2018

Feral Goats and Sheep

Steven C. Hess
USGS Pacific Island Ecosystems Research Center

Dirk H. Van Vuren
University of California, Davis

Gary W. Witmer
USDA-APHIS-Wildlife Services, gary.w.witmer@usda.gov

U.S. Department of Agriculture
Animal and Plant Health Inspection Service
Wildlife Services

U.S. Government Publication

Hess, S.C., D.H. Van Vuren, and G.W. Witmer. 2018. Feral goats and sheep. pgs. 289-309. In: W.C. Pitt, J.C. Beasley, and G.W Witmer, editors. Ecology and Management of terrestrial vertebrate invasive species in the United States. CRC Press, Boca Raton, FL. 403 pp.

Steven C. Hess, USGS Pacific Island Ecosystems Research Center
Dirk H. Van Vuren, University of California-Davis
Gary W. Witmer, USDA APHIS NWRC, Fort Collins, Colorado

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Steven C. Hess, Dirk H. Van Vuren,
and Gary W. Witmer

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ORIGIN, ANCESTRY, AND DOMESTICATION

Sheep and goats are among the earliest animals domesticated by mankind (Zeder 2009). Both goats and sheep may have made better candidates for domestication than other animals like deer because they follow a single dominant leader, the herdsman (Geist 1971). They now have a nearly ubiquitous worldwide distribution, and they are among the most abundant of all commensal animals. However, they have also become some of the most widespread invasive feral mammals, particularly on the 100 or more islands throughout the world where they have been introduced, causing severe damage to island ecosystems, in some cases for hundreds of years (Rudge 1984; Chynoweth 2013). Problems caused by feral goats and sheep are a subset of the larger problem of domestic livestock and natural systems. Feral goats are perhaps more widespread than feral sheep because goats have not been as highly modified by the process of domestication (Francis 2015).

The Bezoar ibex (*Capra aegagrus*) is the most likely ancestor of domestic goats (*C. hircus*) from both genetic and paleontological evidence (Pidancier et al. 2006). The domestication process started at least 10,000 years ago in highlands of western Iran, beginning with the selective harvesting of subadult males and the transition from hunting to herding of the species (Zeder and Hesse 2000). Multiple independent domestication events may have occurred or domestication may have incorporated multiple ancestral lineages (Pidancier et al. 2006). Traits selected during domestication include behavior, dairy, meat, skins, pelage color, mohair, cashmere, horns, pathogen resistance, and even intestines for catgut. Selection for reduced body size may have been related to the ability to better survive in hot and arid environments (Zeder 2009). A profound reduction in horn size occurred after humans began

to control breeding, particularly in males, possibly associated with the absence of selective pressures for large horns used in mate competition (Zeder 2009).

The West Asiatic mouflon (*Ovis orientalis*) is generally recognized as the wild ancestor of domestic sheep (*O. aries*; Zohary et al. 1998). Herd demographics may have been manipulated to maximize harvests in northeastern Iraq and southeastern Turkey as early as 12,000 years ago (Zeder 2009). Further domestication involved breeding for high yields of wool, meat, and milk, and for docility (Ryder 1983). Moreover, the nature of the fleece changed subsequent to domestication; mouflon fleece was an annually molted brown coat consisting of wooly underfur covered by guard hairs, whereas domestic sheep fleece consists only of white wooly underfur that is not molted and grows continuously (Ryder 1987). Further, domestication may have conferred resistance to common parasites and diseases of wild sheep through selective breeding. Lungworm (*Muellerius* spp.) infections typically do not produce clinical signs in domestic sheep (Pugh 2002) but may be more pathogenic in non-adapted hosts such as bighorn sheep (*O. canadensis*; Demartini and Davies 1977; Pybus and Shave 1984) and possibly mouflon (Panayotova-Pencheva and Alexandrov 2010; Powers et al. 2014).

FORAGE AND WATER NEEDS

Domestic sheep are generally considered grazers, but feral sheep are forage generalists, consuming a wide variety of grasses, forbs, and shrubs according to availability (Van Vuren and Coblentz 1987; Wood et al. 1987). Goats are often regarded as browsers; however, preference for grazing or browsing is determined primarily by environmental conditions, such as seasonal and geographic variation of forage, and thus goats may be considered mixed feeding opportunists (Lu 1988). Goats primarily derive water directly from plant foods in many environments (Robbins 1994), but have also been observed drinking salt water (Gould Burke 1988). While domestic goats have a minimum water requirement of 1.0%–1.5% body weight per day, selective pressures may enable feral goats to survive in environments with even less available water (Dunson 1974). This ability to survive in the absence of permanent water sources enables feral goats to persist in remarkably arid environments (Figure 14.1).

LIBERATION AND BECOMING FERAL

Feral sheep have become established at only a few locations in the United States, nearly all of them islands. The discovery of the Hawaiian Islands by Europeans, like many other islands of the Pacific, marked the beginning of introductions of many animals for labor, milk, and meat. Notably among these were domestic goats and sheep to establish strategic resupply outposts for ships on Cook's voyage in 1778–1779 and on Vancouver's voyages in 1793 and 1794 (Tomich 1986). These livestock proliferated without any predators or competitors and quickly became feral. Sheep were reported at the summit of Mauna Kea, the highest peak in the Pacific, only 32 years after their introduction to Hawaii (Ellis 1917). Later introductions to the Hawaiian Islands included European mouflon (*Ovis musimon*) from the Mediterranean Islands, which are small wild sheep closely related to the early

FIGURE 14.1 Feral goats were able to persist in Hawaii Volcanoes National Park for more than a century and a half despite the complete absence of surface water, primarily deriving needed water from plants. (Photo courtesy of Jack Jeffrey Photography.)

ancestors of domestic sheep. Mouflon were first introduced to the island of Lānaʻi in 1954 for sport hunting opportunities. They were then intentionally hybridized with feral sheep and released between 1962 and 1966 on Mauna Kea, Hawaii Island (Giffin 1982; Tomich 1986; Scowcroft and Conrad 1992). A third mouflon population was founded between 1968 and 1974 at the Kahuku Ranch on Mauna Loa, which began to merge with the Mauna Kea population by the end of the twentieth century (Hess et al. 2006; Ikagawa 2014).

Domestic sheep also were introduced to Shackleford Banks, a barrier island off the coast of North Carolina, as early as the late 1700s (Wood et al. 1987), presumably as part of a ranching operation. The sheep were considered semiferal by the 1940s (Engels 1952) and feral by the late 1970s (Wood et al. 1987). Similarly, domestic sheep were introduced to Santa Cruz Island, California, during the 1850s for ranching; the breed was probably Spanish merino (Van Vuren and Bakker 2009). Sheep on Santa Cruz Island were actively ranched during the late 1800s, including the importation of Leicester and Rambouillet rams, presumably to improve breed quality. However, ranching activities declined by the early 1900s, and the sheep became increasingly feral; by the 1930s, they were completely feral. Domesticated livestock that become feral are released from artificial selection imposed by animal husbandry and might be exposed to environmental pressures to which their domesticated traits are ill-suited. For sheep, ever-growing wool that is no longer shorn can

cause thermal stress in warm environments; further, unmolted tail wool fouled with feces can increase the risk of fly strike disease. Feral sheep also often face increased intraspecific competition, which might favor a smaller body size than that preferred by sheep breeders. Hence, sheep that have become feral often exhibit traits such as a reduced body size; spontaneous shedding of their wool, especially on the tail; and a reversion to a pigmented fleece (Van Vuren and Bakker 2009). Some of these traits might have commercial, scientific, or aesthetic value (Van Vuren and Hedrick 1989); for instance, Santa Cruz Island sheep are considered a unique heritage breed by the Livestock Conservancy. Although the environmental tolerance of feral sheep has not been determined, they have persisted for long periods at altitudes ranging from sea level to 2900 m, and at latitudes ranging from the equatorial tropics to the subarctic on the Island of St. Kilda (57°N).

Early introductions and long periods of isolation on islands have caused some feral goat populations to experience substantial genetic drift, producing unique recombinations of breeds. Feral goats present on San Clemente Island and Santa Catalina Island, California, are thought to have descended from those brought by the Spanish in the seventeenth century or the English in the eighteenth century (Coblentz 1978); goats had been brought to San Clemente from Santa Catalina Island in 1875. Original breeds included La Blanca Celtiboras, La Castellana Extremenas, and common dairy and meat goats of Spain, the Malagueñas and Murcianas (Dohner 2001). San Clemente Island domestic goats derived from feral populations have been recognized as a unique heritage breed by the Livestock Conservancy. Goats also were introduced in 1592 to the small, dry, Caribbean island of Mona, between Hispaniola and Puerto Rico, by Spanish explorers and were reportedly abundant enough to sustain hunting by 1632. They were hunted continuously during part of the nineteenth century to feed guano miners, but hunting was curtailed in the 1970s to allow populations to rebound. Goats also have been introduced to other parts of the Puerto Rican archipelago and the U.S. Virgin Islands, but were removed from Buck Island by the late 1940s to allow for more natural ecological conditions. Goats have been introduced widely throughout the Hawaiian Islands, have repeatedly escaped captivity and become feral, and are able to persist in some of the most arid environments with minimal vegetation (Chynoweth et al. 2013). Goats were introduced to Guam, now a territory of the United States, during the Spanish colonization and had become feral by the early 1700s, but numbers were decimated by 1801 because of overhunting. A small population persists today on cliffs on the northern portion of the island (Conry 1988). Feral goats altered native forests for more than a century on Sarigan and Anatahan in the Commonwealth of the Northern Mariana Islands, U.S. possessions in the western Pacific, but were eradicated from Sarigan in 1998 and from Anatahan in 2005 (Kessler 2011). Goats had also been introduced to the remote, small Pacific island of Jarvis at an unknown time but were extirpated by 1935 (Hess and Jacobi 2011).

ECOLOGICAL EFFECTS

Impacts of feral goats and sheep on islands are exacerbated by the fact that islands seldom support native large mammals, especially herbivores and carnivores. Hence, plants that evolved on islands may lack, or may have lost, defenses against herbivory,

rendering them especially vulnerable to introduced herbivores (Coblentz 1978; Bowen and Van Vuren 1997). Further, these herbivores typically enjoyed a predator-free environment and little competition from other large vertebrate herbivores, potentially explaining why sheep and feral goat populations on islands have reached extraordinarily high densities (Bowen and Van Vuren 1999; Burness et al. 2001).

The introduction of sheep and goats to islands has generally resulted in the degradation of native vegetation, particularly endemic species. Feral sheep on Santa Cruz Island ate most vegetation within reach, and the result in some areas was a grassland of greatly reduced cover and height of herbaceous species and a fourfold increase in the extent of bare ground (Van Vuren and Coblentz 1987). In woody communities, consumption of shrubs and trees by feral sheep altered the growth form of larger plants and prevented shrub regeneration by removal of all seedlings (Hobbs 1980; Van Vuren and Coblentz 1987). On the Island of Hawaii, browsing by feral sheep prevented regeneration of endemic vegetation, including māmane seedlings (*Sophora chrysophylla*; Scowcroft and Giffin 1983), while bark-stripping by sheep caused direct mortality of mature māmane trees (Figure 14.2; Scowcroft and Sakai 1983). On the Puerto Rican island of Mona, 12 of 86 plant species consumed by goats were under protection status and four of the most commonly consumed species needed special conservation attention (Meléndez-Ackerman et al. 2008). Goats were also believed to compete with an endemic iguana species for herbaceous forage

FIGURE 14.2 Feral sheep in Hawaii have been responsible for the degradation of forest environments and the endangerment of native bird species. (Photo courtesy of Jack Jeffrey Photography.)

on Mona, and to be detrimental to plant populations on other Puerto Rican islands (Wiedwandt 1977).

While consumption or trampling results in direct damage and loss of plants, feral goats and sheep also cause numerous indirect effects, including soil erosion (Coblentz 1978). After protective ground layers of vegetation have been removed, bare substrates become exposed to physical disturbance from hoof action, precipitation, and wind, all of which may further exacerbate erosion. Hoof action has been implicated in the large-scale ecosystem process of soil compaction, which makes soils hydrophobic (i.e., reduces soil water penetration), causing greater soil runoff. For example, hoof action by feral sheep on Santa Cruz Island resulted in extensive disturbance to soil surface particles (Van Vuren 1982), a significant increase in soil compaction (Brumbaugh 1980), and the denudation of over 7% of the soil surface due to trail formation (Van Vuren and Coblentz 1987). The combination of vegetation removal and hoof action by feral sheep has resulted in a dramatic increase in erosion, including gully formation and landslides (Brumbaugh 1980; Pinter and Vestal 2005). Further, stream flows were altered; water infiltration into the soil decreased and surface runoff increased, resulting in higher stream flows early in the season (Van Vuren et al. 2001). On Kahoʻolawe Island of the Hawaiian chain, as much as 2.4 m of soil has been lost in some areas and an additional 1.9 million tons were lost annually as a result of goat and sheep impacts (Kramer 1971; Kahoʻolawe Island Conveyance Commission 1993; Loague et al. 1996), and Yocom (1967) estimated that approximately 1.9 m of soil was lost as a result of goat activity in some areas of Haleakalā Crater on Maui. Damage to nearshore marine environments from silt has been attributed to erosion caused by goats and sheep as well (Kahoʻolawe Island Conveyance Commission 1993; Stender et al. 2014).

Defoliation and trampling by feral sheep can alter vegetation structure as well, including depletion of the herbaceous layer and removal of all shrub leaves within reach (Van Vuren and Coblentz 1987). Further, because sheep can completely defoliate low-stature shrubs and prevent regeneration in tall-stature shrubs and trees, wholesale conversion of plant communities has occurred in areas where feral sheep are present. On the Island of Hawaii, feral sheep caused the destruction of the māmane forest and reduced native cover (Warner 1960; Scowcroft 1983). On Santa Cruz Island, sheep caused a major reduction in the extent and density of woody vegetation (Cohen et al. 2009), including a drastic reduction in the coastal sage scrub community (Brumbaugh 1980), which consists of low-growing shrubs palatable to sheep. Moreover, feral sheep grazing promotes invasive grasses over native grasses (Van Vuren and Bowen 2012).

Community-level interactions among plants and herbivores can aggravate changes in ecosystem processes, leading to positive feedback cycles that reinforce community change. Herbivory can promote productivity of grasses and accelerate ecosystem processes by enhancing the light regime of grasses and by the deposition of feces (Frank et al. 1998, 2002). The proliferation of alien grasses further contributes to changes in nutrient cycling, hydrology, fire regimes, and gradual conversion from forest to savanna and grassland environments (D'Antonio and Vitousek 1992). Grasses throughout the tropics are instrumental in determining fire frequency and severity, often resulting in a positive feedback loop known as the "grass/fire cycle" whereby forest and woodland

become gradually replaced by grassland (D'Antonio and Vitousek 1992). While feral goats and sheep may reduce fine fuel loads that lead to fires, they also commit ecosystems to directional change from forests to savannas and grasslands.

Alteration of the composition and structure of plant communities by feral goats and sheep has implications for associated species that depend on those communities for habitat, especially birds. For example, degradation of the māmane forest on the Island of Hawaii caused the rarity of the palila (*Loxioides bailleui*), an endangered bird that relies almost entirely on māmane trees for food (Banko et al. 2002; Hess et al. 2014). Even a moderate alteration of shrub community structure by feral sheep on Santa Cruz Island, involving removal of all lower leaves of shrubs and depletion of the herbaceous layer, resulted in a sharp reduction in numbers, species richness, and diversity of birds, especially ground-nesting birds and insular endemic species (Van Vuren and Coblentz 1987).

MANAGEMENT AND ERADICATION

The severe ecological degradation caused by feral goats and sheep was slow to be realized and addressed. Some early control programs emphasized population suppression to reduce damage, but this approach was problematic. Population suppression must be continued indefinitely, at considerable cost, and even a brief cessation of management activities could lead to population recovery. Further, once an island ecosystem has been degraded, even low densities of goats or sheep might be sufficient to continue further degradation (Van Vuren 1992). The concept of eradicating entire populations of destructive nonnative mammals came about as a solution to primarily agricultural or economic problems, but had not been applied to ecological problems until the mid-twentieth century. By the late twentieth century, many biologists came to a consensus on the negative impacts of feral goats and sheep on islands (Coblentz 1978) and began developing techniques to remove entire island populations (Daly 1989). There are now many examples of successful management efforts resulting in the dramatic recovery of native biota.

The first eradication of goats from an island occurred on the Hawaiian island of Niʻihau. Goats had been established in the early 1900s, and eradication by contract hunting became warranted by 1911 (Kramer 1971). Lānaʻi was also affected by excessive browsing, and by 1900, large areas were deforested by sheep and goats introduced in the mid-1800s (Hobdy 1993). Charles Gay began to eradicate goats and sheep from his Lānaʻi ranch in 1902 and fenced the summit cloud forest to protect the watershed. The ornithologist George C. Munro came to run Gay's ranch in 1911 and spent much of his first decade there shooting sheep and goats. Feral goats were eventually eradicated from Lānaʻi by 1981, and feral sheep were eradicated later in the 1980s, although European mouflon remain numerous on Lānaʻi (Hess and Jacobi 2011).

Goats had been periodically culled from Hawaii Volcanoes National Park (HAVO) on Hawaii Island since 1927 but with no lasting effect due to reinvasion of animals from surrounding areas (Figure 14.3; Baker and Reeser 1972). Managers of national parks in Hawaii took further actions on the recommendation of the Leopold et al. (1963) report on wildlife management in national parks, which stated: "A visitor

FIGURE 14.3 Feral goats remained abundant in HAVO for more than a century and a half despite periodic attempts since 1927 to reduce their populations. (NPS photo courtesy of Don Reeser and Bryan Harry.)

who climbs a mountain in Hawaii ought to see mamane trees and silverswords, not goats." Eradication of goats from 554 km^2 of HAVO took place from 1968 to 1984 (Tomich 1986), demonstrating the technical feasibility of eradicating ungulates from large areas of multitenure islands and providing specific techniques necessary to accomplish the task. For example, the Judas goat method was devised in HAVO to find remaining animals that eluded eradication efforts by exploiting the gregarious behavior of female ungulates (Taylor and Katahira 1988). Radio-collared females that found and associated with surviving remnant groups could easily be rediscovered; those groups could then be captured or shot, but the Judas female would be spared to repeatedly seek out other animals. The method has been repeatedly applied to many other eradication programs (e.g., Keegan et al. 1994; Campbell and Donlan 2005; Cruz et al. 2009). Following eradication, reinvasion was mitigated by dividing areas into fenced units of manageable size, a difficult logistical process at the time for large areas and for dense tropical forests on volcanic substrates (Figure 14.4). After a century and a half of degradation, a previously undescribed endemic plant species, ʻāwikiwiki or *Canavalia kauensis* (now *C. hawaiiensis*), was found growing on the dry lowlands of Kukalauʻula where goats had been excluded from small areas prior to large-scale eradication (Figure 14.5; St. John 1972).

Haleakalā National Park on Maui also had an intense but sporadic goat control program since early in the twentieth century, with more than 10,000 person-days of active hunting over a four-decade period (Kjargaard 1984). Goats were eliminated

FIGURE 14.4 Fences were constructed to divide HAVO into units of manageable size and prevent reinvasion of feral goats from surrounding areas during eradication efforts. (NPS photo courtesy of Don Reeser and Bryan Harry.)

from the 45-km^2 Kīpahulu District by the late 1980s after 51 km of fence was constructed between 1983 and 1987 (Stone and Holt 1990). Eradication of goats from the entire 137-km^2 park was completed in 1989 using Judas goat techniques developed in HAVO (L. Loope, pers. comm.). Goats and sheep were also eradicated from nearby Kaho'olawe Island in 1990 by ground shooting, helicopter hunting, and the use of Judas animals (Kaho′olawe Island Conveyance Commission 1993).

Santa Cruz Island supported at least 21,000 feral sheep in 1980 (Van Vuren and Coblentz 1989). Sheep removal was complicated by the large size of the island (249 km^2), rugged terrain with few roads, and differing land ownership; the western 90% was owned by The Nature Conservancy (TNC) and the eastern 10% was privately owned. TNC chose a combination of fencing and shooting from the ground to remove sheep from their portion of the island. Trapping and shipping of live animals to the U.S. mainland were considered but not adopted because of logistical limitations posed by island ruggedness and lack of access, and because a market for live feral sheep could not be found (Schuyler 1993). TNC first built over 160 km of fencing that partitioned the island into 23 segments, each between 137 and 4517 ha in size, including a fence that separated TNC lands from the eastern end of the island (Schuyler 1993). Shooting from the ground required an extended time, but fencing the island allowed segments to be cleared sequentially without the risk of recolonization from neighboring areas, and also limited density-dependent recovery by sheep to the segment being hunted. Hunting began in late 1981 (Schuyler 1993); by December 1986 more than 31,000 sheep had been shot, and by January 1988 only 40 sheep remained. By June 1988, a total of 37,000 sheep had been shot

FIGURE 14.5 Feral goats had been excluded from small areas prior to large-scale eradication, which resulted in the emergence of a previously undescribed endemic plant species, ‘āwikiwiki or *Canavalia kauensis* (now *C. hawaiiensis*) after a century and a half of degradation. (NPS photo courtesy of Don Reeser and Bryan Harry.)

and five sheep remained, which were subsequently found and shot (Schuyler 1993). Feral sheep remained on the eastern 10% of the island, which was acquired by the National Park Service (NPS) in 1997. Because this portion of the island had gentler topography, and given concerns over the opposition to lethal removal by animal rights organizations, NPS employed live-capture and removal (Faulkner and Kessler 2011). Beginning May 1997, sheep were captured by baiting or herding into corrals; as numbers declined, remnant sheep were pursued individually and captured. In December 1999, the last sheep had been captured and removed, totaling 9200 individuals (Faulkner and Kessler 2011).

Feral goats became established on Santa Catalina Island by the mid-1800s and reached numbers as high as 30,000 by the 1930s (Schuyler et al. 2002). Despite ongoing control efforts by sport hunters and island managers, 8000 goats remained by 1990. Control intensified from 1990 to 1994, when about 95% of remaining goats were shot from the ground and from the air, but funding ran out and control was suspended. Shooting resumed in 1996, with an additional 600 goats removed. Concerns for animal welfare caused a shift to removal by live capture in 1999 (121 goats captured), followed by a return to hunting a year later (66 goats shot). Renewed concerns for animal welfare resulted in an attempt to live capture the last 25–30 goats

(Schuyler et al. 2002). With the aid of the Judas goat method, the last goats were removed by live capture in 2002 (Campbell and Donlan 2005).

After the 468-km^2 Kahuku Ranch was acquired by HAVO, a directed volunteer program was initiated in 2004 to reduce the abundance of European mouflon and prevent further degradation to native biota (Stephens et al. 2008). Staff hunting, shooting from helicopters, and the use of forward-looking infrared radar (FLIR) were successful, and eradication became the goal. More than 6600 mouflon were removed, and the number observed during aerial surveys dropped from 1785 in 2004 to 378 in 2014. No mouflon were observed in two intensively managed subunits during the last survey, although small numbers have been periodically detected with game cameras and dispatched since that time (Judge et al. 2016). The Kahuku Unit may soon become the largest area from which mouflon will have been eradicated (Figure 14.6).

One of the few continental areas in the United States where free-ranging sheep have become problematic is Amistad National Recreation Area, Texas (Slade 2005). A single breeding pair of European mouflon entered the park from a neighboring ranch during the mid-1970s and proliferated over the next 20 years, reaching over 400 individuals by the mid-1990s. Population growth then further accelerated, reaching more than 2000 individuals by 2005, competing for forage with native white-tail deer (*Odocoileus virginianus*), and damaging fragile soils. More than 1300 sheep were removed using net guns from helicopters, which reversed ecological degradation

FIGURE 14.6 European mouflon sheep were introduced to the Kahuku Ranch beginning in 1968; Kahuku Ranch was later acquired by HAVO and eradication of mouflon commenced in 2004. (USGS photo.)

(Slade 2005). Other locations in the United States where European mouflon have been introduced and continue to roam freely include: North Haven Island, Maine; Speiden Island, Washington; California; Texas; and New Mexico.

MANAGEMENT FAILURES AND PROTRACTED ERADICATION ATTEMPTS

Many efforts to eradicate feral goats and sheep have not proceeded as anticipated; although intentions have been well justified, challenges to these operations have been sometimes surprising. A well-documented example is on Mauna Kea, where feral sheep have repeatedly reached excessive numbers, devastating the watershed and semiarid subalpine woodland environment. Foresters for the Territory of Hawaii conducted sheep drives starting in 1934 that eliminated tens of thousands of individuals. The Mauna Kea Forest Reserve (MKFR) was fenced in between 1935 and 1937 (Bryan 1937a), and nearly 47,000 sheep were removed in the following 10 years by foresters and Civilian Conservation Corps workers using drives on foot and horseback (Bryan 1937b, 1947). Populations rebounded when sport hunting became a management goal of wildlife biologists after World War II, and by 1960, the dire condition of the Mauna Kea forest was decried but not widely known outside of Hawaii (Warner 1960). Despite this knowledge, hybrid European mouflon x feral sheep were released from 1962 until 1966 to further improve hunting opportunities (Figure 14.7; Giffin 1982). Exclosures, aerial photography, and altered tree size classes all demonstrated the effects of browsing and bark stripping by sheep, goats, and other ungulates on the subalpine vegetation and associated wildlife (Scowcroft 1983; Scowcroft and Giffin 1983; Scowcroft and Sakai 1983). U.S. Federal District court orders of 1979 and 1986 mandated the removal of goats and sheep to protect the endangered palila that feed and raise their nestlings on māmane seed pods. More than 87,000 sheep have been removed from the MKFR over a 75-year period, but sheep have not yet been eradicated (Banko et al. 2014). Patchy recovery of māmane occurred after sheep removals began (Hess et al. 1999); however, habitat loss has been compounded by drought, which has further contributed to the ongoing long-term decline of palila (Banko et al. 2009, 2013). The fence surrounding Mauna Kea has recently been reconstructed to contemporary standards, and sheep removals have accelerated (Hess and Banko 2011). Although the subalpine woodland of Mauna Kea has demonstrated the ability to regenerate after feral sheep and goat populations have been reduced (Scowcroft and Giffin 1983, Reddy et al. 2012), the cumulative degradation to this ecosystem may preclude long-term suitability for dependent native wildlife such as palila.

Another example is on San Clemente Island, where concerted efforts to eradicate the over 20,000 feral goats on the island were initiated in 1972 by the U.S. Navy, the owner of the island, because of the threat that goats posed to several federally listed plants and animals endemic to the island (Keegan et al. 1994). Trapping and shooting removed about 16,000 goats, but many remained (Van Vuren 1992). In the late 1970s, the U.S. Navy decided to shoot the remaining goats from helicopters, but because of a lawsuit by Give Our Animals Time (GOAT), the U.S. Navy was directed to use trapping as a nonlethal means to complete the eradication. Another

FIGURE 14.7 Feral domestic sheep were intentionally hybridized with mouflon and released between 1962 and 1966 on Mauna Kea. Although federal court orders of 1979 and 1986 mandated the removal of all sheep goats from Mauna Kea to protect an endangered bird species, hybrid sheep remain abundant throughout high-elevation areas of the Hawaiian island. (Photo courtesy of Jack Jeffrey Photography.)

3000–4000 goats were removed by trapping, but some goats remained, so shooting was resumed in 1983. However, a series of lawsuits, as well as directives from the Department of Defense, repeatedly interrupted these efforts, and a small remnant population eluded all attempts at removal (Van Vuren 1992). The population was eliminated when the last 263 goats were shot between 1989 and 1991 using the Judas goat technique, totaling 29,000 goats trapped or shot since efforts began in 1972 (Keegan et al. 1994).

ECOSYSTEM RECOVERY AND UNEXPECTED EFFECTS

Removal of feral goats or sheep usually results in a remarkable recovery of native vegetation. On Mauna Kea, exclusion of feral sheep resulted in a rapid increase in regeneration and growth of māmane and other native species (Scowcroft and Giffin 1983); within about 40 years, māmane recovery within exclosures had progressed to the point of potential suitability as habitat for the palila (Reddy et al. 2012). On Santa Cruz Island, feral sheep removal resulted in a nearly two order magnitude increase in native grass biomass (Van Vuren and Bowen 2012); a two- to fourfold increase in density of native shrubs, including the reappearance of low-growing shrubs that had been locally extirpated by sheep grazing (Wehtje 1994; Van Vuren 2012); and the

transition of a degraded grassland into a coastal sage scrub community (Beltran et al. 2014). Recovery of vegetation had cascading effects that included major changes in bird density and species richness (Van Vuren 2013) and a drastic reduction in the occurrence of landslides (Pinter and Vestal 2005).

Managers often expect the restoration of the original community after eradicating a feral herbivore, but undesired or unexpected consequences can result from overlooked ecological linkages (Zavaleta et al. 2001; Morrison 2011). The removal of feral goats and sheep can sometimes result in the proliferation of invasive plants that had been suppressed by these generalist herbivores (Zavaleta et al. 2001). In a meta-analysis of vegetation response after goat eradication from islands worldwide, species richness as well as the percentage cover, often including exotic plant species, increased despite the presence of rodents and other mammalian herbivores on some islands; percentage cover increased more on tropical islands than in other locations largely due to exotic plants (Schweizer et al. 2016). On Santa Cruz Island, fennel (*Foeniculum vulgare*), an invasive weed that had been suppressed by feral sheep grazing, increased explosively after sheep eradication (Beatty and Licari 1992; Klinger 2007). Fennel crowded out native vegetation in most of the areas in which it grew, and it has proved problematic to control (Dash and Gliessman 1994). Such undesired or unexpected changes can extend beyond simple two-species interactions (Morrison 2011). Sheep removal and associated vegetation regrowth on Santa Cruz Island led to an increase in some bird species, but not all; surprisingly, some birds declined, especially those that prefer open, less-vegetated habitats, including insular endemic taxa of conservation concern (Van Vuren 2013). The solution is to proceed with eradication using a holistic approach to restoration and comprehensive, strategic planning which may also require the control of other invasive species that proliferate after the removal of sheep and goats (Zavaleta et al. 2001; Morrison 2011).

In some cases, an initial rapid spread of introduced species occurred following the removal of feral goats, but stabilized over longer periods of time, ultimately benefiting native biota (Kessler 2002, 2011). In highly modified ecosystems, such as heavily invaded tropical dry forests, removal of goats also facilitated the short-term proliferation of an invasive plant (Kellner et al. 2011). Long-term studies on the effects of ungulate exclusion indicate that animal removal can release invasive pyrogenic grasses from top-down control and adversely affect native plants (Cabin et al. 2000). However, when invasive grasses have been controlled after ungulate removal, an increase in natural recruitment of native woody seedlings into larger size classes has been observed (Thaxton et al. 2010).

OPPORTUNITIES AND CHALLENGES

Technical impediments to eradication from a biological perspective have now largely been overcome, allowing the eradication of goats from islands as large as Santiago Island (585 km^2), Galápagos (Cruz et al. 2009). Judas techniques and variations have proven to be highly effective (Taylor and Katahira 1988); the Mata Hari technique induces sterilized females into permanent estrus to attract males, thereby simultaneously reducing the number of pregnant females (Campbell 2007; Campbell et al.

2007). Other techniques that include combinations of hunting, trapping, snaring, toxicants, and the strategic use of fences have also been highly effective to complete the eradication of feral goats and sheep from islands or from large areas of islands. The greatest remaining impediments are perhaps the attitudes and conflicting values of residents and stakeholders toward the lethal removal of animals, particularly for large, multitenure islands (Cambell and Donlan 2005).

Animal rights groups often play a major role in eradications, a role that planning should anticipate. For example, the U.S. Navy was sued by an animal rights group when trying to eradicate feral goats on San Clemente Island, which resulted in long delays and density-dependent recovery of goat numbers (Van Vuren 1992). Protests by animal rights groups also altered eradication plans for feral goats on Santa Catalina Island, although eradication was eventually achieved (Schuyler et al. 2002).

Hunting interests can play an important role as well. Sheep eradication efforts on Santa Cruz Island were halted by a lawsuit from the California Wildlife Federation, which sought to maintain the hunting opportunities for feral sheep (Schuyler 1993). TNC was prepared for such a lawsuit and submitted an effective response; the lawsuit was quickly dropped (Schuyler 1993). Because the island had been segmented by fences, the delay caused by the lawsuit had little effect on eradication progress. Hunting advocates had also expressed longstanding opposition to the eradication of sheep from Mauna Kea (Juvik and Juvik 1984). A major objection was the waste of food resources, which was addressed by carcass salvaging operations using helicopters; however, salvage operations diverted resources that would have otherwise been applied to removing additional sheep (Tummons 2012). Management agencies have also attempted to recruit public hunters in eradication efforts. Sport hunters contributed to sheep eradication on TNC lands on Santa Cruz Island, killing 5300 sheep (Schuyler 1993). On Mauna Kea, all hunting limits for sheep were dropped and hunters were guided to areas with abundant sheep to expedite removal; however, the sheep population apparently increased despite these incentives (Banko et al. 2014). At the Kahuku Unit of HAVO, guided volunteer hunters removed a disproportionate number of rams, which promoted a strong female bias and high population growth rates in the remaining population (Stephens et al. 2008).

Differential land ownership also may represent an impediment to successful eradication efforts. On Santa Cruz Island, for example, the eastern 10% of the island was privately owned in the 1980s, and the owner had no interest in eradication, so eradication had to proceed in two stages, the western 90% followed by the eastern 10%. Also, TNC was more willing to face sociocultural challenges and chose shooting as their primary tool, whereas NPS (the eventual owner of the eastern 10%) addressed animal welfare concerns by employing live capture and transport to the mainland.

Eradication of entire populations requires complete commitment of resources to this goal. Adequate resources need to be in place prior to commencing operations; goat eradication on Santa Catalina Island was delayed two years because of inadequate funding (Schuyler et al. 2002). While the majority of a population can be removed quickly, eradication efforts become progressively more difficult as densities become reduced. Managers of Hawaii's national parks found that reducing populations by half cost the same amount regardless of initial abundance. Density reduction without eradication can trigger density-dependent responses that rapidly

restore numbers; based on demographic information, Rudge and Smit (1970) estimated that a feral goat population reduced by 80% can recover 90% of original numbers in four years. Further, detecting the last animals can be exceptionally difficult because remaining animals become wary of removal efforts; the result can be a premature declaration of success, termination of the program, and in consequence the "Lazarus effect," the reappearance of animals thought eradicated (Morrison et al. 2007). Careful planning is needed for extended monitoring after the last animal has been detected to verify that eradication has in fact occurred (Morrison et al. 2007).

The future for management of feral goats and sheep will most likely see the eradication of entire populations from increasingly larger, more complex islands and areas with thicker vegetation using more sophisticated techniques and tools (Campbell and Donlan 2005; Hess and Jacobi 2011; Chynoweth et al. 2013). In addition to Judas techniques, next-generation tools including remote sensing imagery, real-time telemetry, and thermal imaging devices such as FLIR may greatly improve the efficiency of locating and removing the last remaining animals that require the greatest effort, as well as posteradication monitoring. The outcomes of future eradication programs will likely result in overwhelmingly positive ecosystem responses, as they have already; however, community and multispecies interactions, other newly introduced invasive species, and climate change may all present new obstacles to recovery.

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