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ABSTRACT: The Hawaiian islands provide superlative examples of biological evolution and are perhaps the best sites in the world for biological invasions. Introduced invertebrates such as the Argentine ant (Iridomyrmex humilis) and the western yellowjacket wasp (Paravespula pensvlvanica) reduce native insects and plant pollinators and may have been a factor in native bird declines. Management of invertebrates in localized areas through use of chemicals such as Tahara and diazinon is being attempted. Research on the long term effects of alien birds on native ecosystems is under way, but management currently is restricted to preservation of intact and large areas of native ecosystems. Black rats (Rattus rattus), small Indian mongooses (Herpestes auropunctatus). and feral cats (Felis catus) are thought to be especially important invaders of natural areas in Hawaii. Research on ecology and control methods for all 3 species is under way, with registration of diphacinone for mongooses by the Animal and Plant Health Inspection Service nearly complete. Ungulates have been the most prominent alien animals in Hawaii's ecosystems since shortly after continental man introduced them in the 18th century. Successful control and even eradication of feral cattle (Bos taunis), feral sheep (Qvisaries), mouflon (Ovismusimon). feral goats (Capra hircus), and feral pigs (Sus scrofa) has been accomplished in many areas to date through systematic, long-term programs with salaried personnel. Methods and costs of some of these programs are presented.

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The Hawaiian Islands provide perhaps the best theater for evolution in the world because of their isolation in distance and time, environmental variation, number, and size (large for oceanic islands). Ironically, they are also one of the best sites in the world for biological invasions of all sorts — plants, invertebrates, vertebrates, and diseases (Vitousek et al. 1987). The interactions among native species (with 91-96% endemism of flowering plants (St. John 1973, Gentry 1986)) and aggressive alien species are complex but usually result in the degradation of natural systems and processes. Introductions of birds have succeeded 73% and mammals 93% of the time (Moulton and Pimm 1986). Over 4,600 species of flowering plants have become established, of which 600 are considered invasive (Smith 1985). Extinction rates of native species in Hawaii have been tremendous (63% of known extinct plants and 72% of known extinct birds in the U.S.), and the current endangered or candidate endangered species amount to about one-third of the U .S. total. The purpose of this paper is to highlight problems caused by some of the most important invasive animals in Hawaii and describe current management and research efforts designed to minimize negative effects on natural areas.

INVERTEBRATES

Over 2,000 species of arthropods and 30 mollusks have been introduced to Hawaii. The worst of the arthropods are the ants (35-40 introduced species) and the western yellowjacket wasp (Paravespula pensvlvanica). Three species of ants are especially important — the Argentine ant (Iridomyrmex humilis). the big-headed ant (Pheidole megacephala). and the long-legged ant (Anoplolepis longipes). These species, particularly the big-headed ant, have been implicated in the extinction of Hawaiian arthropod species (Howarth 1985). The Argentine ant, present in Hawaii for over 40 years, is found at elevations ranging from sea level to 2,800 m elevation, and its effects on arthropod fauna in upper elevation ecosystems have recently been reported (Medeiros et al. 1986). One of the chief impacts is ant predation on pollinators (such as noctuid moths and ground-nesting bees (Hylaeus) of rare subalpine plants such as the Haleakala silversword (Argyroxvphium sandwicense macrocephalum). The long-legged ant may be responsible for the near-extinction of native damselflies in windward riparian systems (Medeiros et al. 1986).

The ground-nesting western yellowjacket has been present in Hawaii since 1919, but in 1977 an aggressive race quickly expanded through all main islands. A coincident decline of some species of native arthropods was noted, including pollinators, pomace flies (Drosophila spp.) , and other rare species with localized distributions (Gambino et al. 1987). Social and colonial insect introductions in general have had greater adverse effects on natives than most other invertebrates. The decline of native forest insects may well have been a factor in the decline of some species of native forest birds (Howarth, in press).

Of the 30 species of naturalized mollusks, the predatory rosy snail (Euglandina rosea) from Florida is perhaps the worst (Howarth 1985). It was introduced in the mid-1950s to control the giant African snail (Achatina fulica), a pest in Honolulu gardens. Instead it moved into cooler mid-elevation forests and probably caused the extinction of many species of endemic tree snails (Achatinellidae). Research and Management.—Recommended management for ants includes monitoring the spread of Argentine and

long-legged ants, and eradication from small subalpine and other sensitive areas through use of slow-acting chemicals such as hydramethylnon (Amdro, Maxforce, Tahara). Attractive poison baits can be passed quickly by returning workers through the colony and can destroy large number of individuals. Research on efficacy of chemicals and effects on native arthropods is being conducted by L. L. Loope and associates in Haleakala National Park. Monitoring of ants is being conducted through use of under-rock surveys and bait stations. Since queens are flightless, spread of this species is slow and, it is believed, controllable if managed at an early enough stage. Use of more than one treatment and additional chemicals may be necessary if ants cannot be eradicated initially. Tahara, made from protein from silkworms, is highly attractive to protein-feeding ants (Loope, pers. commun.) and should receive Environmental Protection Agency registration in 1988.

Reduction of yellowjacket populations, at least in some important ecological areas, seems possible through destruction of ground nests with approved toxicants and use of chemicals such as diazinon (Knox-out 2Fm) and carbaryl (Sevin) in Figaro tuna cat food (Loope, pers. commun.). Yellowjacket populations are monitored through use of heptyl butyrate traps year-round at different locations by Hawaii Department of Health personnel. Research on food habits and hive biology of yellowjackets will be initiated in 1988 by Loope and associates in Hawaii Volcanoes and Haleakala National Parks.

As yet, there is no management planned for the snail Euglandina in Hawaii. An assessment of the impact of predatory snails on native snails and development of a recovery plan for the endangered genus Achatinella has been recommended (Howarth, in press).

Three additional management measures have been proposed for invertebrates. First, the improvement of quarantine procedures to reduce the introduction of new species to Hawaii and the spread of species from island to island is needed. The arrival of invertebrates on Christmas trees, cut flowers, construction materials, etc., has been noted elsewhere (Howarth 1985). Second, the use of biological control for some invertebrates may be possible. Yet the introduction of more alien species for whatever reason must be carefully done, with public review, Environmental Impact Statements, and considerable testing and follow up to determine effects on native species. A third and final management measure is increased public education about the value of native invertebrates and the dangers of introduced forms (Howarth, in press).

INTRODUCED BIRDS

Since 1850, more than 130 species of birds have been introduced to Hawaii. Of these, 15 game species and 30 nongame birds have established populations (Burr 1984). The cattle egret (Bubulcus ibis), barn owl (Tyto alba). Japanese white-eye (Zosterops iaponicus*). red-billed leiothrix (Leiothrix lutea). two species of bulbuls (Pyncnonotus cafer and P. jocosus) , and various gallinaceous birds are among the species of most concern.

Cattle egrets prey on native waterbird chicks such as those of the 'ae'o or black-necked stilt (Himantopus mexicanus). Barn owls prey on seabirds (Byrd and Telfer 1980) and probably compete with the native pueo or short-eared owl (Asio flammeus) for introduced rats and mice. The mejiro or Japanese white-eye probably competes for food with native forest birds such as the common amakihi (Hemignathus virens) (van Riper 1984), elepaio (Chasiempsis sandwichensis), and 'i'iwi (Vestaria coccinea) (Mountainspring and Scott 1985). Alien birds are reservoirs for avian diseases which have contributed to the decline of some species of native forest birds. Bulbuls, currently established only on O'ahu, depend on a broad range of introduced fruits, many of which are available in and near largely natural areas on other islands (Warshauer, in press). Loose flocks are found in nonbreeding season and aggregations occur near abundant food. Ring-necked pheasants (Phasianus colchinus). kalij pheasants (Lophura leucomelana). and other gallinaceous birds, along with the mejiro and others, distribute seeds of alien plants in Hawaii's natural areas.

Research and Management.—Information on distribution and abundance of introduced birds in different vegetation types is available from the Hawaii Forest Bird Survey (HFBS) conducted by the U.S. Fish and Wildlife Service (USFWS) from 1976-1983 (Scott et al. 1986). The State of Hawaii Division of Forestry and Wildlife (DOFAW) is coordinating additional surveys in selected areas. Followup information will give us information about range expansion and population intensification for some species. However, for other species such as raptors and gallinaceous birds, the HFBS sampling design is not adequate to the task.

The optimum management measure for many alien species of birds is thought to be preservation of intact and large areas of native ecosystems (Scott et al. 1986). Corridors of alien habitat favor penetration by alien birds. Reduction of some species such as mejiro and kalij pheasants, which distribute aggressive alien plants such as fire tree (Mvrica faya) and banana poka (Passiflora mollissima). may be possible in some high-value and/or isolated areas. The feasibility and effects of such short-term population reductions should be investigated. Research on the long-term effects of alien birds on native communities is being planned by the USFWS and the National Park Service (NPS) as part of larger ecosystem studies. Improved education of the public as to negative values of introduced birds in natural areas is also needed.

SMALL MAMMALS

Two species of rats, the feral cat (Felis catus), and the small Indian mongoose (Herpestes auropunctatus) are of primary concern in Hawaii's natural areas. The Polynesian rat (Rattus exulans) probably arrived with early Polynesian colonizers and destroyed native bird eggs, insects, and mollusks. This species has been here so long that most of the harm has probably been done, yet rare species of invertebrates such as crickets are still taken in some areas (F. G.

Howarth, pers. commun.). The black or roof rat (Rattus rattus). an arboreal species, was probably introduced between 1870 and 1890. Laysan rails (Porzanula palmeri) and a population of the Laysan finch (Telespyza can tans) were destroyed; mollusks, nesting seabirds, tree-nesting species of native birds, especially hole-nesters, and the cavity-nesting Kaua'i 'o'o (Moho braccatus). are also vulnerable (Scott et al. 1986). Effects of rat-feeding on fruit and flowers of Freycinetia arborea and other native plants can result in diminished food availability for native birds and has been implicated in the disappearance of the Endangered 'o'u (Psittirostra psittacea") from the island of 'O'ahu (Atkinson 1977). Girdling of stems and feeding on flowers and fruit of Hibiscadelphus spp. and other endangered plants is contributing to their rarity. Black rats are now abundant in dry to very wet areas and range from sea level to high elevations on Mauna Loa and Mauna Kea. Densities of about 15/ha in montane rain forest habitat, 5/ha in montane seasonal forest, and 64/ha in lowland kiawe (Prosopis pallida) forest in Hawai'i have been estimated (C. A. Russell, unpubl. data, Tamarin and Malecha 1971). Although primarily vegetarians, black rats can also be selective feeders (Norman 1970, Clark 1981, Gales 1982, F. G. Howarth, pers. commun.); other studies suggest they are more opportunistic (Best 1969).

The small Indian mongoose was introduced to Hawaii deliberately in 1883 to control rat damage in sugar cane (Tomich 1986). Mongooses are opportunistic and omnivorous feeders, preying on eight species of endangered Hawaiian birds including the Hawaiian goose or nene (Nesochen sandwicensis) and several endangered waterbirds. Large mongoose populations now exist in the lowlands of O'ahu, Moloka'i, Maui, and Hawai'i, and the species is fairly abundant at elevations to over 3,000 m or so on Maui and Hawai'i.

Cats were undoubtedly present in Hawaii soon after European contact and are known to have been common forest animals on some islands in the late 1800s (Tomich 1986). Feral cats are now widespread in Hawaii's natural areas, and there are indications that they may be becoming more abundant than in previous years (J. D. Jacobi, pers. commun.; D. L. Espy, pers. commun.). They are most abundant at low elevations but range to at least 2,100 m elevation. Like rats and in contrast to mongooses, cats can be nocturnal hunters and are able to prey on roosting and nesting birds at night. Also like rats, they are arboreal, although the amount of time spent in trees in different habitats is unknown. An increased prey base of alien birds and mammals may support higher cat populations now than in the past, but their relationships to mongoose populations are not understood. Cats are known to prey on dark-rumped petrels (Pterodroma phaeopygia) (Simons 1983) and other seabirds (J.L. Sincock, pers. commun.), and also prey on forest birds to some extent, especially those which forage in the understory (Scott et al. 1986).

Research and Management.—Studies of the ecology and management of rat populations in near-native areas have been initiated by USFWS and NPS. The USFWS work is part of a larger study on limiting factors for native bird species and will probably focus on study areas on Mauna Kea, Mauna Loa, and Hakalau Forest National wildlife Refuge. The NPS study will emphasize control methods development, rat population characteristics and responses to control, economics of control, and efficacy in reducing predation and depredation in small natural areas. Some food habits work has been completed in both Maui and Hawai' i natural areas (F. G. Howarth, pers. commun.; C. P. Stone and C. Russell, unpubl. data), and more is in progress in both USFWS and NPS studies. Rats are sometimes controlled in Hawaii Volcanoes National Park to protect very rare trees through use of poison stations baited with anticoagulants or zinc phosphide at tree bases. Rats are also trapped in live traps in dark-rumped petrel nesting colonies and nene breeding areas in Haleakala National Park (Stone and Keith 1985).

Research on ecology and control of the small Indian mongoose is being conducted by the Animal and Plant Health Inspection Service (APHIS) of the U.S. Department of Agriculture, with the cooperation of DOFAW, USFWS, and NPS. The objective of this effort is to register a drop bait toxicant for use in Hawai'i's natural areas to protect endangered species of ground-nesting birds (J. O. Keith, pers. commun.). An anticoagulant, diphacinone, is extremely effective for mongooses at a concentration of 0.00025% in beef. Bait stations constructed of 10-cm PVC pipe and the extreme sensitivity of mongooses to diphacinone greatly reduce nontarget hazards.

Registration with the Environmental Protection Agency should be completed by APHIS in 1988. However, questions about reinvasion rates, treatment time intervals, effectiveness in protecting nests of endangered birds, and seasonal timing of treatments will probably remain to be answered. NPS will undertake some studies in 1988 in nene nesting areas. Mongooses are presently managed only by live trapping in Tomahawk or Havahart traps baited with cat food around nene release pens by NPS. In State Nene Sanctuaries, live traps and conibear (kill) traps baited with vienna sausage are used (N. Santos, pers. commun.).

Feral cats were recently studied in Hawaii Volcanoes National Park in conjunction with determination of nontarget hazards of diphacinone in mongoose control. Maximum home range diameters for radioed animals (n = 5) in mesic scrub and forest (950-1,150 m elevation) and dry shrub alien grass (0-90 m) were about 10 km for 3-month periods and included a significant portion of nene habitat within the Park (D. L. Espy, pers. commun.). Additional research efforts by USFWS on Mauna Kea as part of a study of limiting factors for forest birds should add a great deal to our knowledge of the importance of feral cats in Hawaiian ecosystems. Emphasis will probably focus on active nest sites in USFWS studies (J. D. Jacobi, pers. commun.).

Cats are controlled in Hawaii Volcanoes National Park by live trapping and shooting, but efforts are insufficient and erratic. In Haleakala National Park, control is by live trapping in petrel and nene nesting areas for approximately 9 months of the year (R. Nagata, pers. commun.). A New

Zealand study by Vietch (1985) indicated that Compound 1080 and gin (steel leg-hold) traps are the best control methods for cats, and that fresh fish is the most effective bait. Cage traps may prove more useful than gin traps in nene habitat, but toxicants and perhaps feline enteritis (Vietch 1985) may also be important tools in population reduction.

UNGULATES

The most visible problems in Hawaii's natural areas are those caused by introduced ungulates. Sheep (Qvis aries) were initially introduced to Kauai in 1791 and to the island of Hawaii in 1793. Goats (Capra hircus) were put ashore on Ni'ihau in 1778 and probably also on Hawaii that year. Cattle (Bos taurus) arrived in 1793 on the island of Hawaii. Although pigs (Sus scrofa) were originally introduced to Hawaii by Polynesians, the European stock brought by Captain James Cook in 1778 is the likely ancestor of today's forest-dwelling animals. Captain Cook and Captain George Vancouver were both interested in stocking the Islands with domestic animals, and the latter was granted a 10-year kapu (ban) on slaughter of cattle, sheep, "and other European animals" beginning in 1794 (Tomich 1986). A number of other ungulates were introduced at later dates, and most of the main islands were eventually well supplied with domestic European stock. The mouflon sheep (Ovis musimon) was one of the later introductions, brought to the island of Hawai'i in 1957 to increase the quality of feral sheep on Mauna Kea by interbreeding (Tomich 1986).

By 1979, damage to mamane-naio (Sophora chrysophylla and Mvoporum sandwicense) forests on Mauna Kea by feral sheep and goats was so pronounced that a court order was issued in 1979 to remove the animals after a lawsuit by Audubon Society and the Sierra Club on behalf of the endangered palila (Loxioides bailleui) (Juvik and Juvik 1984). The ruling was made to comply with the Federal Endangered Species Act. A second ruling in 1987 resulted in a State effort to remove mouflon sheep from the same area for the same reason. Recovery of forest habitat following eradication efforts has been dramatic. The mountain is now closed to public hunting of ungulates except for a season on feral pigs.

Feral cattle have been a major factor in loss of forest vegetation. State of Hawaii Forestry and Wildlife personnel have recently renewed feral cattle eradication efforts on forest reserve lands, thus providing an incentive for ranchers to maintain boundary fencing. But two other introduced ungulates are now of primary concern in Hawaii natural areas. The feral goat frequents dry to mesic habitats on Kaua'i, Maui, Moloka'i, Kaho'olawe, and Hawaii. It is capable of devastating upland and lowland areas, resulting in barren landscapes, severe soil erosion, local extinction of rare plants, and degradation and elimination of habitat for rare birds and invertebrates. Damaged areas often become sites for invasions of alien fire-adapted grasses.

Feral pigs are now present in large numbers in wet forests and in lower numbers in mesic and dry areas on all major islands. These animals dig up forest ground cover consisting of delicate and rare species of orchids, ferns, mints, lobeliads, and other taxa; root for tubers, rhizomes, and earthworms; and consume tree ferns fCibotium spp.) and other ferns for their starch. Like goats, they create disturbed sites for the invasion of aggressive weeds and often aid in dispersal of such disruptive plant species as banana poka and strawberry guava (Psidium cattleianum).

Research and Management.—Feral goats have been successfully eradicated in natural areas through the use of boundary and barrier fencing and organized hunts by paid personnel or volunteers supervised by paid personnel (Baker and Reeser 1972; T. Rodrigues, pers. commun.). Goats in Hawaii Volcanoes National Park were reduced from 15,000 animals in a 260 km^2 area in 1970 to no goats within the fenced area in 1986. Costs of removal of the last wary animals varied from $28 to S159 each (Stone and Keith 1985). In Haleakala National Park, goats were reduced from 1,000 + 150 animals in 75 km^2 of habitat in 1985 (Ohashi and Stone 1985) to an estimated 450 in the same area in 1987. Cost of removal with largely volunteer teams in 1987 ranged from S7.40 to $32.60 per goat (salary and administration costs). Fencing the goat habitat in Halcakala National Park (completed in October 1986) has cost approximately $2 million, and fencing goat habitat in Hawaii Volcanoes National Park today (boundary fences only) would cost about $500,000. Goats have also been eradicated from Lana'i and are being removed from Kaho'olawe by the U.S. Navy with methods similar those used in the national parks.

Elimination of the last few wary goats from an area is facilitated by their social habits and by generally open terrain. In Hawaii Volcanoes National Park, radio-collared animals are released to find feral animals. These "Judas goats" are followed by hunters with radio receivers from the ground, spotted with feral animals, and helicopters are called in. Feral goats arc dispatched and Judas goats are left to seek other feral animals.

Eradication of feral pigs has also been achieved in fenced areas varying from 1-19 km^2 in size. Woven-wirefencing81-120 cm high with barbed wire stretched at ground level and woven wire anchored close to the ground is used. Fence costs vary from $6,800 to $28,500 per km.

Once an area has been fenced, pigs have been successfully removed through use of NPS-employed hunters with dogs and through use of snaring. Hunting in Hawaii Volcanoes National Park has resulted in the elimination of pigs from 6 of 9 areas varying in size from 1-19 km^2 and in the severe reduction (1-2 animals/km^2) of animals in three other areas. Pigs are more easily hunted with dogs in open mesic forests and shrublands than in closed canopy wet forest areas. Cost of removal (including hunter salary and administration) currently averages about $95/animal.

Snaring with customized multistrand 0.3-cm diameter cable snares obtained from Thompson Snare Company* (Lynnwood, Washington 98056) has been successfully used in remote Kipahulu Valley in Halcakala National Park. Two

♦Government endorsement is not implied.

areas have been snared. The upper area (692 ha), comprised of closed wet 'ohi'a (Metrosideros polvmorpha) forest and open shrubland has been enclosed by pig fence since March 1986. The lower area (573 ha) is wet koa (Acacia koa) or mixed koa-'ohi'a forest. The lower elevation parcel has been invaded by alien plants such as strawberry guava Hilo grass (Paspalum coniugatum). and kahili ginger (Hedvchium gradnerianum') (Anderson et al. in press).

There were 1,957 snares in the Valley as of January 1988, and 635,046 snare nights had been logged in the 22-month period since March 1986. Two hundred four pigs were removed at an average cost of S144 per pig (personnel costs only). Snare nights per pig increased from 940 in May 1986 to 13,870 in January 1988. An average of 2.6 person-days per pig has been required to remove animals (range from 0.7 to 10.0 during different periods). Snares are checked at 3-4 month intervals in this remote Valley. Total snare nights, number of pigs removed, and snare nights per pig are summarized in Table 1. Snare density now averages 155 snares/100 ha, and an average of 16.3 pigs/100 ha has been removed from the area.

Table 1. Summary of Kipahulu Valley pig removal program data.

Period	Snare Nights	Pigs Removed	Snare Nights /Pig
March-May 1986	31,008	33	940
May-June 1986	31,556	15	2,104
June-Sept 1986	105,756	42	2,518
Sept 1986-Jan 1987	143,397	33	4,345
Jan-May 1987	161,070	33	4,881
May-Aug 1987	198,730	29	6,853
Aug 1987-Jan 1988	263,529	19	13,870
TOTALS	935,046	204	mean = 4,584

Feral pig activity (presence of scats, tracks, trails, feeding on plants) is recorded at 10-m intervals along 17,500-m transects throughout the Valley. Decrease in activity with management is shown in Figure 1. Pig activity along transects in the upper 692-ha unit is essentially zero after 22 months of control. The upper unit has been snared longer and at greater snare density than the lower unit. Unfortunately, washouts along the lower elevation fence since closure in September 1986 have allowed pig ingress into the lower unit. Since removal of animals must be more rapid than recruitment to effect reduction and eventual eradication, this is of considerable concern. Closure of the fence and increasing snare density in the lower unit will be emphasized in 1988. The fact that the overall activity index is decreasing suggests that population reduction is being effected, and the data for the lower unit indicate that there is less activity in the lower as well as the upper unit.

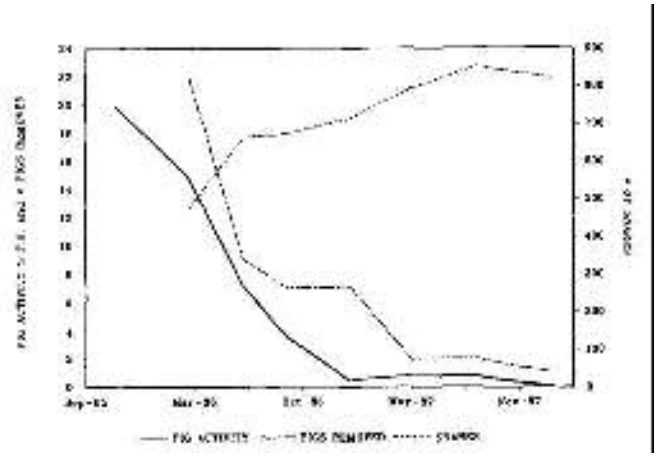

Fig. 1. Feral pig activity in response to pig removal using snares in upper Kipahulu Valley, Haleakala National Park.

In both parks, feral pigs have become more difficult to remove as control progresses. In Hawaii Volcanoes National Park, snares, drop-door and multiple capture traps (e.g., Brock 19 87), and fence traps have been somewhat successful, but many months and considerable personnel time are required to take individual animals. Use of a ramp to provide exit opportunity from a control area is being tested, and one-way gates have also been considered. In Haleakala National Park, extreme remoteness makes emphasis on individual animals difficult, but managers may eventually need to spend more time learning pig behavior patterns before removal of the last few animals. Chemical control has not been used in either park despite success and cost-savings elsewhere with Compound 1080 and anticoagulants (Hone and Stone, in press, Hone 1983). A proposal to test chemicals in a pen situation and to further test food and scent baits has been prepared.

CONCLUSION

Although the problem of introduced animals in Hawaii's natural areas is severe, progress is being made in reducing or eliminating ants, wasps, rats, mongooses, goats, and pigs. Goats and pigs have been successfully eliminated from many areas and severely reduced in others. Feral and mouflon sheep removal from Mauna Kea is proceeding well. Research to register a mongoose toxicant is nearly complete, and control-oriented research on ants, yellowjackets, rats, and cats is beginning. For alien birds which invade natural systems, the best approach so far has been to reduce fragmentation and invasion corridors caused by people. More research is needed on effects of alien birds on native forest birds

and other native and alien biota. Progress with control or eradication of alien animals can be made by dealing with units of high ecological value in which management is feasible; by applying techniques discovered and refined in management-oriented research programs; by adequately funded and persistent management efforts; and through use of continual monitoring to evaluate success.

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