

PART ONE

The Globalization of Nature

*The Causes and Consequences
of Biological Invasions*

CHAPTER 1

From Endemic to Generic

Feral Pigs and the Destruction of Hawaii's Native Forests

The hallways of Los Angeles International Airport are lined with posters—offering glimpses of faraway places—Bangkok, Kathmandu, Paris—each billed as uniquely exotic. I was rushing to catch an 8:30 flight to Honolulu when one of the destination posters caught my eye. It showed a lush ravine lined with flowering trees and shrubs, with a series of knife-edged ridges in the distance. Hawai'i. An exotic destination if there ever was one.

Or, more properly, an *alien* destination. It is unlikely that anything in that poster was native to the islands. The showiest of the flowering trees were African tuliptrees. The understory was mostly Indian kahili ginger. I was headed for a place that was largely no longer itself.

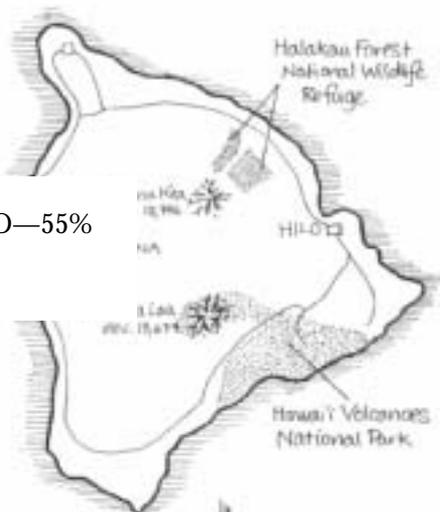
When the first Polynesian explorers arrived in the Hawaiian Islands about sixteen hundred years ago, upwards of 90 percent of the species they encountered were found nowhere else. This high level of endemism—the quality of belonging or being unique to a particular place—arguably made the islands the most biologically distinct place on the planet. These first Hawaiians converted some of the native lowland ecosystems to agriculture and caused the extinction of a number of species endemic to those habitats. However, because these people brought relatively few nonnative species with them on their 2,400-mile canoe voyage, the damage they did to Hawaii's native ecosystems was mostly limited to the lowland areas where they lived and farmed. (One notable exception is that a number of upland species of flightless birds were driven to extinction at least in part through overhunting.) Their impacts were not substantially different from those of any other agricultural people who settled a place where farming did not pre-

MAUI



PROTECTED AREAS

HAWAII
(THE BIG ISLAND)



FERAL PIG
Sus scrofa



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viously dominate the landscape: they cleared land, hunted animals, and gathered plants. Beyond the margins of their fields, Hawai'i remained largely Hawaiian.

The wholesale transformation of the undeveloped Hawaiian landscape gained speed only in the nineteenth century, when European explorers and settlers began to introduce one species after another to the islands in an attempt to make what they saw as a strangely depauperate and seemingly fragile environment a little more bountiful and robust. The response of the ecosystem to this constant influx of nonnative species made apparent some of the fundamental differences between an isolated island ecosystem such as Hawai'i and a continental system elsewhere in the world. The islands' ecological history created an inherent vulnerability to invasion by introduced species. Subsequent human-induced degradation further promoted the eventual devastation of the islands' native communities by invaders. Species by species and acre by acre, native Hawai'i has been disappearing since the moment it first appeared on a map.

When I got off the plane in Honolulu, the smell of the breeze across the open-air concourse was instantly familiar. It reminded me of Panama, where I'd lived for two years as a Peace Corps volunteer. Both the feel and the substance of the Hawaiian landscape were generically tropical. Apart from the mountains in the distance, there was nothing within miles to distinguish this from any other coastal city in any other tropical country in the world. Much of Hawai'i—in fact, almost all of the inhabited portion of the state—is now as generic as a strip mall.

Below 2,000 feet elevation, nonnative species overwhelmingly dominate the Hawaiian landscape, and even at higher elevations many native species are losing ground. Overall, nearly 50 percent of the species found in the wild on the islands are introduced. A large and growing portion of the state—in 1999, about half of Hawaii's land area—is no longer a native system that has been invaded by alien species; it is an alien system with a few native hangers-on. This process of transformation is creeping steadily upslope, each year moving a little higher into the remaining native forests.

Though many introduced species are implicated in the conversion of native systems to alien ones, there is a strong consensus among scientists and land managers that feral pigs, more than any other invader, are now responsible for initiating and driving this process further into the state's remaining intact native forests. As direct agents of forest destruction, pigs root up the soil, trample native vegetation, and eat sensitive native species. But their indirect impacts are perhaps even more significant. By creating openings and rooting the soil, pigs open up forests to invasion by disturbance-adapted

nonnative species—many of which are transported by the pigs themselves, as seeds in their droppings or in their coats.

I have come to the islands to document the many impacts of pigs on native forests, both directly and through the self-promoting complex of alien species that accompanies them. But I am also here to investigate the cultural and political implications of feral pig management, for this is an issue where the biological and the political are inseparable. Though the technology and the resources to control pigs are readily available, the issue of eradication—even in dedicated natural areas—is highly contentious. Whether any native forest still exists in Hawai'i a century from now depends to a significant degree on how feral pigs are managed over the next couple of decades.

A Refuge for Native Hawai'i

It takes at least a full day to hike into Kipahulu Valley. The mountains and cliffs that ring this valley in the highlands of eastern Maui comprise some of the most difficult terrain on the islands, and no public trails lead in from the outside world. But very few people have ever gone in on foot anyway. Kipahulu is a closed scientific reserve, and those with permission to enter generally do so via helicopter. Such rugged terrain has kept out more than just hikers and explorers. In this section of Haleakala National Park is some of the highest-quality forest remaining in Hawai'i—a forest where virtually everything is native, and almost all the historically recorded species still survive. This valley is the kind of place that has earned Hawai'i a reputation among conservationists as one of the most beautiful and most unusual places on Earth.

But no place in Hawai'i—not even Kipahulu—is entirely safe from invasion by nonnative species. The valley is crisscrossed by fences and laced with snares, the tools of a pig eradication campaign that began in the 1980s and that keeps the valley pig-free today. Even so, nearly a half century of pig presence prior to the eradication campaign allowed a number of nonnative plants to make inroads into the native vegetation, and the most frequent visitors to the valley today are Park Service weed control crews. It would now take, at most, only a decade or two of inattention even for Kipahulu, one of Hawaii's most pristine places, to fall into irreversible degradation.

Kipahulu's first systematic exploration came in 1945, when a pair of Park Service rangers ventured over from the Haleakala Crater to investigate the possibility of incorporating the valley into Haleakala National Park (at that time known as Hawai'i National Park). Chief Ranger Gunnar Fagerlund and Ranger-in-Charge Frank Hjort hacked through thickets of *uluhe* fern and



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The Kipahulu Valley is one of the most isolated and pristine ecosystems left in the Hawaiian Islands. (Steve Anderson)

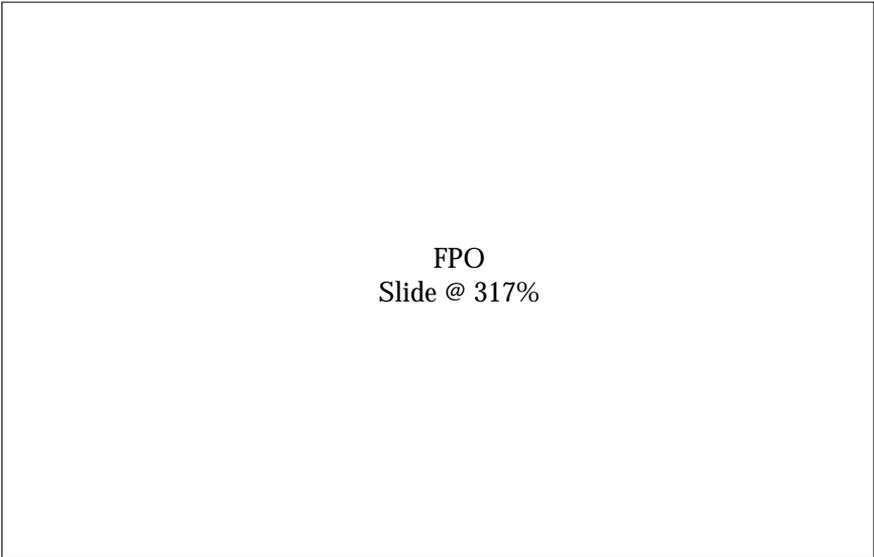
worked their way around cliffs on a five-day hike down to the coast. The forest was so dense and the terrain so rugged that even these experienced outdoorsmen covered only a mile or two a day. They reported seeing pigs just over the ridge from Haleakala Crater, but pig sign disappeared as they moved down into the valley. The valley was essentially free of alien plants all the way down to about 1,800 feet elevation. Fagerlund and Hjort described the valley as an ideal example of untouched “virgin wilderness” and strongly recommended that it be protected.

For the next twenty-two years, Kipahulu disappeared from the map. An occasional hiker might have ventured over the rim of the valley from Haleakala Crater and pig hunters probably worked the lower elevations, but there is little chance that anyone set foot in the heart of the valley until 1967, when a scientific expedition sponsored by The Nature Conservancy spent a month documenting the valley’s biological richness. The 1967 expedition found that, unfortunately, while human attention was turned elsewhere, nonnative animals had been moving in from above and below. From the 7,350-foot-high valley rim down to about 6,300 feet elevation, the landscape showed serious pig and goat damage, and alien plant species were establishing and spreading wherever rooting and browsing were most severe. At the bottom of the valley, the upper limit of heavy pig activity had moved

from 1,800 feet to 2,500 feet. And perhaps most significant, pigs were present even at the valley's once-pristine core. Though the expedition's report noted that pig disturbance in the central valley "appears to be minimal as yet," it emphasized in its recommendations that "immediate steps should be taken to reduce or eliminate the wild pig population. . . . Their damage to the vegetation is insidious but serious, and has in addition led to the establishment and spread of exotic plants in the valley."

The 1967 report provided the impetus for The Nature Conservancy to purchase a portion of the valley and transfer it that same year to Haleakala National Park. (The state of Hawai'i transferred ownership of the remainder of the valley to the Park Service in 1974.) The Park Service's initial management strategy was simply to designate the area as a closed scientific reserve and allow no public access whatsoever. However, reports from park rangers of serious weed infestations along the route of the main 1967 trail prompted the Park Service to send a small expedition into the valley in 1976 to ascertain whether human disturbance had opened up the area to invasion by alien plants. The 1976 expedition found that weeds had indeed spread significantly in some areas and that lower section of the 1967 trail—from about 3,500 feet elevation downward—was dramatically degraded. But the human impact of the earlier expedition was not responsible for the difference at lower elevations. Pig sign was everywhere in the area below 3,500 feet, and what had been mostly intact forest understory in 1967 was now a vast pig wallow. "It is impossible to determine what the effects of the 1967 expedition were in this area," the report stated, for "any effects have long since been masked by the effects of pigs."

The members of the 1976 expedition were worried not only by the presence of pigs but also by the spread of the strawberry guava tree into the valley from below. They also highlighted the possibility (confirmed in recent years) that "pigs may play a role in its spread, both in carrying seeds and in removing competing vegetation." Though earlier reports on the status of the valley had mentioned such a connection, the 1976 report was the first to note just how serious a threat the synergistic relationship between pigs and nonnative plants was to the integrity—and even the continued existence—of the native forest ecosystem of Kipahulu. Pigs were not only moving guava and other weeds up into the forest; the weeds were moving the pigs as well, for new infestations of guava trees served as higher-elevation food resources for pigs. "The current situation in the [lower] part of the valley . . . should probably be described as an emergency," the report concluded. In the strongest of language, it then urged that pigs be eliminated completely,



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Nonnative feral pigs have devastated many of Hawaii's remaining natural areas. (Jack Jeffrey Photography)

before the pig-driven process of forest transformation degraded the valley beyond hope of recovery.

No action was taken, however, until after a 1982 study assessed pig population levels quantitatively and made explicit the consequences of failing to remove the pigs. Among other likely impacts of continued pig presence, the study predicted that strawberry guava stands would continue to replace native forest, the pool of alien species would increase, and water quality would decline. These concrete data persuaded Congress to provide funding for eliminating pigs, and as the 1982 study neared completion, plans for an eradication campaign began to take shape.

At the same time, the Park Service launched an interdisciplinary research project to document ecological changes in the valley as pigs were eliminated from the ecosystem. The valley was divided into three management units, and all but the lowest reach of the valley (the area already dominated by aliens) was fenced in with hog-proof wire. Permanent transects and study plots were established in the middle and upper reaches of the valley to monitor density and impacts of pigs, as well as the relative proportions of native versus nonnative vegetation as eradication progressed.

Pre-eradication population densities in the valley were 6.0 animals per

square kilometer in the upper (more isolated) unit and 14.3 per square kilometer in the lower unit—both significantly lower than in many other natural areas. The Park Service team maintained an average of nearly 2,000 snares in the field for the forty-five months of the control program, ultimately removing 53 pigs from the upper unit and 175 from the middle unit. By January of 1989, pig populations in both units had dropped to zero.

Four years after the last pig was killed, the Park Service team revisited two of the most heavily damaged study sites (one in the upper unit and one in the lower unit) of those that had been evaluated for pig impacts before control was initiated. In the upper unit site, 60 percent of the forest floor was bare ground and 40 percent was in native vegetation just before pig control. Four years after pig eradication, the forest floor in the upper unit was completely covered in native plants. In the middle unit site, 7 percent of the forest floor was bare ground, 3 percent was covered in native species, and 90 percent in alien grasses (all of which are significantly more tolerant of pig rooting than are native species) before the pig control program was initiated. Four years after pig eradication, 70 percent of the forest floor in the middle unit was covered in native species and 30 percent in alien grasses.

According to Steve Anderson, Haleakala National Park's Natural Resources Program Manager, the difference between areas that showed complete recovery of native vegetation and those that did not was probably related directly to the intensity and duration of pig impacts. In the upper unit, pig invasion was recent enough and of low enough intensity that there remained rhizomes of native *pohole* ferns in the soil. Though pigs had introduced nonnative Hilo grass even into these most remote sites, the fern rhizomes in the soil allowed native vegetation to resprout and overtop the grass soon after pigs were eradicated. In the lower unit, however, pigs had been present long enough and at high enough densities that significant areas were entirely devoid of native vegetation—even roots and rhizomes—when pig eradication began. As a consequence, nonnative species introduced by pigs were able to establish themselves in persistent pockets throughout the forest.

While the upper unit once again enjoys almost pure native cover, the fate of the lower unit remains uncertain. The difference in recovery between the upper and lower sites suggests that the postinvasion window of opportunity in which full recovery is possible may be quite short and that even relatively low pig densities can have significant effects on native vegetation. In fact, Steve Anderson is convinced that in the long run, there is no such thing as an acceptable pig population density in native Hawaiian forest, for even at very low population levels, pigs will decimate sensitive native plant popula-

tions, create disturbed areas in the forest, and bring in invasive weeds. “If you’re managing for a full complement of native species,” he said, “the only acceptable level is zero.”

Much of Kipahulu was cleared of pigs within the window of opportunity that allows for full recovery of native vegetation. But many of Hawaii’s other native forests have long since passed the point where the more sensitive native species are likely to recover to anything resembling preinvasion levels. For example, ongoing pig presence at the Big Island’s Hakalau Forest National Wildlife Refuge may be driving to extinction the very native bird species and rare plants that the refuge was established to protect. Though this forest is also considered one of Hawaii’s most ecologically valuable, the degradation it continues to suffer even under conservation management may prove irreversible. Whether Hakalau survives as a native forest community depends largely on how quickly the refuge is able to follow Haleakala’s model and eliminate pigs.

Pigs and Birds in the Hakalau Forest

Jack Jeffrey doesn’t like to spend much time in the office. He is a wildlife biologist, and there isn’t much of biological interest in the vicinity of the U.S. Fish and Wildlife Service office in Hilo. When we met in the parking lot at 7:00 in the morning to head up to Hakalau Forest National Wildlife Refuge—the 33,000-acre tract of rain forest on the windward side of the Big Island that Jack is charged to protect from pigs, rats, weeds, and a horde of other threats—he didn’t waste any time on administrative details. As soon as the rest of the expedition arrived, we jumped in his battered green Fish and Wildlife Service truck and headed up the road toward the refuge.

Hilo is at the center of what was once a major sugar-producing region. The abandoned canefields that stretch for miles out of town are now overgrown with a tangle of nonnative trees and grasses. It is only above the upper reaches of the former agricultural lands—around 2,500 feet elevation—that small native ‘ohi’a trees begin to dominate the landscape. Past the old canefields, the road climbs through sparse, lava-strewn ‘ohi’a forest for about half an hour, but at about 6,000 feet, native vegetation gives way once again to agricultural lands. The mamane-koa forest that once blanketed the shoulders of Mauna Kea at these upper elevations was destroyed many years ago by cattle, goats, and sheep, and has been maintained as pasture ever since.

We turned off the main road and cut across the pasture to the northwest. It was an hour-long drive on a bumpy gravel track to the Hakalau field station. As we bounced and swerved along the road, Jack generally managed to

keep at least one hand on the wheel as he related the natural history of the forest and railed against the pigs that have invaded Hakalau. The two have been intimately linked since long before the refuge was established in 1985, and the continued presence of feral pigs is the single largest threat to the native species—even to the entire natural community—that the refuge is mandated to preserve.

“What is this refuge here for?” Jack demanded. The answer came in the same breath. “It’s here for preserving habitat for endangered species,” he exclaimed, with a clear emphasis on “endangered.” Under this definition, nonnative feral pigs clearly do not qualify as legitimate beneficiaries of refuge management. However, Jack is frustrated by the fact that pig control efforts are proceeding slowly and sporadically and have yet to reach large portions of the refuge. Among Jack’s primary responsibilities as refuge biologist (and what I was going to help him with today) are periodic surveys of pig activity at Hakalau. It is a part of his job he fervently wishes he no longer had to do.

We pulled into the field station around midmorning. From the station down to the forest edge, the dirt road wound between young koa trees that volunteers have planted by the thousands across the abandoned pastures that comprise the top portion of the refuge. Getting the trees to survive and establish was initially rather difficult, for open pasture is a much harsher environment than the small forest gaps to which koa seedlings are adapted. With a little experimentation, though, Jack and his colleagues developed a set of techniques that served as a surrogate for the protection that would have been offered by surrounding trees, and survivorship increased dramatically. Now birds are beginning to use the trees, and a few native plants—mostly tree ferns—have taken root in their shade. Over time, the planted koa trees will form a “nurse” environment that will allow the native ecosystem to move upslope into the old pastures. “Plant it, and they will come,” Jack said. The strategy appears to be working. Some of the more common native birds have already been sighted in the young koa groves.

The immediate goal of reforestation is simply to begin the restoration of native vegetation on the degraded upper reaches of the refuge. Over the longer term, though, its purpose is more specific and in a sense far more urgent than overall ecosystem restoration: to reconnect the koa-‘ohi’a forest in the refuge with the remnant forest of mamane trees further upslope. The goal of such a project is to reestablish an unbroken corridor from mid- to high-elevation forests, for it now appears that the survival of many of the refuge’s birds may in the long run depend on access to higher-elevation habitat. While all of Hawaii’s common endemic forest birds and five of the

island's seven endangered forest birds are found on the refuge, today almost none of the rarer species are found below 4,500 feet. At lower elevations, there are nonnative mosquitoes that carry introduced diseases—avian malaria and avian pox—against which native birds have virtually no resistance. Below this invisible line, bird mortality increases sharply, and the endangered species are the first to go.

But all of this replanting may be too late for the endangered birds. *Culex quinquefasciatus*, the species of mosquito found on the islands, is distributed across the tropical, subtropical, and warm temperate regions of the world, and there is no biological reason why it can't survive at much higher elevations. Though surveys have so far found few adult mosquitoes in forests above 4,200 feet at Hakalau, incidence of disease is definitely moving upslope. As late as 1977, the Hawai'i creeper was found almost down to 2,600 feet, but in 1995 it was found only above 4,500 feet. Scientists studying avian disease believe that although breeding populations of mosquitoes are now established only at lower elevations, the species is such an efficient vector of avian disease that the small numbers of mosquitoes blown to higher elevations by onshore winds may be enough to infect and kill significant numbers of native birds well above the elevation where mosquitoes currently breed. The replanted koa forest might not establish itself quickly enough to provide mature habitat in time for the birds—especially given the pressures that are driving disease upslope through the refuge.

The most worrisome of these pressures are the habitat changes caused by feral pigs. We parked the truck at what is now the upwardmost edge of the forest and began our hike down into pig territory. For the first hundred yards or so, we followed a fence between a unit with many pigs and one with relatively few. The difference between the two was obvious: On the side of the fence with high pig density, pig sign was everywhere, and there was as much bare ground as grass (most of it nonnative). But on the other side, we had to work our way through and around and under downed logs and tree ferns and thickets of native shrubs. Unlike the highly disturbed tract on the other side of the fence, the matrix of this forest was still largely composed of native species.

Nonetheless, damage in the unit with fewer pigs was everywhere—the signs were simply harder to see. We stopped for lunch in a small clearing left by a downed tree fern—a sure sign of pig presence. The starchy cores of tree fern trunks are a preferred food for pigs, and toppled ferns are a common sight in this forest. Their hollowed trunks are the source of another subtle but catastrophic consequence of pig presence: Once a tree fern's core is eaten out, the trough that remains fills with water and becomes a perfect location

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Well-maintained pig-proof fences are an essential component of the management of Hawaiian natural areas. (Jack Jeffrey Photography)

for mosquitoes to lay eggs. Though there is sometimes enough standing water in streambeds at Hakalau for mosquitoes to breed, pigs increase the availability of standing water in the forest. Given the efficiency of even very low densities of mosquitoes at transmitting avian disease, the habitat modifications that pigs cause are at least partially responsible for the fact that there are no endangered native birds below 4,000 feet at Hakalau.

According to Dennis LaPointe, a scientist who studies avian disease at the U.S. Geological Survey Pacific Island Ecosystems Research Center's Kilauea Field Station in Hawai'i Volcanoes National Park, the Hakalau Refuge is courting disaster by focusing its efforts on the top of the refuge. "Pig management should be from the lower boundary up, not from the upper boundary down," he said. No one can be sure how quickly disease will continue to move upslope, but pig disturbance in the lower reaches of the refuge can only make the invasion spread faster. Jack Jeffrey was just as emphatic about the urgency of the pig problem. "Time is of the essence with these birds, and we have to do something soon," he said. "If we don't have the backing of the public and the money to do control work, I see us still killing pigs twenty years from now. And by that time the birds will survive only at the upper reaches of the refuge—if they are still around at all."

Jim Jacobi, another biologist stationed at the Kilauea Field Station,

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This native Hawaiian *apapane* is being bitten by a nonnative *Culex* mosquito, a species that carries diseases deadly to Hawaii's native birds. (Jack Jeffrey Photography)

agreed. He emphasized that there would be a significant lag time between the elimination of pigs and the disappearance of the breeding grounds they have created, for the cavities created by pig-toppled tree fern trunks may persist for years. “This is a desperate situation,” he said, “and we’ve got to deal with these problems *now*.”

In addition, there may be very little time left to save the critically endangered plants on the Hakalau Refuge. On the way back up to the truck, Jack pointed out a native lily growing high in the cleft of a tree. “Where there are no pigs, that plant is common on the ground,” he said. Many of the endangered plants on the refuge are in trouble specifically because pigs find them particularly attractive. One such plant—*Cyanea shipmanii*, a palmlike understory species—is represented in the wild by only five known mature plants (and a hundred or so seedlings in Hakalau’s plant nursery). Constant disturbance and predation by pigs prevents effective reproduction, and it is likely that the natural seed banks for these species are tremendously depleted. Chronic low-level pig impacts are not as dramatic as massive invasion, but for the most sensitive species, the long-term consequences can be equally catastrophic.

After a certain point—and at Hakalau that point may have already been passed—spontaneous recovery of such species becomes unlikely, even after

many years of release from pig pressure. For example, the Waikimoi area on Maui was noted in the 1920s for the tremendous numbers of lobeliads (a group of native understory plants) that grew there. When pigs invaded the area some time around midcentury, the lobeliads were probably among the first to suffer significant damage. In 1983, The Nature Conservancy purchased Waikimoi as a nature preserve and promptly began a pig eradication program. But although pigs have been eliminated from most management units and are scarce in the remainder, some species of lobeliads are still rare, as are the native honeycreeper birds that rely on their nectar as a food source. At Hakalau, it is likely that many sensitive plant and animal species have already suffered similar long-term damage.

According to Dick Wass, the refuge manager for Hakalau, it will take at least twelve more years to clear the entire refuge of pigs. "We don't actually have a target date for complete eradication," he said. "We don't want to do this all at once." In the mid-1990s, control efforts were stalled for a year as the refuge wrote a "Feral Ungulate Management Plan" and prepared an Environmental Impact Statement for the plan. In 1998, control was just getting under way once again, but it will be years before lower remote sections of the refuge are even fenced, let alone cleared of pigs. The Fish and Wildlife Service has not developed nearly as much momentum or capacity in feral ungulate control in Hawai'i as has the Park Service, and its lack of experience shows in its reluctance to pursue with single-minded dedication its mandate to protect native species and ecosystems. "I'm really concerned," Jim Jacobi said, "because I don't think Fish and Wildlife has the staff or the money to deal with these problems." The future does not look bright for the birds and plants that Hakalau was established to protect.

The long-term consequences of continued pig impacts at Hakalau have the potential to extend well beyond the loss of native birds and understory plants. Scientific research in Hawai'i is just beginning to expand its emphasis from endangered species preservation to whole-ecosystem conservation, and a major focus of this work will be the impacts of the decline or loss of individual species on overall ecosystem integrity. Although work is in the early stages and no concrete evidence yet exists, it is conceivable that the loss of some key pollinator of a major native tree species could have cascading effects throughout the forest ecosystem. Perhaps most worrisome is that the ecosystemwide effects of the loss of this kind of key species would not be felt until long after it was too late to do anything about it. "If you've frayed the fabric too much," said Maui forester Bob Hobdy, "it falls apart." Where the point of such catastrophic change falls will vary with circumstances, but there is always a point beyond which recovery is not possible. Hakalau may still be a decade or two short of that point. But the longer pigs remain, the

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About half of the state of Hawai'i—the lightly shaded coastal areas on this map—are mostly or completely dominated by alien invasive species. (Hawai'i Natural Heritage Program)

more likely it will be that the forest will enter a long downward spiral of degradation from which there can be no return.

Many places in Hawai'i are already well past this catastrophic point. The Nature Conservancy's base map of Hawaii's remaining native communities leaves about half of the state blank. These are the places where most conservationists have given up, because the native ecosystem has essentially disappeared and any natives that remain are no more than isolated remnants. The conservation community has learned to let the few natives in these places go because, as Alan Holt of The Nature Conservancy put it, "No matter how much money you spent, you could not bring these places back." Places that are past the point of no return are of conservation interest only in that no one wants to see them grow any bigger. They are like a cancer that metastasizes, spitting out invaders into the still-healthy portions of the Hawaiian ecosystem. With dedication and consistent effort, the invaders might be contained indefinitely—but such places are themselves lost.

"The Hawaiian Tropical Paradise"

We could have been driving through the poster I saw at L.A. International Airport. The narrow coast road along windward east Maui was lined with

gorgeous tropical foliage and jammed with tourists who should have been keeping a closer eye on the road. The views from this road are the kind that have earned Hawai'i status as a "tropical paradise" in the minds of visitors and residents alike. But like the scene in the airport poster, this paradise is Hawaiian only in the eyes of those who created it. Almost all of what is native to this place is gone. These are the blank places on the map.

Bob Hobdy and I wound our way across one lush tree-lined ravine after another, with mountains rising from the road's edge and ocean reaching out to the horizon. Bob has seen many changes in the island's forests—most of them for the worse—in his years as a forester and a naturalist on the island of Maui. We took a drive along the windward Maui coast on a sunny January afternoon to discuss the impacts of a century of management on the island's forests.

Forestry in Hawai'i began not out of concern for the forests themselves, but rather for the vast quantities of fresh water they provide. In a land of steep slopes and no lakes, forest foliage and root-bound soil are the islands' principal water storage system, holding water like a sponge and releasing it in a steady flow. As early as the late 1800s, agricultural interests began advocating forest protection, and many large private plantations and ranches set aside forested land above their fields in order to ensure an adequate water supply. The territorial government followed suit in 1903 with the creation of a Forest Reserve System, with the intention of maintaining permanent forest cover on territorial lands that were not used for other purposes. By 1939, more than a million acres of reserve land set had been aside, about 150,000 acres of which were on Maui.

While much of the land designated as reserves was still in native forest, significant portions had already been denuded by loggers and ranchers or by feral animals at the time they were incorporated into the system. As a consequence, tree planting was nearly as important an activity of the Division of Forestry as was protection of existing forests. The vast majority of the trees planted, however, were nonnative. In 1908, a massive unexplained dieback of native forest on flat-topped ridges in Maui caused great alarm throughout the islands and fueled the drive to plant nonnative tree species. Prevailing opinion in the early years of the twentieth century was that decline of native forests was inevitable and that replacement with fast-growing, aggressive introduced species was the only way to maintain forest cover. As a consequence, Hawaii's forests did not simply succumb to self-spreading introduced trees; in many cases, they were actively replaced by foresters who believed that just about anything was better than native forest that died inexplicably and left nothing but shrubs and ferns to hold the soil.

But Bob Hobdy is not convinced that the native forests were intrinsically that fragile. While research in the 1970s and 1980s demonstrated that 'ohi'a dieback is in many cases a natural, cyclical phenomenon, Bob suspects that this particular forest dieback may also have coincided with the first large-scale invasion of these native 'ohi'a forests by feral pigs. In that case, the real cause of the "Maui forest disease" may have been a catastrophic alteration of basic ecosystem dynamics. In fact, Bob said, chances are good that rooting and compaction by large numbers of pigs could have made the wet soil on flat-topped ridges anoxic (greatly deficient in oxygen), killing tree roots and inhibiting the establishment of seedlings. While large feral mammals were considered vermin and pig control was a part of forest reserve management programs at the time, early foresters did not have the resources to eliminate pigs from the vast areas of forest that they had invaded. Pigs pushed the 'ohi'a into a steep decline, and the loss of native forest became a self-fulfilling prophecy as nonnative trees were brought in.

Bob has witnessed the loss of many thousands of acres of native forest in his years on Maui. He pointed over the mountains toward a remote area on Maui's far east end that he knows well. In the 1970s, he had flown over what had been a near-pristine 'ohi'a forest in that area just after it had been invaded by pigs. "The effect was really catastrophic," Bob said. The pigs had turned the whole place into a mudfield, and today, the entire area is a sea of alien weeds. In this case, the process of conversion to an alien system needed no help from humans. Even though many of the overstory trees survived the initial invasion, the forest ecosystem is on its way out, for the weeds prevent the establishment of native tree seedlings. The remaining mature trees are little more than standing ghosts.

Pigs are implicated in the destruction of native wet forest more often than any other introduced species. What they leave behind is the kind of semifunctional hodge podge of alien species that we drove through for hours along windward east Maui. "That's the stunning thing here," Bob said. "Most places you go in the world, you can find at least some natives mixed in. But here the domination is complete." We pulled off to the side of the road so I could take a few pictures. I asked if there was anything native within view of where we stood. Bob spent a minute surveying the vegetation before he answered. "No," he said slowly. He shook his head as we got back in the truck. This native forest has not simply been altered, he explained. It has been replaced. This is an entirely new ecosystem.

And this is a system that continues to change as more invasive species are introduced. A few miles down the road, we stopped at the Waikamoi Nature Trail, a popular tourist spot known for its 2- and 3-foot-thick euca-

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In some places, a second wave of even more aggressive invaders is replacing earlier non-native arrivals. This stand of Australian black wattle trees is being smothered under a carpet of South American banana poka vines. (Hawai'i Division of Forestry and Wildlife)

lyptus trees (an introduced species) that were planted in the 1930s to control erosion. As we walked through the grove, Bob pointed out that there are virtually no young eucalypts taking hold among the thickets of ardisia—a large introduced shrub—that forms the understory along the trail. Ardisia and a handful of other relatively recent introductions appear to be the next wave of dominant invaders in Hawai'i. Since the environment they have invaded—the alien-dominated lowland forest—was itself composed of aggressive nonnative species, the plants that comprise this second stage of invasion are tougher still. Most are short-statured, shade-tolerant plants that in their native habitats are either understory or early successional species. Here in Hawai'i, these invaders tend to form impenetrable 10- to 30-foot-high single-species stands under which almost nothing else will grow. The result is a tangle of undergrowth so aggressive that it allows no overstory. Lowland east Maui may be turning into a forest without trees.

Bob is not optimistic about the future of Hawaii's remaining native forests. "I believe that we have set in motion biological processes over which we have scant control," he said. There are dozens, perhaps hundreds, of introduced plants present in Hawai'i that are waiting for an opportunity to invade a favorable environment and spread explosively. Healthy native

forests can resist invasion by all but a handful of these introduced species—but only so long as they are free from nonnative disturbance. Wherever pigs and other introduced mammals incur upon native forest, that forest will suffer drastic losses of sensitive native plants, invasion by alien weeds, and in some cases a drop in native bird populations. Inevitably, that forest will be pushed toward the kind of generic ecological pandemonium that is already the rule in much of what once was Hawai'i.

The Making of a Vulnerable Ecosystem

Are Hawaiian ecosystems uniquely vulnerable to catastrophic change as a consequence of invasion by nonnative species? Do islands suffer from an intrinsic fragility unknown on the mainland? The evidence would seem to indicate that they do—or at least that Hawai'i does. For example, nonnative birds introduced to Hawai'i have successfully established at a much higher rate than is the rule for introductions on continents. While an average of only about 10 percent of continental introductions become naturalized, more than half of the birds introduced to Hawai'i by European settlers have breeding populations on the islands. And the fact that half of the state (including large stretches of uncultivated land) is dominated by nonnative species serves as evidence that introductions to Hawai'i have been remarkably successful.

The most commonly cited reasons for vulnerability to invasion in the Hawaiian ecosystem and in island ecosystems are ecological. For instance, many insular species are not as well defended against predation, disease, and herbivory as are their mainland counterparts, which means invaders are often presented with abundant, easily consumable food resources. (Jack Jeffrey said that from a nonnative feral animal's point of view, Hawaii's forests are "just like a salad bar.") The absence of many kinds of organisms in the native biota of most islands—few or no large predators or herbivores, for example, and few diseases and parasites—provides invaders with unoccupied niches in which to establish and frees them from the competition and predation that otherwise would keep them in check. As was noted in a recent analysis of Hawaii's predicament, "Isolated oceanic islands were predisposed to certain types of human-related invasions because of long isolation from the continual challenge of some of the selective forces that shape continental organisms."

But these sorts of intrinsic ecological factors are not the only reasons for Hawaii's vulnerability to invasion. Some kinds of vulnerability have been induced by the choices people have made about land use in an island ecosys-

tem, and Hawaii's current state is as much a product of its history as of its biology. There are several ways in which human actions have served to exacerbate the intrinsic vulnerability of this isolated ecosystem.

First, Hawai'i was by no means a "pristine" environment when Europeans arrived and began to introduce large numbers of alien species. Polynesian settlers and their descendants had at one point farmed or burned almost all land below 2,000 feet elevation, and this kind of massive disturbance probably made these lands significantly more vulnerable to invasion than the undisturbed ecosystem would have been. In addition, Polynesian hunting pressure had already driven a number of bird species to extinction before European settlement, creating artificially open niches in bird communities that left them more vulnerable to invasion by introduced birds. In short, the fact that some Hawaiian ecosystems were significantly altered by humans for a thousand years before European-induced invasions began may have been just as responsible for the vulnerable condition of the Hawaiian biota as were the evolutionary effects of isolation.

Second, Europeans tended to discount the value and the hardiness of native island species, and as a consequence, the Hawaiian chain has been subjected to an inordinately large number of species introductions in historic times. State agencies and private individuals have brought in more than 80 species of game animals to provide sport in an environment that had almost nothing native that was worth shooting. Plant enthusiasts have imported showy ornamentals from across the tropics, and foresters have planted anything that might conceivably grow, together adding roughly 10,000 alien plant species to the islands' 1,000-species native flora. In the early 1900s, a group of Honolulu residents went so far as to form a club whose sole purpose was to import birds to Hawai'i, bringing in 52 nonnative songbirds over the course of several decades. Perhaps in part because European settlers saw Hawai'i as an empty place waiting to be filled, its native biota is outnumbered by attempted introductions to a degree not often seen in continental ecosystems.

Finally, existing invaders have begun to create opportunities for new invasion that have little to do with the inherent vulnerability to invasion of the original native ecosystem. For example, the spread of feral pigs into native forest has been driven at least in part by the range expansion of strawberry guava and other nonnative food sources such as introduced earthworms. There are dozens of such examples of ecological relationships between nonnative species that have eclipsed the constraints of the original system, where the rate of establishment of new nonnative species is increasingly independent of the characteristics of the native ecosystem. While

Hawaii's vulnerability has its origins in the islands' evolutionary ecology, the process of ecosystem transformation that threatens to destroy what remains of native Hawai'i has taken on a life of its own.

What this all means is that induced vulnerability to invasion may in the long run be at least as significant as intrinsic vulnerability in determining the pace and the path of ecosystem conversion to domination by alien species. As a consequence, continental ecosystems may under some circumstances become just as vulnerable to catastrophic transformation as are island ecosystems. Many different combinations of intrinsic and induced vulnerability can create an opening for the kind of invasion that can trigger a critical shift in some fundamental ecosystem process such as nutrient cycling, food webs, or disturbance regimes, thereby putting a broad spectrum of once-dominant native species at a general competitive disadvantage. This sets up a positive feedback cycle by which nonnative species rapidly take over both the dynamics and the composition of the system.

The Mechanics of Pig Control

While the consequences of this kind of positive feedback are sometimes largely irreversible, in other contexts there is still much harm to be prevented and much restoration that can be done. In any ecosystem—insular or continental—often the most powerful means of preventing or even reversing ecosystem transformation by invasive alien species is to eliminate the forces that fundamentally alter ecosystem processes. In Hawai'i, this above all means eliminating pigs from native forests. Pigs change the rules of the game, forcing native species to compete in a system whose dynamics no longer match those species' evolutionary history. As Alan Holt of The Nature Conservancy of Hawai'i has argued, the Hawaiian ecosystem is durable and viable only if "the fundamental rules don't change too much." Trying to protect native species without first getting rid of pigs and other feral ungulates is like trying to push water uphill—you would do much better to realign the terrain first. Therefore, while combating specific plant invaders is often useful and sometimes quite necessary, weed control alone is not as effective as eliminating the engine that opens up the system and drives in the weeds to begin with.

The technologies for eradicating pigs are well developed. Hawai'i Volcanoes National Park on the Big Island was a pioneer in feral pig eradication, and in the 1980s, the park showed that eliminating pigs was possible even in dense forest and extremely rough terrain. The key to its success was single-

minded determination in pursuit of its goal. Beginning in 1980, park personnel fenced off tracts of land, used professional hunters and trained dogs to bring the pig population level down, and then set snares and traps and hunted by helicopter throughout the area to kill the few remaining pigs. Most of the pigs were killed during the first six months of the program, but complete eradication took about three years and required the use of snares and traps.

The extra effort required to kill the last few pigs—and it was a major effort, since the ones that consistently manage to evade hunters are tremendously wary and elusive—was absolutely crucial. Merely keeping pig populations suppressed through sporadic public hunting would have done little for the preservation of the park's sensitive natural areas, for at least 70 percent of a population must be removed each year in order to have any effect on pig numbers. (Between 1930 and 1980, over 11,000 pigs were killed in the park mostly through sporadic hunting, with no appreciable effect on long-term pig numbers.) Even a professional hunting program would have been a waste of both time and money if it had failed to make complete eradication its goal. This kind of thorough, systematic approach has been the model for every one of the natural areas in Hawai'i that has been successfully cleared of pigs.

Given the political will, it would be possible to eliminate pigs from most if not all remaining natural areas on the islands within a decade or two. But while some progress is being made, eradication is not happening nearly as fast as it could. The most immediate reason for slow progress is lack of funds. However, the real impediment to eradication is not financial, but social. Pig hunting is of great cultural significance to a small but highly vocal segment of the state's population (some native Hawaiians, others descendants of more recent settlers). In addition, some animal rights groups have in recent years made pig snaring one of their key issues. So long as a significant portion of the population remains sympathetic to the notion that pigs are legitimate residents of native forests or believes that pig presence is preferable to snaring, Hawai'i's native species will continue to disappear as pigs degrade the state's remaining natural areas beyond recognition.

Pigs and People

Pigs have been in Hawai'i for almost as long as people have been there. The second wave of Polynesian settlers probably brought pigs with them by canoe when they arrived around the twelfth or thirteenth century. However, the pig that the Polynesians introduced is not the same animal as the one that is destroying forests today. The modern feral pig is descended largely from

European pigs that escaped or were released from hog farming operations over the last few hundred years. While Polynesian pigs were generally rather small and rarely ventured far from the coastal villages where they were raised, their European cousins are much larger and more fecund and move readily into remote areas.

Unfortunately, very few people make any distinction between these two very different animals. They have transferred the cultural significance of the Polynesian pigs onto the mostly European hybrid that has replaced them—the only pig most hunters have ever known. The confusion is compounded by the fact that rural culture in Hawai'i has largely shifted from a subsistence to a cash economy. What is now largely sport is still suffused with the language of need, creating a strong emotional argument that plays well in the popular press. Articles with titles like "Oahu Pig Hunters an Endangered Species" and "As Preservation Efforts Rise, Hunters Fear Own Extinction" are common in Hawai'i newspapers, and any threatened loss of hunting ground is met with vigorous protest.

Many hunting advocates feel that they have already given up too much to a cause whose benefits they do not value. George Martin, a pig hunter on the Big Island, doesn't believe it can be proven that pigs are destroying the forests. The problem, he says, is that scientists have too low a threshold for what constitutes "destruction." He concedes that there is a role for fencing and eradication, but only of very small plots to protect representative samples of rare plants. Fencing pigs out of thousands of acres of forest, George contends, "is wrong." He believes that pigs in fact do a service to the forest by rooting out nonnative species—a contention any scientist will hotly dispute—and that the forest can adapt to pig presence.

The consequences of this culture are manifested in the patchwork of conservation areas and pig management areas that continue to vie for position on the Hawaiian landscape. For example, the two major units of Hakalau Forest National Wildlife Refuge are divided by a tract of state land that is managed specifically for a sustained yield of pigs. Statewide, there is one federal program that provides Hawai'i with funds to manage nonnative game animals and another that pays for fencing and eradication of these same animals, often on adjacent tracts of land. Even on land dedicated to native ecosystem preservation, pig control is sometimes too hesitant to be effective because pig hunters with little knowledge of ecology are allowed to influence decisions about ecological conservation. Until land managers feel they have a local as well as a national mandate to eradicate pigs, only the most creative and persistent among them will be able to muster the resources and the backing to get the job done.

Pig eradication is further complicated by an animal rights campaign that targeted The Nature Conservancy and the state of Hawai'i throughout the early 1990s for their use of snares. People for the Ethical Treatment of Animals (PeTA) launched a letter-writing campaign, picketed The Nature Company and other major corporate donors to the Conservancy, promoted antisnaring legislation in the Hawai'i legislature, and vandalized several Conservancy preserves in Hawai'i. Both the Conservancy and the state were forced to divert significant resources to countering the misinformation that was spread as part of the campaign. Ironically, some hunters joined forces at least temporarily with the animal rights campaign to ban snares. Their combined efforts set back pig control significantly in several natural areas at a time when there was no time to lose.

At the same time, the antisnaring campaign forced the conservation community to articulate the rationale for snaring in particular and for pig control in general, and to find ways to create a larger community of support for native forest protection. The Nature Conservancy took the lead in improving public appreciation for native ecosystems and public understanding of what it takes to protect them, but many other agencies and individuals did outreach work as well. The key was to make abundantly clear what was at stake: the survival of Hawai'i's remaining native forests and of many of the species that comprise them.

For most people, the rationale for pig eradication makes sense once they learn something about the ecological consequences of inaction. Virginia Mead, a member of both The Nature Conservancy and PeTA, had initially been opposed to the use of snares, believing that there ought to be alternatives to snaring even in the most remote and rugged sites. "I went to the PeTA-TNC meeting pushing for an end to the snares," she explained. "I came out understanding that removing the snares before a viable alternative is implemented dooms the native animals to a cruel death and the extinction of their species." And Eddie Oliveira, an east Maui native and lifelong pig hunter, recognizes the importance of pig eradication as well. "To preserve our native forests, we need fencing to keep the pigs out," he said. His appreciation for native forests comes from a lifetime spent in the mountains, and the fact that he is on good terms with both the native forest and his human neighbors has done much to advance the cause of conservation in his east Maui community. Hawai'i needs many more like him.

The last time I was in Hawai'i, I stopped in at a small barbershop in the village of Mountainview on the Big Island to get a haircut. The shop was in the

front room of a house on the only street in town. I sat down in the chair, and the woman who ran the shop asked me what brought me to town. I told her I was writing a book on the impacts of nonnative species on natural areas and was headed up to Hawai'i Volcanoes National Park to talk with a couple of biologists about pigs. "Oh, those pigs do a lot of damage," she said. And as she cut my hair, she talked about growing up on the island and about the native birds she used to see when she was young.

More than fences, more than snares, more than weed crews, Hawaii's forests depend on people like her. As much as it is driven by ecology, conservation is ultimately a human enterprise. The fight to protect Hawaii's native diversity from pigs and weeds must be won in barbershops and living rooms before it can hope to succeed in the remote valleys and mountains.

