research reveals that feral swine depredation is a real problem for agricultural producers. Further research and more robust data collection will be necessary to effectively quantify feral swine depredation costs.

Disease

Feral swine are a potential reservoir of both zoonotic and nonzoonotic diseases that could impact the U.S. economy through a number of channels (Roger 1988; Paarlberg 2002). Of the 42 serious pathogens with a wildlife component reported by Miller et al. (2013), feral swine are explicitly involved in seven. Survey respondents indicated concern or experience with feral swine spreading disease to livestock or acting as a potential disease reservoir (Barrett and Pine 1981; Rollins 1993). They have also been known to carry diseases dangerous to humans (Bengsen et al. 2013). For example, feral swine are a potential vector for new forms of influenza because they have the required receptors for both avian and human strains of the virus, which provides an opportunity for the viruses to combine (Hall et al. 2008).

While the disease threat posed by feral swine is clearly recognized within the literature, it has thus far been difficult to accurately model their role as vectors during a disease outbreak. Current disease transmission models are largely focused on the spread of a single disease between a limited number of species (e.g., Ward et al. 2007, 2009). However, the complexity of the feral swine problem requires a model flexible enough to accommodate the potential for transmission of multiple pathogens across multiple species.

The cost of one outbreak of foot-and-mouth disease (FMD) in the United States involving feral swine is estimated to range from $7.5 million to $5.8 billion USD for a single state (Cozzens 2010; Cozzens et al. 2010). Feral swine have also been identified as an important reservoir for transboundary animal diseases such as classical swine fever virus, African swine fever virus, and porcine reproductive and respiratory syndrome (Jori and Bastos 2009; Reiner et al. 2009; Müller et al. 2011). Additionally, there is concern over potential losses in cattle associated with transmission of pseudorabies (Aujeszky's disease) from feral swine (Bitsch 1975; Hagemoser et al. 1978; Crandell et al. 1982).

Research on pathogen transmission between feral swine and livestock has been making progress. Pineda-Krch et al. (2010) developed a disease transmission model to simulate the spread and control of FMD among feral swine and beef and dairy herds in California. The model incorporates elements of space and randomness. Results show that introduction of FMD from feral swine to livestock could result in a large and rapidly moving outbreak. However, tested containment strategies showed potential to reduce the size and duration of the outbreaks.

Ward et al. (2007, 2009) built a disease spread model that explicitly models the potential for FMD spread between domestic cattle, feral swine, and white-tailed deer in Texas. The model considered geographic relationships between the species and found that densities, distributions, and the resulting potential for contact between affected species were important in determining the extent of the outbreak (Ward et al. 2007, 2009).

Beyond the modeling of an outbreak, the next challenge is valuing potential damage to the agricultural sector and economy as a whole. The potential damage to commercial livestock production is related to the number of exposed animals. U.S. livestock sales totaled $90 billion in 2012 (USDA NASS 2014), with $5 billion in beef exports (USDA ERS 2013), and $6.3 billion in pork exports (MEF 2014). Almost 13% of total beef production, and 27% of pork production is exported (MEF 2013). Even limited outbreaks can be exceptionally costly, due to the potential for international banning of U.S. imports of the affected species, which triggers price effects for the entire U.S. herd. Coffey et al. (2005) estimate that the single reported case of bovine spongiform encephalopathy (BSE) in December 2003 (which did not involve feral swine) cost the U.S. beef industry between $3.9 billion and $5.7 billion in lost exports alone in 2004.

Some of the only studies on the economic impacts of disease transmission involving feral swine are Cozzens (2010) and Cozzens et al. (2010). Cozzens (2010) found that potential producer losses in Kansas due to feral swine transmission of FMD to domestic livestock could be as much as $6.1 billion. Total economic impact for a hypothetical transmission of FMD to livestock from infected feral swine in Missouri was estimated at $12.6 million (Cozzens et al. 2010).

There are also concerns about contamination of the human food supply by feral swine. The deadly September 2006 outbreak of *E. coli* O157:H7 was traced back to feral swine–contaminated spinach (Kreith 2007). In response to the outbreak, consumer expenditures on leafy greens declined by $69 million; spinach producers in particular lost $234 million because lettuce and similar produce were substituted for spinach (Arnade et al. 2009). This example illustrates the economy-wide impacts that disease outbreaks can generate, affecting both consumers and producers.

In addition to food safety issues tied legitimately to feral swine, consumers are also sensitive to perceived but unproven disease threats associated with feral swine. In 2009, an outbreak of H1N1 influenza was initially called “swine flu” by authorities. This mislabeling led to substantial negative consumer response, even though Attavanich et al. (2011) determined that pork remained safe to consume throughout the entire event. Agricultural sector losses of $159 million were attributed to media coverage of “swine flu” (Attavanich et al. 2011).

The ability to measure both the epidemiologic and economic impacts of a multispecies, multipathogen outbreak induced by feral swine is still beyond the scope of currently available models. However, evaluation of the costs associated with single-disease outbreaks of FMD or BSE between feral swine and other species shows the damaging potential of even small-scale disease transmission events, including costs from both real and perceived food safety threats. While the full magnitude of feral swine disease impacts are not currently known, it is clear from available evidence that they pose a legitimate threat to the U.S. agricultural sector.

Control

Given our discussion of the damages feral swine cause, it is no surprise that considerable effort and resources have been devoted to the control and management of feral swine populations. There is substantial interest in obtaining an accurate measure of feral swine management costs, to compare with the damages incurred, which are the implicit cost of failing to control existing feral swine populations. The feral swine herd in Texas has been estimated at two million (Higginbotham et al. 2008). Current nationwide population estimates range between four and five million feral swine (Pimentel 2007; Higginbotham et al. 2008; USDA APHIS 2013). However, census is extremely difficult and few studies have generated a reliable national population estimate.

Feral swine are incredibly prolific, capable of speeding up their reproductive cycles under pressure (Hanson et al. 2009) and increasing their reproduction rates when population is below the local carrying capacity (Bengsen et al. 2013). All of these factors create unique and costly challenges in the management and control of feral swine. Saunders and Bryant (1988) found an inverse relationship between control efforts and control success. Specifically, the more feral swine were shot from a helicopter (within a fixed study area), the more difficult it became to detect and shoot the remaining individuals. This confirms the potential infeasibility of eradicating established populations. In fact, studies have shown that lethal control efforts must result in mortality rates ranging between 60% and 80% in order to impair the ability of feral swine to maintain their population (Hone and Pedersen 1980; Barrett and Pine 1981; Kreith 2007; Bengsen et al. 2013). Cost estimates for feral swine control are presented in Table 3.3.

The difference in average removal costs between the two studies based in Australia (Hone and Pedersen 1980; Saunders and Bryant 1988) may be due to a couple of different reasons. First, the two studies used different control methods as the primary method of control. Hone and Pedersen (1980) placed poison baits at water sources known to be frequented by feral swine and then observed the baits to record any nontarget species take. Saunders and Bryant (1988) used helicopter

TABLE 3.3
Control Costs

Geographical Area (Source)	Description	Estimates (USD)
California (16)	Feral swine related costs incurred from management within natural areas in California	$4.29M/yr.
California (16)	Feral swine eradication efforts during 3-yr. study period	$3.89M/yr.
California (16)	Per km construction and maintenance cost of exclusion fence at pinnacles national monument (~20-yr. life span)	$58,403/km
California (18)	Total construction cost of exclusion fence at Pinnacles National Monument (~20-yr. life span)	$1,871,690
California (18)	Eradication efforts at Pinnacles National Monument	$1,053,138 (over ~3 yrs)
California (18)	Annual maintenance cost of exclusion fence at Pinnacles National Monument	$68,629/yr.
Florida (14)	Average removal cost	$41.18/head
Texas (11)	Average removal cost	$69.61/head
Australia (24)	Average removal cost	$91.60/head
Australia (25)	Average removal cost	$16.52/head

Sources: 11. Higginbotham, B., G. Clary, L. Hysmith, and M. Bodenchuk. 2008. Statewide Feral Hog abatement pilot project, 2006–2007. Texas AgnLife Extension Service. Available online at http://feral-hogs.tamu.edu/files/2010/05/06-07-Feral-Hog-Abatement-Pilot-Project.pdf. Accessed December 12, 2016; 14. Engeman, R.M., et al., 2004b, *Journal for Nature Conservation,* 12, 143–147; 16. Sweitzer, R.A. and B.E. McCann. 2007. Natural areas ecological damage and economic costs survey report. Unpublished report submitted to all interested survey respondents. Prepared by R.A. Sweitzer and B.E. McCann. Department of Biology, University of North Dakota, Grand Forks, North Dakota, USA, 37pp.; 18. Kreith, M., 2007, Wild pigs in California: The issues, University of California Agricultural Issues Center, Davis, California; 24. Hone J. and Pedersen H. 1980. *Proceedings of the Ninth Vertebrate Pest Conference*, pp. 176–182. University of California, Davis; 25. Saunders, G., et al., 1988, *Wildlife Research,* 15, 73–81.

Note: All figures have been adjusted to 2012 USD using BLS (2014).

shooting in an effort to eradicate feral swine from a specific eradication zone. The labor requirements of the additional bait observation in Hone and Pedersen (1980) are a likely contributor to the additional cost; indeed, labor made up over half of the total estimated project cost. Additionally, the Saunders and Bryant (1988) study killed a much larger number of pigs (946 compared to 120 in the other study), suggesting there may be some economies of scale driving down the average pig removal cost.

Methods of feral swine control deemed acceptable differ by stakeholder groups. Acceptability of management practices is influenced by stakeholder group identification (e.g., residents vs. tourists), awareness of a feral swine problem, and social factors (Koichi et al. 2013). For example, feral swine are so well established in the local culture around a national park in Texas that residents do not consider them nonnative (Weeks and Packard 2009). Control efforts are met with considerable resistance, especially when professional hunters are hired. Similarly, feral swine control efforts conducted by "outsiders" in Hawaii (e.g., U.S. federal agencies), without public consent, have been met with considerable public opposition (Weeks and Packard 2009). Stakeholders' conflicting views of control strategies are one of the primary hurdles to effective feral swine management.

DISCUSSION: IMPROVING ESTIMATES OF DAMAGE FROM VIS

Current Knowledge Gaps

Our review of the literature has revealed an incomplete understanding of the economic damages and control costs arising from VIS. Improvements to this understanding can occur through several pathways. First, there is a need for improved data collection using methods that allow for replication and extrapolation. Second, these improved data and associated research insights need to be integrated into future management decisions to identify economically efficient (or at least the most cost-effective) management strategies for VIS. Last, regional economic models should be used to rigorously link primary damage impacts to the appropriate economic sector in order to estimate secondary impacts.

To improve data collection, a nationwide surveillance effort is needed to estimate feral swine damage to agricultural products and livestock. Ober et al. (2011) and Mengak (2012) both used survey methods that are scientifically replicable. And several recent surveys have been conducted that could be used as foundations for developing a nationwide questionnaire related to feral swine damages and society's attitudes about them (Hamrick 2013; Adams et al. 2005; Higginbotham et al. 2008; Ober et al. 2011; Mengak 2012).

Each category of damage—destruction, depredation, disease—suffers different data challenges that are difficult to overcome. Destruction has been the most thoroughly addressed damage category, but its estimates vary in scope and approach. This makes comparison between studies difficult and calculation of an accurate national aggregate nearly impossible. Geographic scales range from as small as a single farm to as large as the entire state of Texas. Furthermore, destruction estimates sometimes include only crop damage, and other times include only environmental damage or control costs. It is therefore very difficult to generalize findings from one study on environmental damages to total damages across the larger United States. It is possible that GIS (Geographical Information Systems) could be used to combine and extrapolate disparate data, but estimates will be ad hoc at best, relying on rules-of-thumb and heuristics. Ideally, there would be common survey questions, agreed-upon units of measure, and standard reporting protocols (including mean and variance of estimates to enable inference), such that companion studies could be undertaken to inform a nationwide estimate.

Regarding the next damage category, depredation of livestock by VIS, verifiable data are currently lacking. There is considerable qualitative information, however, that may help researchers identify incidents of VIS predation. For example, insurance companies may have data on depredation losses, but presumably only for producers who carry coverage and file a claim. A state-level policy requiring the universal reporting of livestock killed by feral swine would provide more complete data, which would then enable better-informed response. Some states, such as Texas, could serve as a model for reporting livestock losses in the field (Higginbotham et al. 2008).

Regarding the final damage category, disease losses attributable to VIS, we also lack a complete picture of current and potential disease risk. This is by far the most difficult category of damage to measure, but potentially the most important that needs to be addressed, due in part to potential implications for international trade. The severity of an outbreak depends on probabilities of infection and transmission between individuals and between species, as well as the medical severity of the disease itself.

Unfortunately, the probabilities of an outbreak and how feral swine density and distribution affect those probabilities are largely unknown. As disease spread models incorporate new data, or develop more flexibility to account for uncertainty in existing data, this daunting goal will become more achievable. Groups like the National Institute for Mathematical and Biological Synthesis (NIMBioS) are currently working to develop simulation models that fully capture the livestock–wildlife interface. Scientists across disciplines are also making strides toward the One Health Initiative approach of combined human and veterinary medicine. These advancements will help uncover the true scope of risks stemming from feral swine diseases.

In an attempt to mitigate damage caused by feral swine, substantial resources have been committed to management and control efforts. These efforts impose both direct costs (in terms of outlays of actual dollars on lethal and nonlethal control efforts) as well as indirect costs (in terms of lost time and resources devoted to controlling feral swine), both of which represent resources that could have been allocated elsewhere. However, management and control costs are categorically different than damages inflicted by feral swine. Management and control costs are a choice made in response to damages or potential damages. These two forms of expense should therefore be recorded separately. By erroneously combining damage estimates with management and control efforts, granularity in information that is needed for effective decision-making is lost.

A Way Forward: Bioeconomic Modeling

Bioeconomic modeling is another analytical tool that can be used to address some of the knowledge gaps about VIS impacts and efficient management strategies. Bioeconomic models describe biological processes and predict the effects of management decisions on those processes. Therefore, they can be used to determine the most cost-effective management policies given biological constraints and bioeconomic feedback loops. Development and use of these models is constrained, however, by limited budgets and time, as well as gaps in our biological understanding.

The combined use of bioeconomic models with regional economic models can provide the most comprehensive estimate of total economic impact of a VIS, as well as net benefits of alternative management strategies. Such modeling would benefit significantly, however, from improved estimates of damage, depredation, and disease, along with associated animal density and population control data to determine the mathematical relationships that exist between them.

SUMMARY

In reviewing the existing research, a number of gaps in our knowledge about VIS abundance, damage, and efficient control strategies have become clear. These gaps represent opportunities to expand upon the knowledge needed for meaningful VIS management. Currently, the literature does not contain adequate estimates of VIS populations, ranges, expansion, current levels of damage within any of the three categories (destruction, depredation, and disease), or measures of control costs. For example, feral swine are known to damage timber production (Jackson 1990; Whitehouse 1999; Mengak 2012), yet no actual measure of the economic impact of this destruction exists. Many of the estimates of VIS damage come from a single publication, Pimentel et al. (2005). Such limited results highlight the need for more impact studies, although research about feral swine damage seems to be increasing at a much greater rate than research about other VIS.

The lack of economic impact estimates is problematic because they are necessary to determine the efficient level of control and management effort. One obvious factor missing in most VIS analyses is a discussion of potential trade implications of disease transmission from VIS to livestock. Disease transmission can not only restrict animal movements within the United States, but also restrict our ability to export livestock commodities. Such restrictions can inflict significant damage to the U.S. economy, as evidenced during the 2003–2004 outbreak of BSE (albeit unrelated to VIS).

Impact estimates summarized in this chapter also highlight the need for more comprehensive national estimates of damage from VIS. The precise size of nationwide populations of various VIS and their rate of expansion are not known with certainty. Alternative methods are needed to identify areas in which VIS occur and to estimate their prevalence. If nationwide data were available, modeling exercises could then be used to determine a national estimate of potential damage from one or more VIS. Arguably the most ambitious goal would be to develop a national disease spread model that includes wildlife populations alongside domestic animals and humans. A quality estimate of the nationwide potential for VIS-transmitted diseases would provide a significant step forward toward understanding and ranking potential VIS impacts, as well as developing prevention or control strategies.

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