Biology and Impacts of Pacific Island Invasive Species. 9. *Capra hircus*, the Feral Goat (Mammalia: Bovidae)[1]

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Abstract: Domestic goats, *Capra hircus*, were intentionally introduced to numerous oceanic islands beginning in the sixteenth century. The remarkable ability of *C. hircus* to survive in a variety of conditions has enabled this animal to become feral and impact native ecosystems on islands throughout the world. Direct ecological impacts include consumption and trampling of native plants, leading to plant community modification and transformation of ecosystem structure. Although the negative impacts of feral goats are well known and effective management strategies have been developed to control this invasive species, large populations persist on many islands. This review summarizes impacts of feral goats on Pacific island ecosystems and management strategies available to control this invasive species.

Descended from the wild goat (*C. aegagrus*) from central Asia (Zeder and Hesse 2000), domestic goats (*Capra hircus*) have been introduced to islands worldwide. The original purpose of insular domestic goat introductions was likely for sailors to populate oceanic islands with a food source to access during later voyages (Campbell and Donlan 2005). Released domesticated goats can quickly develop self-perpetuating feral populations given their ability to survive in a variety of habitats, on a wide variety of forage, and with limited water. Goats have been considered by some to be "the single most destructive herbivore" introduced to island ecosystems globally (King 1985:3).

NAME

Capra hircus (Linnaeus, 1758)

Synonyms: *Capra hircus*, *Capra hircus aegagrus*, *Capra aegagrus hircus*.

Common names: briar goat, brush goat, feral goat, goat, hill goat, scrub goat, Spanish goat, wood goat.

DESCRIPTION AND ACCOUNT OF VARIATION

Goats are even-toed hoofed ungulates of the order Artiodactyla and have been considered to comprise from one to nine species (Shackleton and Shank 1984 and references therein). Feral goats on Pacific islands (Figure 1) are assumed to have been introduced by European sailors as a food source and are, therefore, most likely derived from continental European domestic goat breeds. Feral goats exhibit substantial intraspecific variation and are sexually dimorphic. Generally, males are 20% larger and have larger horns than females (Fleming 2004). Both males and females have

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Figure 1. Feral goats, *Capra hircus*, on Hawai'i Island. (Photo: Mark Chynoweth)

horns made of living bone surrounded by keratin. Goats typically weigh between 25 and 55 kg, stand 1–1.2 m at the shoulder, and are 1–1.5 m long. All males and some females are bearded as adults. Both sexes have 30–32 teeth, with upper and lower teeth in the back to chew cud and a dental pad in place of upper incisors. Goats sometimes resemble sheep but can be distinguished by their short, upward pointing tails. Pelage coloration is typically black, but individuals can be white, gray, brown, red, black, or any combination thereof.

DIET

Feral goats are versatile generalist herbivores capable of surviving on grasses, forbs, browse, and even marine algae. Coblentz (1977) documented goats using almost every plant species present within a study area in California. However, feral goats demonstrate strong dietary preferences. In general ungulates, including feral goats, demonstrate preference and avoidance at least partly based on foliage chemistry (Forsyth et al. 2002). McCammon-Feldman (1980) suggested that goats actively select the highest-quality forage. Although the most palatable forage is typically sought out and consumed first, poor-quality forage is often used to sustain populations (Coblentz 1977, Green and Newell 1982). Consequently, feral goats can extirpate preferred forage species (Coblentz 1977).

Goats are often regarded as browsers. However, tendency to graze or browse is determined primarily by environmental conditions, such as seasonal and geographic variation of forage. Instead, it may be more appropriate to classify goats as mixed feeding opportunists (Lu 1988). As browsers, goats are known to assume a bipedal stance to reach upper sections of shrubs and trees, and even to climb into trees to access foliage. In the process of browsing, goats often strip bark and girdle trees (Spatz and Mueller-Dombois 1973).

An important trait that enables feral goats to persist in arid island environments is their remarkable ability to survive in the absence of a permanent water source. Domestic goats have a minimum water requirement of 1.0%–1.5% body weight per day, but selective pressure may enable feral goats to survive in dry ecosystems with even less available water (Dunson 1974). Goats primarily derive preformed water from plant foods in many scenarios (Robbins 1994) but have also been observed drinking salt water (Gould Burke 1988). Limited water requirements have contributed to the success of feral goats as an invasive mammal on numerous Pacific islands.

ENVIRONMENTAL IMPACT AND ECONOMIC IMPORTANCE

Detrimental Aspects

Nonnative feral goats are notorious for their negative impacts on island ecosystems (Coblentz 1978). Remote Pacific island plant species evolved in geographic isolation from herbivorous mammals, losing many of the secondary chemical (e.g., tannins, turpenes) and morphological (e.g., thorns) defense mechanisms to deter herbivory (Kelsey and Locken 1987, Bowen and Vuren 1997, Sheley and Petroff 1999). Consequently, native and endemic plant communities are often unable to recover from persistent herbivory and trampling, resulting in their replacement by more tolerant and resilient nonnative species (Augustine and McNaughton 1998). Intense browsing and grazing by goats can extirpate preferred species and cause the desertification of entire islands. In some cases, such as Santa Fe Island in the Galápagos, feral goats eliminated 100% of seedlings from large trees (Clark and Clark 1981). Importantly, the presence of nonnative ungulates can affect competition between native and introduced plants. A comparison of Pacific islands with and without introduced ungulates indicates that some island plant communities can more effectively resist nonnative plant invasions in the absence of nonnative ungulates (Merlin and Juvik 1992).

Removal of feral goats from entire islands, or ungulate exclosures within islands, demonstrates this transformative effect; native and nonnative vegetation typically shows an immediate positive response to release from grazing and browsing pressure. Within fenced units in dryland Hawaiian forests where goats have been removed, native species demonstrate increased survival rates (Scowcroft and Hobdy 1987). On Hawai‘i Island, heavily browsed areas demonstrate a lack of recruitment and an older age class structure for the dominant tree species, māmane (*Sophora chrysophylla*) (Scowcroft and Sakai 1983), and reduced sucker growth on endemic koa (*Acacia koa*) (Spatz and Mueller-Dombois 1973). On Guadalupe Island, Mexico, presumed extinct and extirpated plant species have recovered from seed banks after goat removal (Keitt et al. 2005).

Foraging preferences of feral goats on Pacific islands vary greatly, depending largely on the composition of available plant communities. Goats are observed feeding on both native and nonnative species, but native Pacific island plants are often consumed first because they lack defenses against herbivory and are, therefore, often more palatable. For this reason, even low-density goat populations can have negative consequences for native flora. In Hawai‘i Volcanoes National Park, D. K. Morris (unpubl. data) observed that stomach contents of feral goats depended largely on density of animals present in an area. In areas with low goat density, where native vegetation was abundant, stomachs contained 98% native species. In contrast, nonnative plants composed 99% of stomach contents in areas of high goat density where native vegetation was scarce. Although native species are often preferentially consumed when available, nonnative plants support goat populations where native species do not occur.

In addition to direct effects from browsing, grazing, and trampling, feral goats have important indirect effects; the alteration of plant communities through modification of plant structure and destruction of habitat leads to declining native wildlife populations, and alteration of nutrient cycles (Zhang et al. 2009, Gabay et al. 2011). These indirect effects can lead to ecosystem state changes that alter the function of an ecosystem. Notably, browsing and grazing can promote a cycle of pyrogenic plant invasion and proliferation of fine fuels leading to increased fire frequency and severity (Cabin et al. 2000), thereby facilitating the conversion of tropical dry forests to invasive grasslands (D'Antonio and Vitousek 1992).

Native island plant communities are particularly vulnerable to invasion by nonnative plants (Wilcove et al. 1998), which quickly occupy the available space created after goats remove native vegetation. The impacts of nonnative herbivores differ between native and exotic plant communities. Nonnative herbivores are known to facilitate both the abundance and species richness of nonnative plants, whereas native herbivores often suppress nonnative plants (Parker et al. 2006, Oduor et al. 2010). These impacts include dispersal of both nonnative and native plant seeds via excrement and attachment to fur (Janzen 1984), and trampling of plants on paths, wallows, and in resting beds. Nonnative plant species can often quickly replace native plants as a direct or indirect result of nonnative ungulates by overwhelming seed banks and manifesting pioneer traits (Sheley and Petroff 1999). These effects can be enhanced or reduced with extreme weather events such as drought or enhanced precipitation.

Following intense grazing and trampling of goats on islands, erosion can occur (Coblentz 1978). Goats can remove 6 kg/day of dry matter compared with 3.8 kg/day for sheep and 2.9 kg/day for cattle (Thornes 1985 and references therein). Once vegetation is removed, erosion can occur rapidly with precipitation, wind, and further disturbance via goat movement. Yocom (1967) speculated that approximately 1.9 m of topsoil disappeared as a result of goat activity on Haleakalā Crater on the island of Maui. As such, overgrazing by goats can contribute to massive erosion and subsequent runoff that can damage nearshore marine ecosystems, as in the case of Kaho'olawe Island, Hawai'i (Loague et al. 1996).

Feral goats have been associated with the decline of native fauna because of habitat modification as well as direct competition with native herbivores. Examples include the Hawaiian goose (*Branta sandvicensis*) on Maui (Yocom 1967), as well as declines in populations of yellow-footed rock-wallabies (*Petrogale xanthopus*), brush-tailed rock-wallabies (*Petrogale penicillata*), mallee fowl (*Leipoa ocellata*), and the thick-billed grasswren (*Amytornis textilis*) in Australia (Biodiversity Group 1998), and native jackrabbits (*Lepus insularis*) and woodrats (*Neotoma lepida*) on Isla Espíritu Santo, Mexico (León-de la Luz and Domínguez-Cadena 2006). In Hawai'i, the endangered palila (*Loxioides bailleui*), an endemic finch-billed honeycreeper, relies primarily on the native māmane tree (*Sophora chrysophylla*) as a food source (Banko et al. 2009). Nonnative ungulates, including primarily goats and sheep, have heavily browsed and degraded māmane forest habitat, where they prefer accessible foliage, saplings, and bark of mature trees as forage (Scowcroft and Sakai 1983). In addition, the removal of feral goats has led to the recovery of endangered fauna, such as the Galápagos rail (*Laterallus spilonotus*) on Santiago Island (Donlan et al. 2007), and increased ability for reintroductions and conservation introductions to occur (Bellingham et al. 2010).

In addition to ecological impacts, feral goats pose several potential problems for domestic livestock populations (Heath et al. 1987). Feral goats may introduce novel pathogens or act as a reservoir for existing diseases and parasites (Hein and Cargill 1981). For example, in New Zealand feral goats have been found to carry 22 nematode, two cestode, two trematode, four arthropod, and three protozoan parasites (Parkes et al. 1996). Disease and parasite transmission to domestic populations could occur either in pasture areas or if feral populations are gathered and driven to slaughter. Zoonotic diseases such as tuberculosis, brucellosis, and rabies are potentially transferable to humans (Smith and Sherman 1994). Feral goats also compete with domestic livestock for forage and contribute to overall degradation of rangelands (Thompson et al. 2002).

Beneficial Aspects

Economically, the goat may be more valuable to the world's agricultural system than any other animal species (Dunbar 1984). Domestic goats are one of the primary livestock species in the developing world used for both dairy and meat, but domestic goat dairy products also provide for special dietary needs in developed regions. Feral goats represent a major source of meat and skins. In the past, feral goat populations were harvested from Pacific islands for the goat skin trade (Yocom 1967), but Australia has become a leader in the industry more recently. In Australia, feral goats continue to be harvested for both commercial enterprise and conservation objectives (Ramsay 1994, Forsyth et al. 2003).

In addition to limited commercial value on islands, feral goats also have recreational, subsistence, and cultural value for some Pacific islanders. Feral goats are harvested as a source of meat and provide a small number of employment opportunities through hunting outfitters. There are divergent societal views regarding the value of feral goats, with some individuals and groups regarding these animals as a sustained-yield hunting resource and others regarding them as an undesirable pest (Hess and Jacobi 2011, Kessler 2011). To address these issues related to conservation and ecological restoration, decision analysis can be used to incorporate social values and stakeholder preferences into management strategies (Maguire 2004).

Ecologically, although often considered negative, long-term impacts of feral goats on Pacific islands are not always straightforward (Cabin et al. 2000). In highly modified ecosystems, such as heavily invaded tropical dry forests, removal of generalist herbivory by feral goats has been shown to facilitate the short-term proliferation of invasive plants (Kellner et al. 2011). Long-term studies on the effects of ungulate exclusion indicate that animal removal can also release invasive pyrogenic grasses from top-down control (Cabin et al. 2000). However, when invasive grasses are controlled after ungulate removal, an increase in natural regeneration of native plants has been observed (Thaxton et al. 2010). Importantly, nonnative ungulates are a known critical barrier to native species conservation and restoration efforts, and the ecological benefits of feral goat populations on Pacific islands are very few.

Although direct benefits are not often seen from goat presence, it is possible that native species could benefit from goat presence by moving nutrients from inaccessible areas through fertilization via feces (Gould and Swingland 1980). However, it can also be assumed that exotic plant species disproportionately benefit from this same process, and often respond much faster (Funk and Vitousek 2007, Ostertag et al. 2009). In some cases, an initial rapid spread of introduced species has occurred following nonnative ungulate eradication (Kellner et al. 2011, Kessler 2011), but some invasions have also stabilized over longer periods of time, benefiting native biota (Kessler 2011). Limited examples also exist where native fauna may experience benefits from goat presence. Desender et al. (1999) observed an increase in the diversity of xerophilic terrestrial invertebrates in the Galápagos as a result of goat grazing due to a temporary increase in habitat heterogeneity.

Both domestic and feral goats have often been used for biological control of weeds, improvement to ranges (Sakanoue et al. 1995, Goehring et al. 2010), and even for the control of control brush in fuel breaks (Green and Newell 1982). Domestic goat breeds, such as Angora or Nubian, can provide mohair and milk, respectively, while simultaneously improving rangelands or controlling weeds. Although feral goats can be used for the same purposes, small-scale prescribed or targeted grazing and browsing by domestic animals typically yield better results (Green and Newell 1982).

GEOGRAPHIC DISTRIBUTION IN THE PACIFIC REGION

The geographic distribution of the feral goat in the Pacific region includes essentially all islands that have suitable habitat (Table 1). Goats have been deliberately introduced to most islands, and these introductions have failed only on atolls (e.g., Kiribati and Tuvalu

TABLE 1

Presence of Feral Goats on Select Pacific Islands

Pacific Islands	Present	Absent	Notes
American Samoa		x	
Australia	x		
Bonin Islands	x		Archipelago-wide eradication program is in progress[a]
Cocos Islands	x		
Cook Islands	x		
Easter Island		x	Domestic goats present
Fiji	x		
French Polynesia	x		
Galápagos Islands	x		Archipelago-wide eradication program is in progress[b]
Guam	x		
Hawaiian Islands	x		
Indonesia	x		
Japan	x		
Juan Fernández Islands	x		
Kiribati		x	Introduced, but failed
Marshall Islands		x	Introduced, but failed[c]
Micronesia	x		
Nauru		x	
New Caledonia	x		
New Zealand	x		
Niue	x		
Norfolk Island		x	Eradicated in 1856
Northern Mariana Islands	x		
Palau		x	Domestic goats present
Papua New Guinea	x		
Philippines	x		
Pitcairn Island	x		
Solomon Islands		x	Domestic goats present
Taiwan	x		
Tokelau Island		x	Introduced but failed[c]
Tonga	x		
Tuvalu		x	Introduced but failed
Vanuatu	x		
Wake Island		x	
Wallis and Futuna		x	Domestic goats present

[a] Yoshikazu Shimizu, pers comm.
[b] Carrion et al. (2011).
[c] Alik et al. (2010).

[see Hussain 1987]). Goats have been eradicated to maintain watershed function and protect native species on numerous islands (e.g., Lāna‘i in Hawai‘i, Santiago in the Galápagos [Keitt et al. 2011]).

HABITAT

The remarkable adaptability of goats as a species has enabled feral populations to establish themselves across a wide range of habitats throughout the Pacific. Goats demonstrate a wide range of physiological capabilities that allow them to survive in a variety of temperatures, altitudes, and habitats (Shackleton and Shank 1984). Few factors limit their distribution, such as deep snow, tundra, and desert habitats. However, feral goats generally appear to prefer xeric grasslands and high topographic variability (Shackleton and Shank 1984).

On Pacific islands, feral goat populations exist from low to high elevations and in xeric to mesic habitats (Stone 1985). As opportunistic herbivores, feral goats use an assortment of forage for subsistence, including native and nonnative plants (Yocom 1967, Baker and Reeser 1972). Preferred feeding areas appear to be open, dry grasslands, shrublands, or forests (Morris 1969, cited in Baker and Reeser 1972). However, goats can be observed in nearly every tropical insular habitat. The majority of native plant communities on islands are heavily invaded and subsequently impacted by feral goat populations in some manner.

HISTORY OF INTRODUCTIONS

Domestic goats have arguably been intentionally introduced to more islands worldwide than any other mammal with the possible exception of domestic cats (Duffy and Capece 2012). Goats have been introduced to all continents (except Antarctica) and can inhabit a range of climates and conditions. Their unique ability to survive on a wide variety of forage and limited water supply made them ideal candidates for food supplies on remote and arid islands. In addition to intentional introductions, domesticated goats have also repeatedly escaped captivity to establish feral populations.

The earliest known introduction to an oceanic island was that of St. Helena in 1513 (Dunbar 1984). In the Pacific region, the Juan Fernández Islands may have had the first known introduction, in the sixteenth century (Wester 1991). Most renowned for his role in goat introductions was Captain Cook, who was responsible for releasing goats in New Zealand, Hawai'i, and many smaller islands in the South Pacific during the late eighteenth century (Tomich 1986). In other locations, goats were imported to control brush or for the agricultural industry, only to escape captivity and establish feral populations. Goat introductions are not well documented because it was common practice to carry these animals aboard ships and release them as a future food source. Shipwrecks could also have released goats onto oceanic islands (Dunbar 1984).

Only on small oceanic atolls with very limited resources have goat populations failed to become established. In some cases, goat populations have crashed due to overbrowsing and desertification. However, this evidence should be considered circumstantial because goats may often be the only animal present during the final stages of land cover change (Dunbar 1984). It is interesting that isolation on islands has caused some feral goat populations to experience substantial genetic drift. In some cases, such as San Clemente Island, California, domestic livestock that are derived from feral populations may be recognized as a unique heritage breed by the American Livestock Breeds Conservancy.

PHYSIOLOGY AND BEHAVIOR

Feral goats are well adapted to survive in a wide variety of conditions, exhibiting a suite of behaviors that are remarkably similar to those of conspecific domesticates. Goats are social animals that prefer traveling in herds (i.e., tribe or trip), with a modal group size of two to four animals (O'Brien 1988). Large herds of up to 100 individuals are not uncommon. In Hawai'i feral goats have been observed to occur in groups of up to 200, at least temporarily (M.W.C., pers. obs.). Three types of herds usually exist: (1) all males (bachelor herds); (2) mixed sex and age groups; and (3) females and young. Frequent fission and fusion occur throughout the day as goats travel through their home range in search of forage. Average home range size differs significantly between males and females, and also between geographic areas and resource availability (O'Brien 1984*a*). Estimates range from 0.4–5.3 km^2 on Aldabra Island (Gould Burke 1988) to 139.2–587.7 km^2 in Australia (King 1992). Although some social characteristics vary between populations, others are more common. Group size, group composition, home range variations, sexual segregation, and use of permanent night camps are all common characteristics among populations (O'Brien 1988).

Goats have excellent eyesight with a panoramic field view of 320°–340°. Their unique rectangular pupil, common to other ungulates, enables increased peripheral depth perception (Abbott 1907). Furthermore, tests on male goats indicate capacity for color vision (Buchenauer and Fritsch 1980). Feral goats also possess an acute sense of hearing and are able to direct their ears toward a source of sound. Likewise, their sense of smell is well developed and is often used to evaluate potential food items. Feral goats make several distinct vocalizations (bleating) related to offspring, danger, and agonistic behavior. Mothers and offspring are able to locate each other based on these auditory cues (Ruiz-Miranda et al. 1993).

Physiologically, goats have a mean body temperature of 38.6°C–39.7°C, resting heart rate of 70–90 beats per minute, respiration rate of 12–20 breaths per minute, and a life span of 10–12 yr (Nowak and Paradiso 1983). As ruminants, goats have a four-chambered stomach consisting of rumen, reticulum, omasum, and the abomasums. As goats consume grasses and forbs (grazing) as well as shrubs and trees (browsing), the muscular and microbial action of the rumen physically and chemically breaks down nutrients at 1–1.5 ruminal movements per minute (North 2004).

REPRODUCTION

Breeding systems of feral goats are highly variable, ranging from year-round breeding in Hawai'i (Ohashi and Schemnitz 1987) and New Zealand (Rudge 1969) to seasonally polyestrous breeding cycles in more-temperate latitudes (Turner 1936, Asdell 1964). Reproductive cycles vary greatly, because females have the ability to come into estrus year-round (Phillips et al. 1943). Coblentz (1980) observed quadrimodal birth pulses on Santa Catalina Island, for which the proximate cause was unknown. Males appear to be able to bring females into estrous, but number of ruts throughout the year may ultimately depend on environmental conditions.

Goats typically reach sexual maturity at 6 months of age (Ohashi and Schemnitz 1987), with young females typically entering breeding stage immediately, but young males are often outcompeted by older, more experienced males. Operational and actual sex ratios are usually female biased (O'Brien 1988, Keegan et al. 1994). During the rut, a buck releases an oily substance with a strong scent to attract females. This type of scent-urination is a form of communication for both males and females (Coblentz 1976) during flehmen (open mouth, curled back lip) behavior involved in olfactory perception of this and other compounds (O'Brien 1982). As in many social ungulates, males compete for females in estrus. However there is some evidence that females have substantial control over which male with whom they choose to breed (Margiasso et al. 2010). Males demonstrate two principal mating techniques: tending, where a dominant male defends estrus females, or coursing, where males of all ages attempt to disturb a tending pair (Saunders et al. 2005).

Gestation period is approximately 150 days (Yocom 1967), with twinning being common (Rudge 1969). Where environmental conditions are favorable, females may give birth twice a year (Ohashi and Schemnitz 1987). In New Zealand, average live weight for female kids is 4.6 ± 0.7 kg, and average live weight for male kids is 5.7 ± 1.1 kg (Kirton 1977). Following parturition, females either leave or stay with kids for a brief lying-out phase (O'Brien 1984*b*), often in a protected shaded location (O'Brien 1983) followed by a crèche (i.e., nursery group) formation in some herds (O'Brien 1988). Females accompanied by kids often separate themselves from other adults to reduce competition for resources (Calhim et al. 2006). Offspring begin to feed themselves after 2–3 weeks but remain close to their mother until approximately 6 months, when they either remain with the family group or join another herd.

POPULATION DYNAMICS

Reproductive abilities of feral goats enable rapid population growth, particularly in island ecosystems where competition and predation are typically minimal. Watts and Conley (1984:814) stated that "the combination of an early initial breeding stage, short gestation, postpartum estrus, high breeding rate, and twinning allow goat populations to achieve annual growth rates of 10–35%." Hence, population doubling times can be as low as 2.3 to 7.3 yr (Watts and Conley 1984). This rapid growth rate needs to be considered in management of these animals, because Rudge and Smith (1970) predicted that a population reduced by 80% could potentially recover to 90% of the original level in 4 yr.

Feral goat densities on Pacific islands depend on a variety of factors, including environmental conditions and level of animal control. In harsh atoll conditions, densities can be as low as five to eight goats per square kilometer (Burke 1987). In favorable conditions, such as those on Macauley Island, New Zealand, densities have reportedly reached as high as 400 goats per square kilometer (Nowak and Paradiso 1983). Goat populations can expand rapidly under favorable environmental conditions, making these animals formidably invasive on Pacific islands.

Isolated island populations of feral goats are quite variable in many aspects, which may be related to small initial introductions from which those populations were derived. Gould (1979) observed variation in color, body size, reproductive rate, population size, water balance, and behavior between two isolated populations separated by water on Aldabra Island. Variations in genetics and behavior may be a combination of a founder effect and the variable environmental conditions of islands that feral goats inhabit. However, over the past few centuries, additional introductions may have reduced the founder effect.

MANAGEMENT

By the mid-twentieth century, many biologists had come to a consensus on the negative impacts of feral ungulates on islands (Coblentz 1978) and began developing techniques to remove goat populations from them (Daly 1989). Strategies to manage goats include taking no action, eradication, annual control in perpetuity, or occasional control in perpetuity (Parkes 1990). In many areas, such as Haleakalā National Park in Hawai'i, intense goat control programs have occurred sporadically since the early twentieth century, with active hunting numbering 10,000 person-days over four decades (Kjargaard 1984). Due to their large physical size and gregarious behavior, feral goats are an ideal candidate for successful eradications on small to midsized islands. Worldwide, >95% of 165 eradication attempts on islands have been successful (Keitt et al. 2011), and goats have been removed from more than 1,360 km^2 in the central Pacific region alone. The largest land area from which goats have been eradicated on any Pacific island was the 585 km^2 Galápagos island of Santiago, Ecuador, in 2005 (Cruz et al. 2009). However, a highly technical eradication from 554 km^2 of Hawai'i Volcanoes National Park on the island of Hawai'i was accomplished in 1984, requiring perimeter fences to exclude adjacent populations (Hess and Jacobi 2011).

Trapping, hunting, poisoning, biocontrol, or any combination thereof can be used to eradicate populations of invasive mammals (Veitch and Clout 2002). All techniques have been used on goats; however the most common method is hunting. Tools to aid in hunting efforts include dogs, aerial hunting from helicopters, exploiting the social behavior of goats, and utilizing local hunters. If the ultimate goal is eradication, public hunting by recreational and subsistence hunters can be ineffective, because hunters often select for trophy-quality males and can shift the sex ratio, leading to increased population growth (Stephens et al. 2008). Although helicopter activity does not appear to cause long-term behavioral changes, short-term effects occur frequently (Tracey and Fleming 2007). Goats with previous exposure to aerial hunting via helicopter are twice as likely to exhibit evasive activity (Bayne et al. 2000).

Toxicants have been briefly explored as an option for population control. Limitations exist due to effects on nontarget species and the ability to distribute baits across the range of an entire goat population. Aerially distributed baits are not considered effective because feral goats do not often eat from the ground (Forsyth and Parkes 1995). Although sodium fluoroacetate (1080) is not a registered toxicant for goat control in New Zealand, Veltman and Parkes (2002) suggested that it might be useful for high-density goat populations in areas that are inaccessible to ground or aerial hunting.

Biological control of goats is unlikely, because both pathogens and predators are not target-specific, posing considerable risks to livestock populations. Goats have no natural predators on Pacific islands. Feral goat populations may experience minimal predation from feral dogs (*Canis lupus familiaris*) and golden eagles (*Aquila chrysaetos*). One example exists of successful biological control using dingoes (*Canis lupus dingo*) on Townshend Island (L. Allen and J. Lee, unpubl. data). However, large predators are not suitable for most areas, because they pose serious potential risks to livestock, native fauna, and humans.

Judas goats are one of the most effective tools to aid in eradication efforts. Judas animals are individual goats, typically female, equipped with a telemetry collar used to locate remnant herds (Taylor and Katahira 1988). Finding collared individuals will lead to another herd because goats are highly social animals. As each herd is eliminated, collared animals are spared to find additional herds. On San Clemente Island in California, Judas goats were able to locate other individuals within their maximum search range within 3 days of eradication of the rest of the herd (Keegan et al. 1994). All animals can be removed using this method (Rainbolt and Coblentz 1999).

Judas goats can also have their reproductive systems manipulated to increase efficacy. Methods to sterilize goats, including tubal occlusion and epididymectomy can be accomplished in the field (Campbell et al. 2005). Female Judas goats can be further modified to become Mata Hari goats, by inducing either prolonged duration or increased frequency of estrus (Campbell 2007, Campbell et al. 2007). Numerous males may be repeatedly attracted by implanting hormones in females to heighten estrous periods.

Removal of all animals is necessary for successful eradication; a small number of failed eradication attempts have resulted from the recovery of few remaining animals because of high reproductive rates (Parkes 1984). Use of multiple techniques and technology such as global positioning systems (GPS), geographic information systems (GIS), remote sensing, and forward-looking infrared radar are helpful for successful eradication of goats on islands. Immigration and recolonization may occur if barriers are not adequate to exclude nearby goats. In New Zealand, a population recovered 30%–40% of the original size in 10 months due to immigration (Brennan et al. 1993).

On many larger islands, goat populations have been excluded from distinct management areas, particularly management areas with high densities of native species and/or native species populations of conservation concern. Fences have been built around sensitive ecosystems to exclude goats from an area, which is technically difficult but more feasible than island-wide eradication from multitenure islands (Campbell and Donlan 2005). Fence construction can be a costly management technique requiring continual monitoring, maintenance, and cyclical replacement to prevent ingress; however, it is an important first step toward native species restoration at a broad landscape scale. Given the costs of controlling populations in perpetuity, it is more cost-effective in the long term to eradicate all target animals from an entire island, regardless of island size.

Fencing and eradication of ungulates from ecologically sensitive areas have been important steps in conservation and restoration; however, most disturbed sites require continual monitoring and specific alien plant management strategies after ungulates have been eliminated. Invasions of nonnative plant species have occurred in areas where animals have been removed (Kessler 2002, Kellner et al. 2011), but some invasive species have stabilized over time (Kessler 2011). In a study of 50 ungulate exclosures throughout Hawai‘i, native biota held their own or increased after removal of ungulate damage in most situations; however, the chance of recovery became reduced as the extent of degradation increased (Loope and Scowcroft 1985). Damage by nonnative ungulates precipitated large-scale invasion of alien plant species. Displacement by alien grasses appeared to be the most important factor inhibiting reproduction of native species in areas other than rain forest. Comparative studies suggest that some plant communities recover better than others after ungulate disturbance is curtailed (Stone et al. 1992). Remote, lightly disturbed rain forest, coastal strand, ‘ōhi‘a (*Metrosideros polymorpha*), and native subalpine bunchgrass and shrub are among the least affected by long-term disturbance by goats and other ungulates in Hawai‘i.

PROGNOSIS

Capra hircus populations are present on islands throughout the Pacific and remain a serious threat to native flora and fauna, as well as a critical barrier to conservation and ecological restoration. Most important, it should be recognized that feral goats have a substantial impact on ecosystem structure and need to be controlled or eliminated to accomplish most, if not all, conservation goals that include restoration of native plant communities. The combination of both being a generalist and having the ability to thrive in arid environments makes goats a formidable invasive species on Pacific islands. Although techniques and technology for eradication have been developed and proven effective, resource constraints and conflicting societal values limit the success of goat management, making eradication on many larger multitenure islands challenging (Campbell and Donlan 2005). Ungulate removal is often considered an essential first step in conservation and restoration of native ecosystems on most Pacific islands. The construction of barrier fences and eradication of feral goats by ground and aerial hunting, coupled with the use of telemetry and other technologies, have been the primary tools that have proven successful on islands throughout the world.

Given the recent gains in knowledge, technological advances, and logistical experience in nonnative mammal eradication, biological limitations to feral goat control no longer exist. In addition, research overwhelmingly supports the removal of these animals to achieve conservation and restoration goals in native island ecosystems. These ecosystems represent major holdings of global biodiversity and are currently experiencing a disproportionately high number of extinctions (Keitt et al. 2011). As more resources are allocated to conservation and restoration of island ecosystems, goat eradications will continue on islands of all sizes, including enclosed areas on multitenure islands. Larger and more technical projects will incorporate next-generation tools (e.g., advancements in GPS, GIS, and remote sensing) to execute effective feral goat removal plans. However, it is important to recognize that management of native island ecosystems will not typically end with goat eradication but rather will entail a long-term commitment to control of other nonnative invasive species, along with active management of native species of conservation concern (Cole et al. 2012).

Feral goats undoubtedly have had a negative impact on native island ecosystems, but their long history on Pacific islands and their impact on ecosystem structure and function should not be overlooked. As Cabin et al. (2000) suggested, feral ungulates may play an important role in nonnative species control in limited circumstances, notably in highly degraded ecosystems that already have large nonnative plant populations. On many Pacific islands novel ecosystems have emerged that have no natural analog and are increasingly managed as a mix of native and nonnative species (hybrid ecosystems). Removal of goats from these novel and hybrid ecosystems is a critical first step, but management activities that include monitoring and control of other invasive species are essential to maintain biodiversity and ecosystem structure. Monitoring ecosystem structure and function before, during, and after goat management will help land managers understand the role of goats in shaping emerging island ecosystems and will guide a management approach to better conserve native species on Pacific islands.

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