Chapter 8

Breeding for bird resistance in sorghum and maize

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Historical

Maize (*Zea mays* L.) and sorghum (*Sorghum bicolor* L. Moench) are grown by farmers world wide but, unfortunately, grain losses seem to occur wherever they coexist with granivorous birds. Although some areas (e.g. midwestern US) have such high crop intensities that bird losses do not appear to be larger than those from other sources such as harvesting and processing, there are many areas around the world where this is not the case. High populations of birds can devastate a traditional farmer within a short period. Maize and sorghums are subject to bird attack more often than most other cereals because they have strong stems and leaves for perching, and because they are widely grown. Considering that they make up over 30% of the total tonnage of cereal-grain production in the world (FAO, 1981) and the many areas where bird losses occur (*Table 8.1*), world-wide losses have a sizable impact on the food supply.

Maize is grown in more widely diverse climates than any other cereal crop (Jenkins, 1941). Sorghum is the only cereal crop that can be grown successfully in many of the vast semi-arid regions of the world. Invariably, granivorous birds occur wherever these crops are grown (De Grazio, 1978) and under the appropriate conditions will attack them. All too often these conditions exist in a developing nation and man loses in his competition for a limited food supply.

Bird damage to cereal crops is a global problem inflicted by a diversity of bird species (*Table 8.1*). Unfortunately, bird problems and associated losses in field crops are poorly documented and understood. The species responsible for damage have not always been identified (FAO, 1973) and only a few workers have attempted to estimate losses and describe problems on a world-wide basis.

Today most bird-damage control specialists focus their efforts on protecting a crop rather than destroying birds. They have found that, generally, large-scale killing of birds is not necessary to reduce crop damage (De Grazio, 1974). This has been dramatically demonstrated with the African red-billed quelea (*Quelea quelea*), which is believed to be the most numerous, and perhaps the most destructive bird in the world (De Grazio, 1974). Hundreds of millions of quelea have been killed by various means (i.e. toxicants, explosives, fire) during the past three decades without any long-term population reductions (Crook and Ward,

TABLE 8.1. World-wide distribution of bird species that feed on sorghum and maize*

Location	*Crop*	*Major species*
Canada and US†		
Canada	Maize	Blackbirds
United States	Maize	Blackbirds, crow
United States	Sorghum	Blackbirds, sparrow
Latin America‡		
Argentina	Maize	Blackbirds, parrots, doves
	Sorghum	Blackbirds, parrots, doves
Bolivia	Maize	Parakeets
Colombia	Maize	Blackbirds, parrots, doves, dickcissel
Hispaniola	Maize	Village weaver
	Sorghum	Village weaver
Honduras	Maize	Blackbirds, parrots, doves
	Sorghum	Blackbirds, parrots, doves
Mexico	Maize	Blackbirds, doves, dickcissel
Peru	Sorghum	Seedeater, meadowlark
Dominican Republic	Maize and sorghum	Village weaver
Europe§		
England	'Cereal grains'	Wood pigeon
France	'Cereal grains'	Crow
Germany	Maize	Crow
Netherlands	'Cereal grains'	European starling
Asia¶		
Bangladesh	Maize	Parakeets, crows
	Sorghum	Parakeets, crows, mannikins, weavers
India	'Cereal grains'	Parakeets, sparrows, crows, buntings, weavers
Korea	'Cereal grains'	Sparrows, doves
Nepal	Maize	Parakeets, mannikins
Pakistan	Maize	Parakeets, crows
	Sorghum	Sparrows, parakeets, weavers, doves
Philippines	'Cereal grains'	Mannikins, sparrows
Africa#		
Botswana	Sorghum	Doves
Cameroon	Sorghum	Quelea, Golden Sparrow, weavers, starlings
Chad	Maize and sorghum	Quelea, Golden Sparrow, weavers, starlings
Ethiopia	Sorghum	Quelea, Golden Sparrow, weavers
Kenya	Sorghum	Quelea, doves, weavers, starlings
Libya	Sorghum	Sparrows
Mali	Sorghum	Quelea, weavers, parrots
Nigeria	Maize and sorghum	Quelea, Golden Sparrow, starlings, doves, weavers
Senegal	Sorghum	Quelea, Golden Sparrow, weavers, starlings, doves
South Africa	Sorghum	Quelea
Somalia	Sorghum	Quelea, Golden Sparrows, Red Bishop, weavers
Sudan	Sorghum	Quelea
Tanzania	Sorghum	Quelea, chestnut weaver, weavers, doves

*Excerpted from De Grazio (1978) with addition of recent information from Bangladesh and the Dominican Republic.
†Blackbirds = *Ageluius* spp., *Quiscalus quiscula*, *Molothrus ater*; Crow = *Corvus brachyrynchos*; sparrow = *Passer domesticus*.
‡Blackbirds = *Agelaius* spp., *Molothrus* spp., *Xanthocephalus xanthocephalus*, *Leistes militaris*, *Cassidix mexicanus*; Parrots = *Forpus passerinus*; Doves = *Zenaida* and *Leptotilia* spp.; Dickcissel = *Spiza americana*; Village Weaver = *Ploceus cucullatus*; Seedeater = *Sporophilia* spp.; meadowlark = *Pezites militaris*; Black-headed Weaver = *Ploceus cucullatus*.
§Wood pigeon = *Columba palumbus*; Crow = *Corvus* spp.; European Starling = *Sturnus vulgaris*.
¶Parakeets = *Psittacula* spp.; Crows = *Corvus* spp.; Weavers = Ploceidae; Sparrows = *Passer domesticus*; Doves = Columbidae; Buntings = *Emberiza* spp.; Mannikins = *Lonchura* spp.
#Doves = Columbidae; weavers = Ploceidae; starlings = *Lamprotornis* spp.; parrots = Psittacidae; sparrows = Ploceidae; Golden Sparrow = *Passer luteus*; quelea = *Quelea quelea*; Red Bishop = *Euplectes orix*; Chestnut Weaver = *Ploceus rubiginosus*.

1963; Funmilayo and Akande, 1979). There are exceptions, such as destroying colonies of birds that are known to depredate local fields (Jaeger and Erickson, 1980). This form of selective lethal control is becoming the preferred means of controlling quelea damage in much of Africa for this reason (R.L. Bruggers, personal communication; M.M. Jaeger, personal communication) but in general, non-lethal means of crop protection is the approach being used.

Breeding of plants which are more resistant to grain predation by birds is an alternative means of crop protection. Because the term 'bird resistance' means different things to different people, Harris (1969) gave a general definition for sorghums that can also apply for maize. He defined bird resistance as 'that mechanism or characteristic of a variety that when given a choice of feeding material birds will not normally depredate'. 'Less susceptible' is a more accurate term but 'bird resistance' is more often used. By Harris's definition, however, bird resistance is understood to be relative to bird population, other feeding sources, and probably several other factors. Therefore, under certain circumstances the most 'resistant' cultivars may be heavily damaged if alternate food is not available.

Plant breeding represents a planned strategy to control crop losses to birds. Geneticists are segregating factors to impart morphological characteristics to a plant or seed that physically or chemically affect the bird's choice of that seed as a food source. Another approach being taken is for biologists or ornithologists to study bird populations and feeding habits of granivorous birds during different periods of the year and to develop an agronomic plan on this basis (Ward, 1973).

Sorghums

Although sorghum represents only about 4.3% (approximately 72 million tonnes) of the total cereal grains produced (FAO, 1981), it is an extremely important crop on a world-wide basis. Sorghum has been classified broadly into four agronomic groups: (1) grain sorghums; (2) sorgos; (3) broomcorns, and (4) grass sorghums (Leonard and Martin, 1963). Grain sorghum is grown primarily as a cereal; sorgos for forage, syrup, or sugar; broomcorns for its long rachis branches for use in brooms; and grass sorghums for hay and pasture. In the Western Hemisphere, sorghum is grown mainly for feed-grain production and forage, but in many developing nations, humans consume the grain for food, and the fodder is used for an energy source or for building construction. Over 85% of all sorgum is grown in developing nations (FAO, 1981). The food, fodder, feed, and industrial uses are especially crucial to human populations in the semi-arid tropics of Africa and Asia which have constantly lived on the threshold of famine or potential famine. Sorghums and millets are the major source of calories and protein for millions of rural poor that suffer chronic malnutrition, high infant mortality and morbidity (Hulse, Laing and Pearson, 1980).

Probably the most important characteristic of sorghum is its ability to tolerate low rainfall and survive under conditions of continuous or intermittent drought, high temperatures, low fertilities and flooding. It is grown instead of the other cereals in parts of Asia for these reasons (Rachie, 1970). Maize has replaced sorghum in many areas of Africa, but data indicate a relatively greater sorghum yield over a wide range of environments (Doggett *et al.*, 1970). Cultivars tolerant to low temperatures and high altitudes are gradually finding a place in Mexico, Brazil, and other Latin American countries.

Plant morphological characteristics

Sorghum is a coarse annual grass that when mature may range from 0.6 to more than 4.5 metres in height. The vegetative appearance of the plant is somewhat similar to that of maize. The culms, which may be rather fine in grass sorghums and up to 5 cm wide in some grain or forage types, are made up of 7–18 or more nodes and internodes. It may be juicy or pithy, sweet or non-sweet (Leonard and Martin, 1963). A leaf is borne at each node with leaves being alternate and on opposite sides of the culm. The surface of the culms, sheathes, and leaves are smooth and have a waxy surface. The number of leaves at maturity is highly correlated with lengths of vegetative period. Each additional leaf adds 3–4 days to the length of the growing period.

The inflorescence is a panicle (*Figure 8.1*) usually ranging from 7 to 51 cm in length and from 4 to 20 cm in width (Snowden, 1936). The panicle, depending on the length of the peduncle, may only partly emerge from the sheath of the top leaf or it may fully emerge and position itself well above the top leaf. The head type may be compact to open or lax depending on the length and strength of the seed or rachis branches. The two glumes are of about equal length and are more or less thickened. The length of the glumes range from about half the length of, to longer than, the grains (Martin, 1970). Glume color is usually black, red, brown or straw (Leonard and Martin, 1963). The texture of the glumes may be hard, leathery or papery in the various sorghum types. When present, the awn is attached to the lemma of the fertile floret. It may be persistent or be easily detached at maturity.

Grain morphological characteristics

The grain is a dry indehiscent, one-seeded fruit known as a caryopsis (Leonard and Martin, 1963). A complete description of the seed is given by Rooney and Miller (1982) and a diagrammatic cross-section is shown in *Figure 8.2*. The caryopsis or kernel is composed of three main parts: about 6% outer covering or pericarp; about 84% storage tissue or endosperm, and about 10% embryo or germ (Bidwell, Bopst and Bowling, 1922). The pericarp or ovary wall is fused with the seed coat or testa of the seed, and thus is technically a matured ovule. If the complementary genes B_1 and B_2 are present, the grain will have a testa or seed coat (a pigmented layer which is highly variable among sorghum lines) immediately outside the aleurone layer. There are large variations in structure and composition among sorghum grains (Bullard *et al.*, 1980). The shape, size, proportion, and nature of the endosperm, germ, and pericarp, the presence or absence of testa, and the colour of the pericarp are all genetically determined.

Sorghum pigments are polyphenolic in composition and are located primarily in the pericarp and testa. White grain (*R-yy* or *rryy*) is without pigment. Yellow (*rrY-*), pink (*R-Y-ii*), and red (*R-Y-I-*) are the non-brown pericarp pigments (Quinby and Martin, 1954). The testa can be brown, purple (Swanson, 1928; Quinby and Martin, 1954; Casady, 1975), or colourless (Ayyangar and Krishnaswamy, 1941). Dominant B_1-B_2 genes are the genetic basis of a pigmented testa (tannins) and with a dominant *S* spreader gene (B_1-B_2-S-) the brown pigment spreads into the pericarp (Blakely *et al.*, 1979). Glover, Rooney and Sullins (1979) found the greatest concentration of polyphenols in the testa (B_1-B_2-S-) with smaller amounts in the epidermis (B_1-B_2 SS). Casady (1975) found that a brown vs. purple testa is controlled by a single pair of alleles, with brown dominant. The symbols T_p and t_p were designated to denote brown and purple testae, respectively.

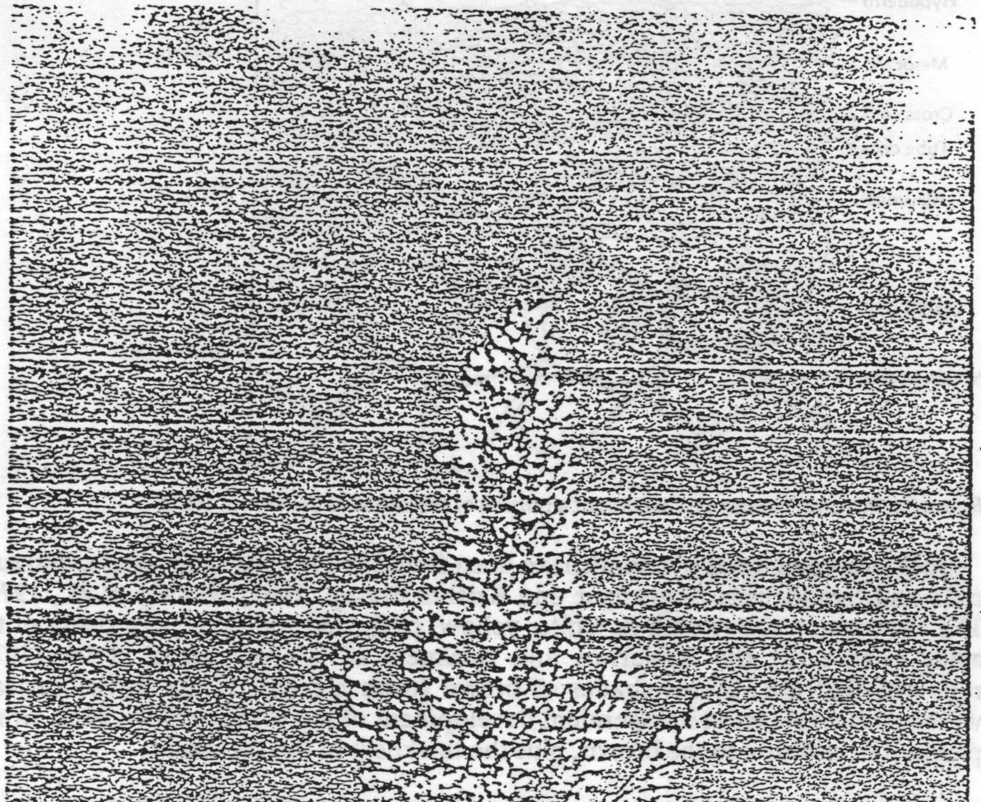


Figure 8.1 Immature sorghum panicle in Ethiopia which has been damaged by the red-billed weaver finch (*Quelea quelea*) (courtesy of W. Erickson, FAO)

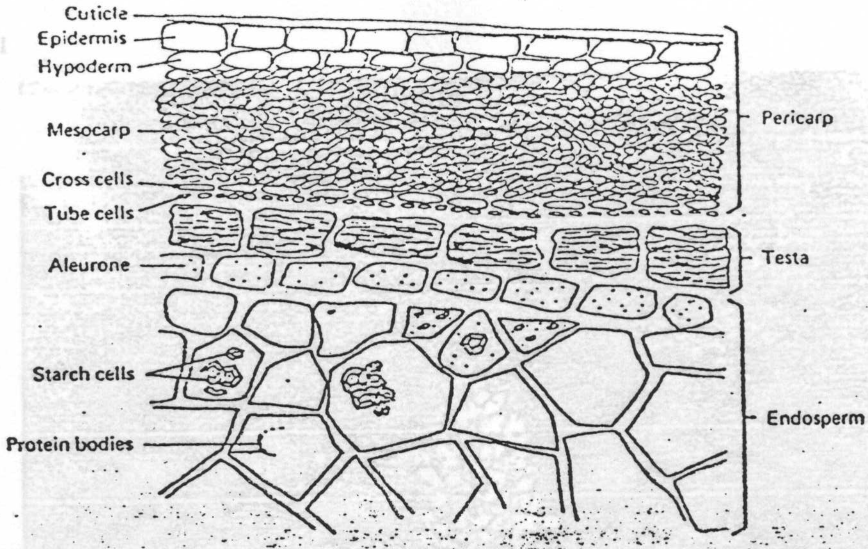


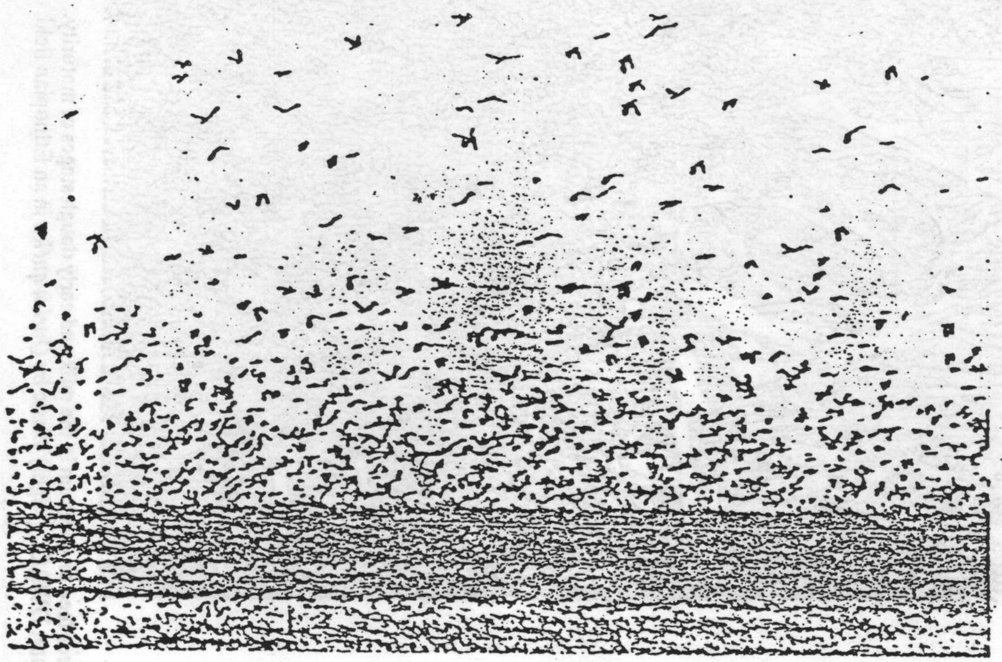
Figure 8.2 Schematic transverse section of a portion of feterita seed (Swanson, 1926)

Both brown and red pigments have been found in the epidermis, cross, and tube cells and hypodermis (Ayyangar and Krishnaswamy, 1941; Blakely *et al.*, 1979). The contrasting colors such as white, yellow, pink, and red occur as a result of the color content of the epidermis and thickness of the mesocarp. York (1976) reported that the various shades of brown (testa present) found in the pericarp were attributable to an independent development of the white, yellow, pink, or red pigment in addition to the brown, plus the thickness of the mesocarp.

Bird problems in sorghum

Unfortunately, sorghum is a highly utilized food for some birds. Every country that grows sorghums has problems with resident granivorous birds that move into the fields and take the grain (*Figure 8.3*). For example, in the Awash River Basin of Ethiopia, sorghum is the main cereal damaged by queleas (Erickson, 1979). It is not as widely grown as farmers would like in this hot subtropical zone of Africa because of this problem, even though it is the cereal most suited to low and erratic rainfall. There are numerous other areas or situations around the world (i.e. in migratory flyways, near lakes or marshes) where sorghums are not grown because of the probability of severe bird damage.

Thus, sorghum is one of the more vulnerable cereal-grain crops to bird damage and crop protection is a difficult challenge. Researchers and operators have learned that it is rare for one method to be a general solution for a vertebrate pest problem. The development of bird-resistant varieties of sorghum is no exception. The soil, climate, altitude, marketing, and cultural practices in the growing area limit the plant characteristics which would be acceptable. In addition, no one cultivar will be effective for all birds. The size of the bird, its feeding habits, and movement patterns may affect the kind of characteristics needed to make a particular cultivar less susceptible to damage. For example, larger birds such as doves (Columbidae) and parakeets (Psittidae) often tend to feed on late dough and mature sorghum (R.L. Bruggers, personal communication; J. Besser, personal communication).



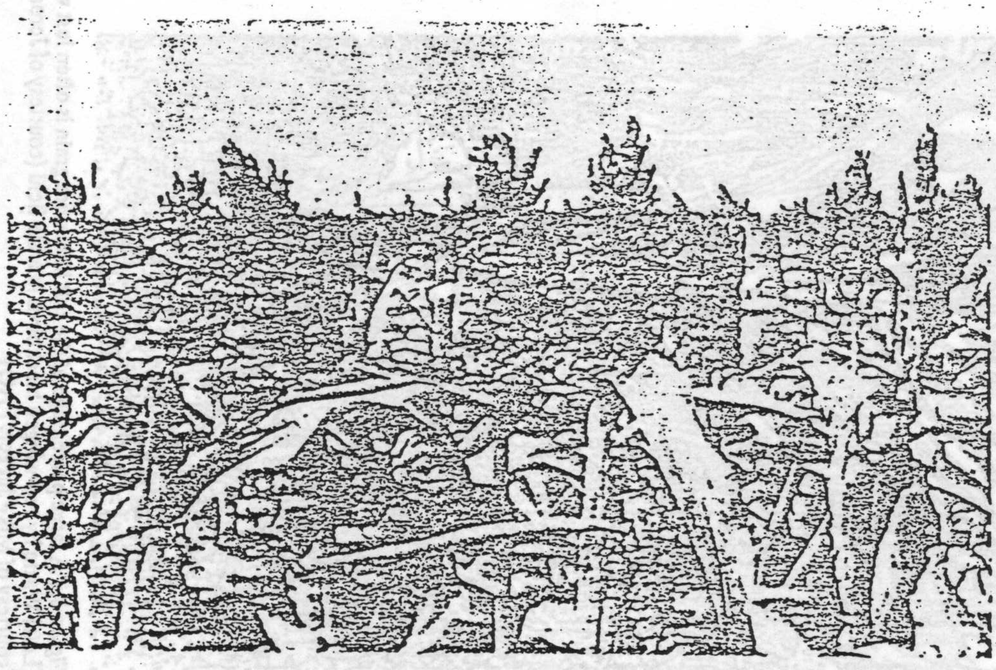


Figure 8.3 (Upper) Red-winged blackbirds descending on a grain sorghum field in Oklahoma, US (courtesy of Richard West, DWRC). (Lower) Subsequent damage to sorghum heads (courtesy of John De Grazio, DWRC)

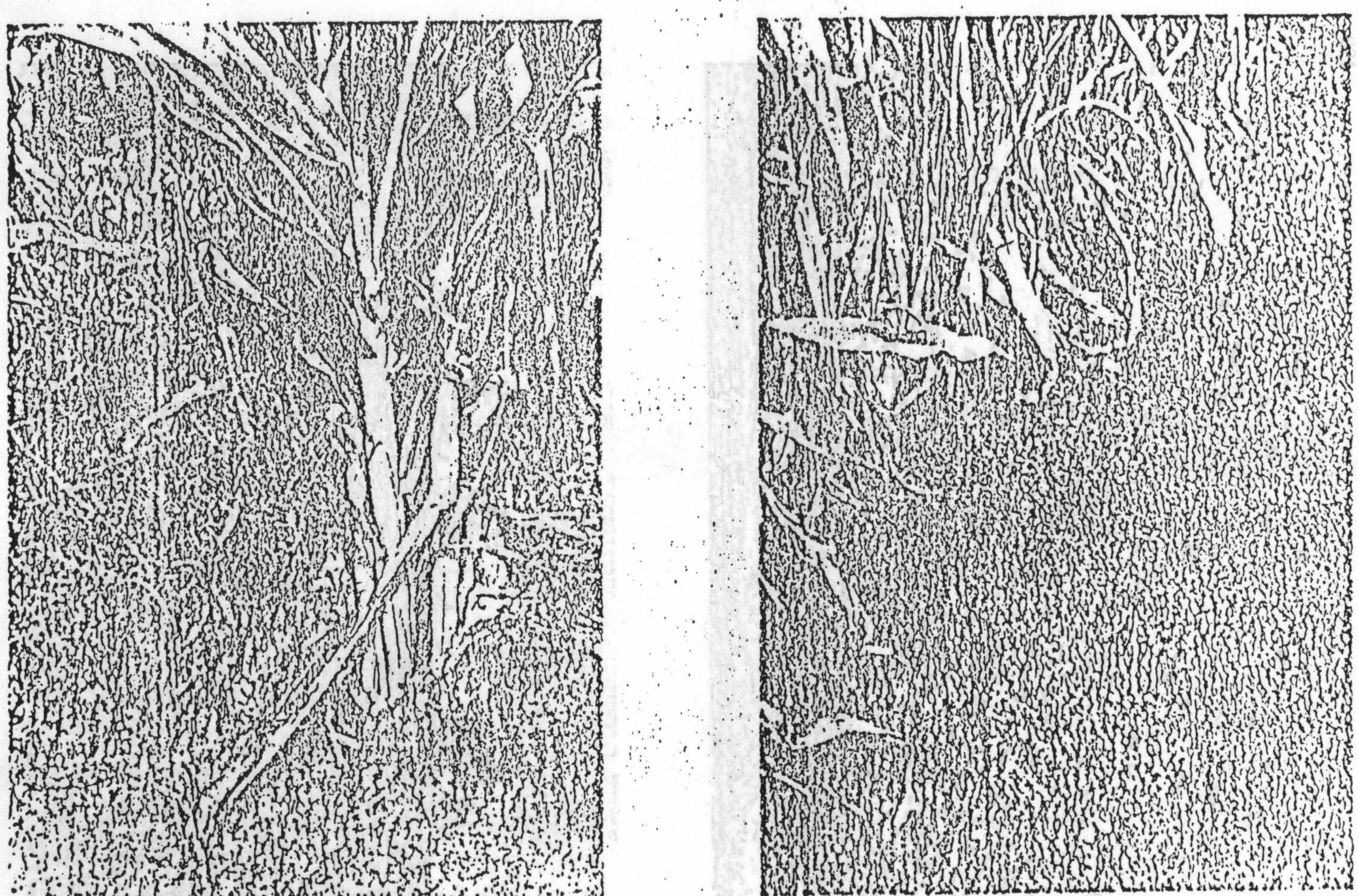


Figure 8.4 A large percentage of the soft immature grain is often lost when birds feed on sorghum in the milk and early dough stages of maturity. (Left) Waste by red-winged blackbirds in a US field (courtesy of Jerome Besser, DWRC). (Right) Waste by *Quelea quelea* in an Ethiopian field (courtesy of Mike Jaeger, FAO)

Small birds such as weaver finches, sparrows, and some species of blackbirds (Icteridae) tend to prefer milk and soft dough stages (J. Besser, personal communication). The crop loss is usually greater when the damage occurs in earlier stages because birds obtain little nutrition per grain damaged and require more grains. There is less biomass per grain for consumption and the amount wasted on the ground is usually much higher. Large waste on the ground and in the head is a common occurrence caused by a range of bird species (*Figure 8.4*). For example, quelea, three-coloured manniken (*Lonchura malacca*), and red-winged blackbirds (*Agelaius phoeniceus*) peck the grain, remove parts and much of the remainder falls to the ground (Doggett, 1970; J. Besser, personal communication; R.W. Bullard, personal observation). The English or house sparrow (*Passer domesticus*) crushes the seed in its beak, thus releasing the milky sap from the seed. Most of the crushed grains remain attached to the seed head in their original position and no further development of the grain occurs (Tipton *et al.*, 1970). A typical pattern of early panicle damage is illustrated in *Figure 8.1*.

As seen in *Table 8.1*, the bird conflict is similar world wide wherever sorghum and sizable numbers of granivorous birds are found together. The survival of the grain depends primarily on the local abundance of alternate food and the feeding choices of seed-eating birds. Unless birds become sick and conditioned aversion takes place, repellents often fail under high feeding pressure (Rogers, 1978). Therefore, it is improbable that sorghum cultivars can be developed which will totally resist attack when the birds are hungry and have no alternate food. However, Doggett (1957), a pioneer plant breeder for bird-resistant properties, saw the opportunity 'that varieties may be bred which are unattractive to birds, and which are attacked only as a last resort'. Preferences in feeding behaviour can be a powerful tool if applied properly in a planned strategy.

Bird-resistant traits

Several morphological characteristics in plants and seeds have been used successfully under certain conditions to confer protection to sorghums. Some characteristics are specific for small birds, some for large, and others apply to certain migratory patterns or feeding habits. No single one is a panacea, but together they provide a genuine opportunity for the informed farmer who carefully selects the appropriate variety and cultivation practice.

LAX PANICLE

Variation in the size and shape of panicles is large in sorghum (*Figure 8.5*). This is due to differences in the length of the rachis, the number of nodes on the rachis, the length of the seed branches, the angle of insertion of these branches, and the number and distribution of branchlets and spikelets on the side branches. A factor Pa_1 is responsible for long panicle branches; pa_1 produces short panicle branches which, because of the absence of the pulvinus-like appendage at their base, results in branches being adpressed to the central stalk (Ayyangar and Ayyar, 1938). This factor tends to operate in heads that are compact and conical in shape. The collateral effects of this gene are a slightly shortened rachis length and lower number of sessile spikelets. Karper (1931) reported that the number of nodes in the head, length of rachis and numbr of seed branches are three of the quantitative

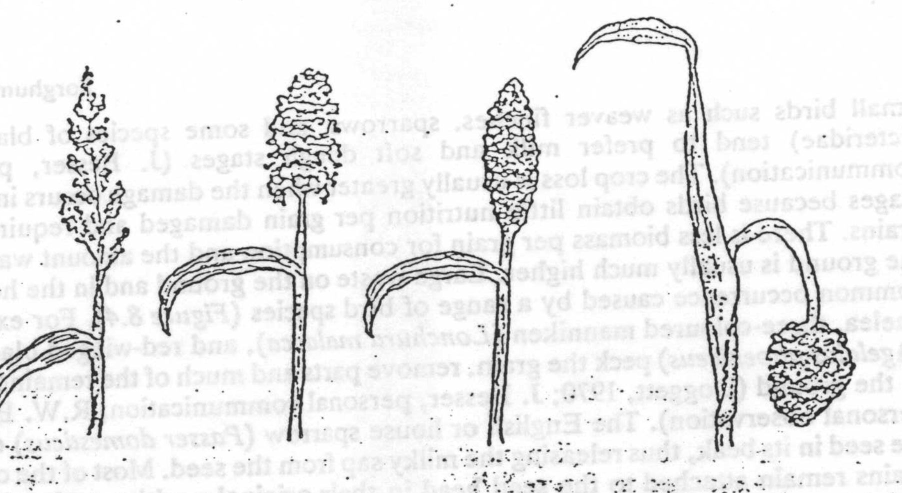


Figure 8.5 Panicle characteristics in sorghum (drawing by Mary Brutin, University of Arkansas)

characters which appear to be inherited in a definite Mendelian manner and are attributable to a single factor.

Another gene, Pa_2, regulates the secondary branches and makes them pulvinate and divergent to the primary branch (Ayyangar and Ponnaiya, 1939). Gene pa_2 results in the absence of the pulvinus in the secondary branches, and consequently the secondary branches are adpressed to the primary branch. This gives the extremely open head (or lax panicle) as found in sudan grass.

Plant breeders have introduced the 'open-headed' or lax cultivars as one means of reducing bird damage. They reasoned that birds could not perch and feed as well on lax-panicle types (Tipton *et al.*, 1970). Bird-control specialists and sorghum breeders generally agree with this concept, but have observed that it operates best for larger birds (i.e. those weighing over 50 g). For example, in a study of several sorghum hybrids in Louisiana, Tipton *et al.* (1970) observed that open-headed varieties were damaged less than compact-head types, but that several inconsistencies were obvious when head-types alone were considered. The effect of bird size was implied because the English sparrow was involved in the vast majority of the damage. Doggett (1957) observed that quelea seem to be able to perch on the most slender panicle branches of sorghum. In studying bird damage problems around the world, Denver Wildlife Research Center (DWRC) biologists have observed that larger birds such as parakeets, doves, crows and blackbirds do not seem to prefer these varieties as much as the smaller weavers, sparrows, and buntings (J. Besser, personal communication; R.L. Bruggers, personal communication; J.W. De Grazio, personal communication). In studies in Botswana, doves appeared to prefer the compact-headed varieties over open-headed ones (Anonymous, 1975). Perumal and Subramanian (1973) made a similar observation at Tamil Nadu, India, where doves and parakeets are known to be a problem (R.L. Bruggers, personal communication).

In the United States, plant breeders have tended to combine the lax panicle traits with the brown testa layer (i.e. shallu hybrids) generally believing that both traits must be present for good resistance (Harris, 1969). The grain-sorghum hybrids that were developed for the Cotton Belt Region of the United States around 1960 produced grain with a brown testa and had open panicles (York and Thurman, 1962; York. 1966; Wanjari and York. 1972; York and Miesner. 1973). Hybrids GA 609, AKS 614. RS 617. and GA 618 had either A lines of 'Combine Kaffir 60' or 'Redlan' with R lines from shallu. The CK 60 and Redlan lines had semi-compact panicles and grain without a testa. The shallu lines had open panicles and grain without a testa. The testa and pericarp genotypes for the A lines were $b_1b_1B_2B_2SS$. The testa and pericarp genotypes for the R lines were $B_1B_1b_2b_2SS$. The genotypes for the hybrids were $B_1b_1B_2b_2SS$. B_1- and B_2- give a coloured testa and S- is the spreader that carries the brown pigment into the pericarp (Wanjari and York, 1972; York, 1976).

These hybrids had a brown testa, a pericarp that contained brown pigment, and an open head which gave excellent resistance to red-winged blackbirds and cowbirds (*Molothrus ater*) in the milk and dough stages of grain development (York, 1966). The grain of these hybrids was reported to contain about 2% condensed tannins (Chang and Fuller, 1964) which apparently overshadowed the open or lax head resistance as the grain of shallu would be destroyed in the same field with the shallu hybrids.

COMPACT PANICLES

Seemingly contradictory, some farmers prefer cultivars with compact panicles for the same purpose—bird-resistant properties. In areas such as the Horn of Africa, Yemens and India, where grain matures under conditions of low humidity, farmers often grow very compact-headed sorghums (B. Gebrekiden, personal communication). Even if birds attack, seeds are removed only from the outer surface because of the difficulty in penetrating into the inner parts of the panicle. Generally using parents within the dura group, plant breeders often combine this trait with others such as recurved heads and large grains (discussed later) into their cultivars. For example, Ethiopian cultivars of this type are cvs Muyra, Abdelot and Degalit.

RECURVED HEADS (PENDANT OR GOOSE-NECKED TYPES)

The panicles of some sorghums frequently become recurved (*Figure 8.5*) after emergence from the sheath. Recurving ('goosenecking' or 'crooknecking') is most prevalent under conditions favouring rapid and abundant growth. Recurving is the result of thick heads being forced out of the side of a too-narrow sheath while the peduncle is flexible and unliquified (Martin, 1932). The more compact types have thicker heads in the heading stage and show a greater tendency to recurve than the slender loose-headed types. Conner and Karper (1917) found that a tightly inrolled upper leaf sheath was associated with a large number of recurved heads.

In the early 1950s plant breeders in Africa recognized goose-necked panicles as having value in reducing grain loss to birds (Doggett, 1957). The curved stem of 'Korgi' which reappears in the progeny of its crosses has been used mostly as the source of this trait. In the progeny with compact heads only the outside seeds are readily taken. Again, the concept involves the matter of bird-feeding convenience.

Some sorghums have a peduncle curved in such a way that the panicle is hidden under the foliage (B. Gebrekiden, personal communication). This trait can be a deterrent to smaller birds that generally prefer to feed in the open.

The use of recurved heads as a means of crop protection has not gained wide acceptance among sorghum breeders over the years since its introduction. Yield levels of the crosses were generally low (Doggett, 1970) and the trait had only limited usefulness in areas of low to moderate bird attack. In years of moderate damage about 50% of the grain was lost (although other varieties were stripped), but in years of severe damage, grain losses were considerably higher.

AWNED LEMMA TYPES

The presence of awns attached to the lemma (*Figure 8.6*) covering the grain is a trait found in both sorghum and millet that makes feeding less convenient for birds. Sorghum may be divided into four classes on the basis of awn development: strong-awned, weak-awned, tip-awned, and awnless. The base of the awn is attached to the middle of the thin, fragile lemma (Sieglinger and Swanson, 1934). In awnless types there is merely a short pointed rib that does not extend to the apex of the lemma. In the tip-awned types the point is extended slightly beyond the apex of the lemma and awns do not extend beyond the glumes. Strong awns extend considerably beyond the glumes, usually exceed a centimetre in length, and in many types are twisted and geniculate. Weak awns extend beyond the glumes less than the strong awns and are somewhat more than half as long. Homozygous weak awns as well as heterozygous weak-awned hybrids of strong-awned × tip-awned can develop.

The awnless character is inherited as a simple dominant to both the strong-awn and tip-awn characters (Vinall and Cron, 1921; Sieglinger and Swanson, 1934). The strong-awn character is inherited as a simple but partial dominant to the tip-awn character (Sieglinger and Swanson, 1934). The inheritance of awn development is explained by the assumption of three pairs of multiple allelomorphic factors, namely, *AA* (awnless), *aa* (strong awn), and $a^t a^t$ (tip awn). In most small-grain crops the presence of an awn is a recessive character (Vinall and Cron, 1921).

Studies have indicated that strong-awned sorghum types are more resistant to bird attack than awnless varieties (Jowett, 1967; Perumal and Subramanian, 1973). A study of awned and awnless varieties of bajara (India pearl millet) gave similar results. In plots mainly visited by house sparrows, highly significant differences in percentage of head damage and grain yield occurred between the different experimental hybrids and also the segregates of the same cross with or without awns (Beri *et al.*, 1969). The effect of feeding convenience or novelty in bird resistance was shown by another of their crosses. This cross, which had grains on heads covered with shed anthers, had both the lowest percentage of head damage and the least loss of grain.

Cultivars such as 'Leoti Red', 'Cuban Guinea', and 'Plantation Pride' have been introduced as having awned lemma which impart bird-resistant properties (Boyd, Green and Chapman, 1961, 1965). Harris (1969) investigated some of these varieties and suggested that the primary cause of their bird resistance was tannin in the grain. Doggett (1957, 1970) reported that, in some of his comparisons involving quelea, the awnless types are eaten first, but after this the awned types are taken readily.

LARGE GLUMES

Large glumes (*Figure 8.6*) which envelop the grain make feeding inconvenient and thereby impart bird-resistant properties to a sorghum cultivar. The length can

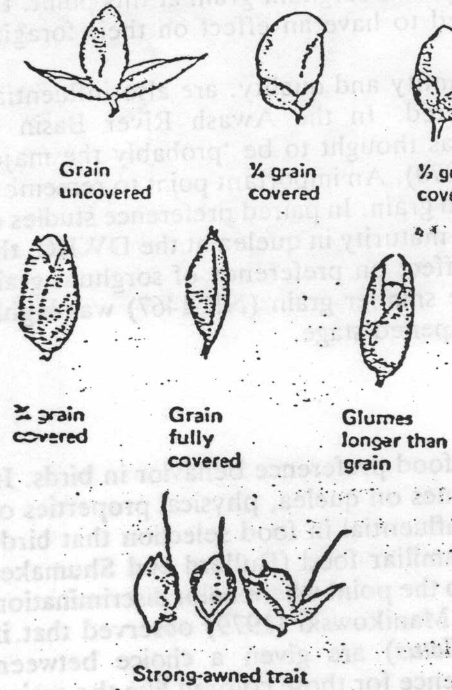


Figure 8.6 Glume and awn characteristics of sessile spikelets in sorghum (drawing by Mary Brutin, University of Arkansas)

range from uncovered grain to glumes longer than the grain. The longer the glume, the narrower it becomes: therefore, grass sorghums have the kernel fully covered, whereas grain sorghums tend to have 25–50% covered by glumes. Ayyangar (1934) reported that the short wide glume was dominant to the long narrow glume.

In their study of panicle characters, Perumal and Subramanian (1973) observed a highly significant difference for glume length. A long-glumed cultivar offered maximum resistance whereas two others with shorter glumes were more bird susceptible. Again, under certain conditions this trait does not provide protection. Doggett (1957, 1970) observed that yellow weavers in East Africa squeeze the glumes, pop out the soft grain, and consume it.

Plant breeders in the United States have also incorporated this trait into brown sorghums. In studies of several bird-resistant strains in Arizona, Voight (1966) observed that the more resistant strains had lax panicles and long tight glumes over dark brown grain. As in the traits discussed above, much of the resistance may have been associated with tannins in the dark brown grain.

SIZE AND HARDNESS OF GRAIN

In situations where small birds attack ripe grain before it can be harvested, large size or hard grains can deter bird attack. Doggett (1957) observed that caged quelea would often spit out hard grains. He also observed that some grains are too large for the beak gape of small birds and they have difficulty consuming them. In most instances, small birds prefer grass seeds when they are available and under these circumstances the size and hardness of sorghum grains would greatly influence food choice. For example, food-habits studies indicate that quelea prefer grass seeds of about 1 mg each, but the proportions of very small (0.3–0.5 mg) or larger

(14–30 mg) seeds increase as the smaller sizes become scarce (Ward, 1965; Crook and Ward, 1968). If the alternate food is ripened sorghum grain at this point, the kernel size and hardness would be expected to have an effect on their foraging behavior.

Factors other than seed size, such as quantity and quality, are also influential. Nutritional requirements must be considered. In the Awash River Basin of Ethiopia, the biomass of available seeds was thought to be 'probably the major factor governing seed selection' (Royama, 1970). An important point to remember is that size and hardness only apply to ripened grain. In paired preference studies of two Northrup King hybrids in four stages of maturity in quelea at the DWRC, the results indicate that kernel size had little effect on preference of sorghum grain during milk or dough stages. However, the smaller grain (NK-1467) was highly preferred over the larger (C-21319) in the ripened stage.

SEED APPEARANCE (COLOR, SHAPE AND SIZE)

Familiarity often has an important effect on food preference behavior in birds. In DWRC studies of 15 sorghum hybrids and lines on quelea, physical properties of grains and pelleted ground grains were so influential in food selection that birds would often not respond initially to an unfamiliar food (Bullard and Shumake, 1979). Lights in the room had to be lowered to the point where color discrimination could not be made. DaCamara-Smeets and Manikowski (1979) observed that if quelea and village weavers (*Ploceus cucullatus*) are given a choice between differently colored grains, they show a preference for those colored like the grains they usually find in their habitat.

Sorghum grain has virtually an infinite number of possible size, color, shape, and texture combinations. It may be red, yellow, buff or brownish yellow, brown, reddish brown, chalky white, pearly white, and white with speckles of red or brown in numerous sizes. It may have a variety of shapes and textures because of factors such as starch deposition in the endosperm. As plant breeders will attest from experiences in their nurseries where several sorghums are grown together, bird-damage patterns are often not explainable on the basis of chemical analyses alone. Differences in appearances of plants and grains, as well as the morphological differences discussed earlier, appear to have an important effect.

CHEMICAL AVOIDANCE—SORGHUM POLYPHENOLS

When bird resistance in sorghum is discussed, most growers, plant breeders and vertebrate pest-control specialists, associate this property with brown sorghums. Brown sorghum grains are known for their tannin-containing testae which, in the immature stages especially, impart astringent palatability qualities that are repellent to birds. Harris (1969), after recognizing various morphological characteristics that impart resistant properties to sorghums he tested, voiced the opinion of most plant breeders: 'I suggest that the primary cause of bird resistance was the presence of tannin in the seed'. We and other scientists from other laboratories have made similar observations: when the feeding pressure of birds is high, the most astringent seed types are the only ones that survive. If feeding pressure is severe, even those sorghums will be ravaged, especially as the grain reaches physiological maturity.

Although the term 'bitter' has often been used to describe a taste property of sorghum polyphenols, most workers attribute bird resistance to the tactile astringent response. Astringency is that mouth-puckering sensation that results from binding of the proteins of the saliva and mucous epithelium, by combination with the tannins (Joslyn and Goldstein, 1964). Our laboratory studies (Bullard *et al.*, 1980) have shown a direct relationship between condensed tannin content of sorghum grains and repellency to quelea and red-winged blackbirds.

Most of the protein-binding properties of sorghums are attributed to procyanidin oligomers (Strumeyer and Malin, 1975; Gupta and Haslam, 1980) located in the grain testa (*Figure 8.2*). The biochemical properties of condensed tannins, such as enzyme inhibition, weathering of grains, tanning of hides, deleterious nutritional effects and astringency, are all related to their ability to bind with proteins (Bullard *et al.*, 1980). The capacity of tannins to form strong cross-links with proteins is broadly related to size, structure and shape of the tannin (Goldstein and Swain, 1963; Quesnel, 1968) and of protein (Hagerman and Butler, 1980) molecules. More specifically, binding depends on the number of separate sites on the tannin molecule which bond with sites on the particular protein. Generally, protein binding increases with size and peaks somewhere between 3 and 10 monomers and then decreases as the molecule becomes insoluble and too large to fit sterically the protein orientation for cross-linking (Goldstein and Swain, 1963; Joslyn and Goldstein, 1964).

The synthesis process in sorghum grains apparently begins as chlorophyll develops in the pericarp (Gupta and Haslam, 1980) with astringent oligomers being present in the early milk stage of development (Bullard, York and Kilburn, 1981). Various investigators have reported an increase in tannin concentrations during seed development that continues (Johari, Mehta and Naik, 1977), plateaus (Tipton *et al.*, 1970), or decreases (Mabbayad and Tipton, 1975; Price, Stromberg and Butler, 1979; Davis and Hoseney, 1979; Rooney *et al.*, 1980; Glennie, 1981; Bullard, York and Kilburn, 1981). The problem is that generally the tannin in brown sorghums has not lost enough protein-binding activity in the mature grain.

Therein lies a dilemma; the benefits to be gained from bird-resistant properties do not come without a price. In most brown sorghums there is enough protein-binding activity remaining in the mature grains to reduce their palatability, digestibility and nutritional quality (Chang and Fuller, 1964; Harris, 1969; McGinty, 1969; Glick and Joslyn, 1970; Schaffert, 1972). All of these negative factors concerning brown sorghums have given them a bad reputation around the world. The result is that high-tannin sorghums have a lower market value and farmers who produce them because of high bird depredation must receive lower prices for their crop or eat an inferior food product.

Fortunately, there appears to be at least a partial solution to this dilemma. There are vast differences among sorghum cultivars in their polyphenolic properties and some hybrids (called group II) apparently become nutritionally acceptable in the mature grain.

Sorghums are classified into three groups (I, II and III) on the basis of their polyphenolic properties. The types not having a testa are classified in group I. The testa-containing sorghums are separated into either group II or III on the basis of differences between vanillin and modified vanillin assays (Price, Van Scoyoc and Butler, 1978). The two assays produce similar values for tannin in group III sorghums whereas the modified vanillin values are much higher than the vanillin for group II varieties. Group II sorghums are currently of interest because, in spite of the presence of tannin, they are nutritionally equivalent to low-tannin varieties (Oswalt, 1975; Hartigan, 1979). Recently, purple-testa sorghums (discussed above) were recognized as belonging to the group II classification (York *et al.*, 1981).

Polyphenolic properties in ripening group II and III cultivars are quite different. In comparisons of polyphenolic changes within eight ripening hybrids by three chemical, three biochemical, and quelea preference assays, group II sorghum values consistently differed over the four ripening stages (Bullard, York and Kilburn, 1981). All hybrids showed an increase in polyphenol activity that peaked in the dough stages and then dropped sharply in the mature grain. The activity of the group IIs tended to peak earlier in grain development and then drop by a much greater extent in the ripened grain. Probable reasons for these differences are too lengthy to discuss here but are detailed by Bullard, York and Kilburn (1981).

The major obstacle to overcome at this point is to develop hybrids that have enough tannin activity in the immature stages to deter attack when bird feeding pressure is moderate to high. In the above studies, tannin activity was consistently lower for group II sorghums in all stages. In co-operative studies between DWRC and Purdue University in Puerto Rico, none of the nine group II sorghums possessed bird resistance compared with that of the four group III sorghums. The three-coloured manniken consumed grain from heads shortly after exposure, regardless of ripening stage. The seven group II sorghums were destroyed at essentially the same rate as for group I sorghums (Butler, 1982). In more recent co-operative studies between DWRC and the University of Arkansas, results look more encouraging. At least three group II hybrids have been found which have tannin activity in the milk and light dough stages comparable to that of the most repellent group III hybrids (i.e. BR-54) and then show the characteristic drop in tannin activity for the mature stage. Final conclusions concerning their efficacy are pending rigorous nutritional tests.

Maize

Maize is cultivated in more widely diverse climates and is distributed over a larger area than any other cereal crop. In 1981 it was grown on more than 134 million hectares which yielded over 451 million metric tonnes or 27% of all cereal grains (FAO, 1981). Maize is a plant with an extraordinary diversity of morphological and biological peculiarities (Kuleshov, 1933). It is produced from latitude 58 degrees N in Canada and the USSR to 40 degrees S in the Southern Hemisphere. It is grown below sea level in the Caspian Plain and above 3700 metres in the Peruvian Andes (Jenkins, 1941). Some maize strains grow less than 1 metre tall, have only eight or nine leaves and require 60–70 days to mature. Other strains grow more than 6 metres tall, bear 42–44 leaves, and need 300–330 days to mature (Kuleshov, 1933). This is remarkable when one realizes that maize is of American origin and that this wide distribution has occurred since the plant was discovered by Columbus. Much of this diversity comes through the widely divergent types developed by the American Indian. As a result of this diversity of germplasms, plant breeders have been able to adapt characteristic cultivars for each climate or region.

The cultivation of maize has brought about many changes around the world. For example, in East Africa it outyielded sorghum in some of the higher altitudes and the more fertile well-watered regions (Doggett *et al.*, 1970). The taste for maize as a food has been readily acquired wherever it has been introduced. Maize grain is used widely around the world as a livestock feed and, as a forage crop, maize is processed as fodder, stover, or silage. Inglett (1970) published an excellent description of food uses for corn and many industrial uses have been found for the starch (Jugenheimer, 1976).

Plant morphological characteristics

The maize plant is monoecious with staminate and pistillate inflorescences being borne on the same plant (Martin and Leonard, 1965). The staminate flowers are borne in the tassel at the top of the stalk, whereas the pistillate flowers are in spikes which terminate lateral branches arising in the axils of the lower leaves (Leonard and Martin, 1963). The mature pistillate inflorescence is the ear.

The pistillate inflorescence is a thickened spike which ordinarily develops into the ear (Hayward, 1938). The lateral branch, a peduncle commonly called a shank, which bears the pistillate inflorescence and later the ear, is a shortened structure similar to the main stem (Weatherwax, 1955). The husks arise from this shank (Mangelsdorf, 1974) with its internodes being so short that the overlapping sheaths of its leaves cover the terminal inflorescence. These leaves show various degrees of modification in structure. Their blades may be well developed, variously reduced, or entirely lacking. The widened sheaths become progressively thinner and softer in texture from the outer husks inward (Weatherwax, 1955).

Maize cultivation and bird problems

Standing maize is subject to bird attack (*Figure 8.7*) from milk stage until harvest (Mitchell and Linehan, 1967; R.A. Dolbeer, P.P. Woronecki and R.A. Stehn, unpublished work). Most birds peck the center of immature kernels and remove the soft contents. The affected ears (*Figure 8.8*) are left with fewer intact kernels (Linehan, 1967). Further damage may result from the ears being opened to the weather and insects (Anonymous, 1952).

The grain is especially vulnerable during the milk and early dough stages when husks on the ears can be readily stripped back by strong-billed birds. Furthermore, maize kernels contain only about 25% of their final biomass at 20 days after silking compared with 70% at 40 days (Woronecki, Stehn and Dolbeer, 1979). Thus, a bird must damage about three times as many kernels at 20 days as at 40 days after silking to obtain the same amount of maize biomass (R.A. Dolbeer, P.P. Woronecki and R.A. Stehn, unpublished work). These factors may override preference *per se* related to stage of kernel development. J.R. Mason, R.A. Dolbeer, R.F. Reidinger and P.P. Woronecki (unpublished work) studied the effects of palatability differences among 10 hybrids on red-winged blackbird preferences and concluded that husk properties were relatively more important than taste preferences.

The majority of damage to ripening maize is caused by larger birds such as blackbirds, parakeets and crows, but some smaller birds are also a problem. For example, in Africa village weavers and chestnut weavers (*Ploceus rubiginosus*) have bills which are heavy and stout enough to tear the maize husks and inflict damage (Bruggers, 1980). Quelea and golden sparrows (*Passer luteus*) are smaller and may feed on maize after the husks are opened by a larger bird species (Erickson, 1979).

Figure 8.7 (Upper) Red-winged blackbirds descending on a maize field in the US (courtesy of John De Grazio, DWRC). (Lower) Subsequent ear damage (courtesy of John De Grazio, DWRC)

Figure 8.8 Maize ear damage caused by village and chestnut weavers in Ethiopia (courtesy of W. Erickson, FAO)

Bird-resistant traits

Several studies have shown that bird damage can vary widely among maize hybrids (Thompson, 1963; Caccamise, 1975; Linehan, 1977; Dolbeer, Woronecki and Stehn, 1982; R.A. Dolbeer, P.P. Woronecki and R.A. Stehn, unpublished work). Thompson (1963) recognized that whereas plant-breeding research had dealt extensively with the major problems of maize culture, bird-resistance properties had not received attention. He examined factors such as high ear placement, mature leaves, erect plants, erect ear shanks and husk and ear characteristics, and found husk extension to have the most promising bird-resistant characteristics. Consequently, four inbred lines and their single crosses were evaluated.

However, husk traits had been examined for insects earlier. Resistance to rice weevil, *Sitophilus oryza* L., and maize earworm, *Heliothis armigera* (Hbn.), were found to be associated with husk length and thickness on the mature ear (Hinds, 1914; Kyle, 1918; Phillips and Barber, 1931; Douglas, 1948; Eden, 1952). Freeman (1945) has used the same germplasm reservoir to develop long husks as a deterrent against both insects. Brewbaker and Kim (1979) associated earworm and fall army worm (*Spodoptera frugiperda*) resistance with husk number since early maturing strains were damaged more severely in their studies. They concluded that insects and other pests of the ear have provided strong selection pressure for this trait. Eden (1952) confirmed that rice weevil injury decreased as the husk extension and layers increased, but observed that the effects of the characters were independent. Cameron and Anderson (1966) found that long husks *per se* are of no value in insect resistance unless they are compressed over the tip (i.e. small silk-channel diameter).

Collins and Kempton (1917) made crosses between cultivars of sweet maize and southern cultivars of field maize. Sugary seeds were selected from the F_1 ears and, in the F_2, plants with well-covered ears were chosen and propagated. The progeny were found to be more resistant to the corn earworm than were the sweet cultivars. The resistance factors were inherited, and both husk thickness and husk extension ($r = -0.71$) were correlated with low damage.

As a result of these developments in insect control and the studies by Thompson (1963), it is commonly recognized that a positive correlation exists between weevil infestation, earworm damage and bird damage to maize hybrids (Ullstrup, 1978). Consequently, studies have been conducted recently at DWRC's Sandusky, Ohio, field station. In examining 21 ear and husk characteristics involving ear length, husk extension, ear circumference, husk weight, silk-channel diameter and ear maturity, Dolbeer, Woronecki and Stehn (1982) showed in a no-choice aviary test that certain ones were correlated with selective bird damage among hybrids. Husk extension beyond the ear tip or kernels had a significant negative correlation ($P<0.01$) with damage. Regression equations using husk extension, husk weight, and ear length as independent variables explained 76–90% of the variation in damage among hybrids. Husk extension beyond the kernels had the highest correlation with damage. Silk-channel diameter was the next highest correlation, followed by ear length. Husk weight, ear circumference and ear maturity were poorly correlated with damage within hybrids. Husk weight and density were negatively correlated with damage but not significantly, suggesting that husk thickness or strength, in combination with extension, influences bird damage.

A relationship exists between maturation time (maturity), leaf number, and husk development (Collins and Kempton, 1917; Kyle, 1918; Kuleshov, 1939; Freeman, 1945; Chase and Nanda. 1967; Allen, McKee and McGahen. 1973). Late-maturity maize has longer and tighter husks (Kyle, 1918). In the Northern States plants are 1.5–2.5 metres tall, have 12–16 leaves, and mature in 90–120 days. In the Corn Belt the varieties are 2.5–3 metres tall, have 18–21 leaves, and mature in 130–150 days. Varieties in the South Atlantic and Gulf States may grow to a height of 3–4 metres, have 23–25 leaves, and require 170–190 days to reach maturity (Jenkins, 1941). Maize workers of the North Central, North Eastern and Southern Improvement Conferences have established 12 maturity classes with representative hybrids in terms of days to maturity (Anonymous, 1959; Jugenheimer, 1976). The maturity class at the Canadian border (earliest) was designated 100 and the class at the Gulf of Mexico (latest) was 1200. The husk length and thickness is greatest in the higher maturity classes (*Figure 8.9*). This classification involved only the dents of the United States and Europe: it did not include the flints and flour types from Mexico, Central America and South America, as described by Kuleshov (1933).

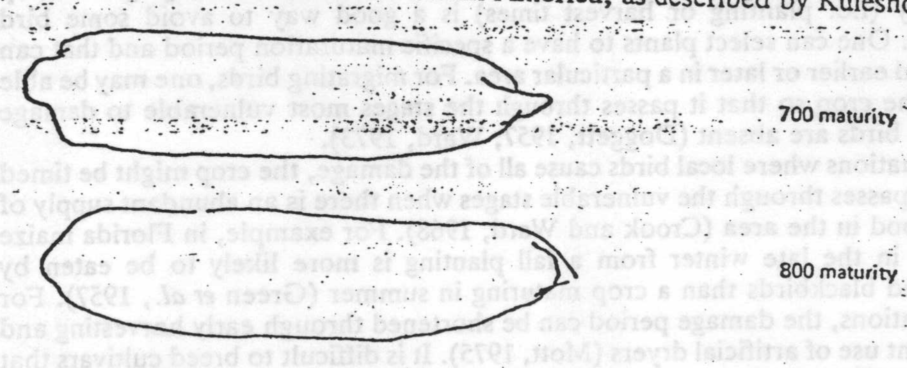


Figure 8.9 Husk length characteristics in maturity classes of maize (drawing by Mary Brutin, University of Arkansas)

The early maturity hybrids have fewer leaves on the main stem (Kuleshov, 1933). In addition to maturity, Allen, McKee and McGahen (1973) found that leaf number was significantly correlated with plant height, silking date and grain moisture at harvest. It can also be affected by growing conditions such as length of the photoperiod, temperature, soil fertility and plant population (Chase and Nanda, 1967; Duncan and Heskoth, 1968).

Recent studies (R.A. Dolbeer, P.P. Woronecki and R.A. Stehn, unpublished work) have shown that damage differences for red-winged blackbirds result more from cultivar preferences than from resistance factors *per se*. In aviary no-choice tests, husk characteristics such as extension were key factors in the observed resistance. However, these characteristics were poor predictors of relative damage in two field tests, indicating that factors such as yield and timing of maturity may be of even more importance in determining damage levels. In other words, for birds that are capable of shedding maize husks, bird damage may be reduced by growing non-preferred hybrids, but only if sufficient alternative food is available for the birds.

General concepts of crop protection

A number of other non-chemical methods involving inheritance characteristics can protect crops from bird damage. For example, if the cultivars are short, planting taller varieties nearby will sometimes divert birds such as English sparrows who, because of fear of predator birds, prefer to feed in the taller cultivars (Manikowski and DaCamera-Smeets, 1979). For late dough and mature sorghum, grain size (discussed earlier) is an important alternative to consider. Changing the crop phenology (i.e. planting or harvest times) is a good way to avoid some bird problems. One can select plants to have a specific maturation period and that can be planted earlier or later in a particular area. For migrating birds, one may be able to time the crop so that it passes through the stages most vulnerable to damage when the birds are absent (Doggett, 1957; Ward, 1973).

For situations where local birds cause all of the damage, the crop might be timed so that it passes through the vulnerable stages when there is an abundant supply of natural food in the area (Crook and Ward, 1968). For example, in Florida maize maturing in the late winter from a fall planting is more likely to be eaten by red-winged blackbirds than a crop maturing in summer (Green *et al.*, 1957). For local situations, the damage period can be shortened through early harvesting and subsequent use of artificial dryers (Mott, 1975). It is difficult to breed cultivars that have a significantly shorter period of grain development. Time differences from flowering to maturity in sorghum are generally insignificant.

Timing can be a very important factor in conjunction with bird-control techniques. Scaring techniques such as gas-operated exploders, .22 calibre rifles, shell crackers, rope firecrackers, recorded bird distress calls, and synthesized sound (i.e. Av-Alarm) can be used to scare birds and disrupt their means of communication (Mott, 1975). In Africa and other regions of the world, children and other members of a farming family traditionally scare birds (*Figure 8.10*) during vulnerable stages of crop maturation (Ruelle and Bruggers, 1982). However, birds adapt to these techniques within a few days and will often feed within a few metres of the scarer or scaring device. If these scaring techniques are timed to begin when the crop first becomes vulnerable and when the first birds appear, then perhaps they can be prevented from establishing a feeding pattern (Mott, 1975). This will help to protect the crop through the most vulnerable stages.

With crop-phenology techniques it is important for the farmer to understand the bird–crop relationship in his area. This has been illustrated with maize. Bridgeland (1979) found over a 2-year period in central New York, that on the average, maize fields incurred 71% of their total damage during a 6-day period starting about 20 days after ears had silked. Under these conditions, having a uniform maturing cultivar co-ordinated with scaring techniques would be very effective. However, in a similar study in Ohio where bird roosts were near, significant damage was

Figure 8.10 Bird-scaring in Ethiopia. Traditional bird control methods of crop protection can often be improved by using crop phenology principles (courtesy of W. Erickson, FAO)

inflicted to maize at any time past about 18 days after silking (R.A. Dolbeer, P.P. Woronecki and R.A. Stehn, unpublished work). In these local flock situations where devices must be maintained for 6 weeks or longer it was believed that costs could easily exceed benefits from damage reduction. Thus, these concepts would apply only if large local concentrations of birds were causing damage.

If it is not possible to alter crop phenology, then crop substitution or diversification may be appropriate. In some situations, the damage could be reduced by the farmers synchronizing their crops so that damage is spread over a larger area (Feare, 1974). In some areas of Africa, wide planting dates, staggered planting, or intercropping are used by traditional farmers to reduce losses to birds (Ruelle and Bruggers, 1982). Sometimes several fields in the same stage will attract large numbers of birds. Ward (1965) observed that quelea are more numerous where food is most abundant. Altering cropping patterns in areas close to roosts (Wiens and Dyer, 1975) is sometimes useful. For example, when there is a choice between sorghum and maize, the latter should be planted because it is less vulnerable to bird attack, especially for small species. In other situations, having a diversity of crops may result in less bird damage. For instance, in Ohio red-winged blackbirds gathered in larger flocks in monocultural areas, flew shorter distances to feed, and did significantly greater damage than in nearby areas where crops were more diversified (Dyer and Ward, 1977).

To cope with large populations of birds there may be a need to provide alternate food supplies. Planting lure or decoy crops (such as millet) to divert birds from higher-valued crops can reduce the overall cost of bird damage (Farris, 1975). In addition, planting a more palatable or familiar cultivar nearby (as in a nursery situation) may help to protect important cultivars. Cultivation practices that limit availability of insect and native-seed production may seriously enhance conditions for avian depredation (Wiens and Dyer, 1975). Plowing should be delayed until all of the fields have been harvested so that birds have alternate feeding sites in the stubble.

Economics of crop protection

Many factors should be taken into consideration before choosing bird-resistant varieties as the primary means of crop protection. Relative yield, market price, ease of harvesting and cost of alternate crop protection measures are all important factors. One consideration that often is overlooked is the economic advantage of crop protection. It is important to know the relationship between depredating birds, amounts of energy or money expended, and reduction in depredation losses (Dyer and Ward, 1977). In order to make cost–benefit determinations accurately one must have an understanding of the range of plant–animal factors involved. For example, often what appears to be damage can stimulate compensatory growth. Linehan (1967) and Dyer (1975, 1976) have implied that compensation takes place in bird-damaged maize and Beesley (1978) reported it for sorghum. Woronecki, Ingram and Dolbeer (1976), in a small study on one cultivar, observed that kernel growth can compensate for low levels of damage. They cautioned that any estimation procedure that is based on surface area of ear destroyed tends to overestimate damage when it is at a low level. Thus, maize fields may not need protection when bird damage is at a low level. For example, less than 1% of the US crop is destroyed annually (Stone *et al.*, 1972), meaning that considering compensatory growth, farmers need not be concerned except for those in local situations where damage is severe.

In addition, one should consider anticipated or actual losses in relation to the effectiveness and costs of the recommended damage control programs. Dolbeer (1981) has developed an equation for cost–benefit determination of blackbird damage control for maize fields, the principles of which can be applied to other crops. We have discussed the unfavorable economics of maintaining scaring devices for long periods of time at low loss levels. Often the bird losses in an area are minor when compared with losses from weeds, insects, disease and harvesting. But because bird damage can be heavily concentrated in some areas and a large percentage of the crop lost, these farmers here can hardly question the costs of damage-control measures. For example, maize losses of 5–15% commonly occur to individual fields in high-damage areas (Dolbeer, 1981) and some losses around the world are greater than this (Anonymous, 1952). It is these farmers who must select a crop-protection method from among the various alternatives. There are numerous publications on bird-control chemicals and scaring techniques but this is the first comprehensive review of the subject of breeding for bird resistance in sorghum and maize. It is intended that the principles discussed herein go even beyond the scope of these two crops to others, especially to other cereals and oilseeds.

Acknowledgements

We thank the following DWRC biologists for their technical advance: John W. De Grazio, J.F. Besser, R.L. Bruggers and J.L. Guarino. We especially appreciate review of the manuscript by: M.M. Jaeger of Colorado State University, L.D. Warren, Director of the University of Arkansas Agricultural Experiment Station, Rogatus K.Z. Moemh from the Bird Control Unit of the Ministry of Agriculture, Tanzania, Brahne Gebrekiden, SAFGRAD Coordinator for sorghum and millets of the Organization of African Unity, and R.A. Dolbeer of the DWRC. This research was conducted primarily with funds provided to the US Fish and Wildlife Service by the Agency for International Development under PASA ID/TAB-473-1-67 'Control of Vertebrate Pests'.

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