fern's restricted habitat in a small crater on Koko Head, O'ahu. Of these alien species, ricegrass (Echinochloa colona) was recognized as the most serious competitor of Marsilea (Wester and Ikagawa 1988). At present, this site is managed by The Nature Conservancy of Hawaii, and volunteer groups are monitoring plant cover and removing encroaching alien grasses.

Fire

Natural Fire Regime and Fire History. Vogl (1969) proposed that naturally occurring fires, primarily from lightning strikes, have been important in the development of the original Hawaiian flora, and that many Hawaiian plants might be fire adapted. While accepting lightning as a potential ignition source, Mueller-Dombois (1981a) pointed out that most natural vegetation types of Hawai‘i would not carry fire before the introduction of alien grasses. Native plant fuels typically have low flammability (Smith and Tunison, in press). However, fire probably influenced evolution of the montane ecosystems of Maui and Hawai‘i, which contain grasslands of the native Deschampsia nubigena and stands of native shrub species and koa (Acacia koa). As for rain forest vegetation, Mueller-Dombois (1981a) cited evidence from charcoal layers in soil pits that indicates an extremely low frequency of fire once every 700-1,000 years prior to human occupation of the Islands. Since carbon in soil layers may also represent lava flows or phreatic eruptions rather than free-burning fires, the true incidence of natural fire may be even rarer (Smith and Tunison, in press). Smith and Tunison concluded that although natural fire regimes in Hawai‘i are "difficult to reconstruct," they are for most areas "best characterized as fire-independent."

In historic times, a few large rain forest fires have been reported, although it is usually unclear whether burned forests were intact or contained aliens that might have encouraged fires. During a drought in 1901, a fire burned an area 24 km (15 mi) long and 3-6 km (2-4 mi) wide in the southern part of the Hamakua District of Hawai‘i Island (Hall 1904). The composition of the forest was described as ‘ōhi‘a (Metrosideros polymorpha) and koa with an understory of ferns, which after the fire was apparently followed by a "growth of weeds." This fire is said to have burned for "months" and destroyed forests over an estimated 12,150 ha (30,000 a) (Bryan 1961a). Other large fires apparently occurred in Hilo and Hamakua forests in the middle of the 19th century, and the native forest trees were able to regenerate (Hall 1904, Horner 1908). Another long-burning fire occurred near Kula, Maui, in the 1880s and reportedly burned for weeks (Nelson 1967).

In the early decades of the 20th century, forest fires in Hawai‘i were usually blamed on the flammability of the indigenous matted fern uluhe (Dicranopteris linearis), which was considered a pest (Judd 1931) and thought to be a nonnative introduction (Bryan 1926b; Hostetler 1970). In 1926, an uluhe-fueled fire burned for a week, destroying much of the Pana‘ewa Forest Reserve near Hilo and causing businessmen and homeowners of Hilo to fear for their property (Chamber of Commerce of Hilo 1926). This forest had somehow escaped development during the Hawaiian period despite its proximity to agricultural lands of Hilo (McEldowney 1979) and had been dominated, at least in its interior, by native trees when Isabella Bird passed through in 1873 (Bird 1966). After the fire, the burned area was planted with alien trees (Bryan 1926b), which today dominate most of the remaining forests of the Pana‘ewa area.

Although large fires have certainly occurred in predominantly native vegetation (see Smith and Tunison, in press, for evidence of a large fire on Mauna Loa slopes 400 years
ago), widespread invasion of alien fire-adapted grasses in the early 20th century (e.g., fountain grass (Pennisetum setaceum), broomsedge (Andropogon virginicus), molasses grass (Melinis minutiflora)) is primarily responsible for the great increase in wildland fires in the second half of the century. Within a few decades of introduction, these grasses and others became well established in open forests and shrublands, as well as in the already-disturbed lowlands. Undoubtedly, an increasing human population and greater access to natural areas probably also played a role in increasing fire frequency.

Very few grasses were introduced in the first half of the 19th century (Nagata 1985), probably because large commercial ranching did not become well established until much later in the century. As ranches continued to be developed and expanded, many grass species were introduced and tried as forage plants (Hitchcock 1922). The period from 1906 to 1936 saw the introduction or first collection of most of Hawai‘i’s range grasses (Whitney et al. 1939). Even grasses of little forage value were brought in accidentally with the seed of palatable species. In some ranchlands, such as Kaupo on Maui, large areas were deliberately burned and seeded with pasture mixes (C.W. Smith, pers. comm. 1989).

Wildfires have increased in both size and number throughout the 20th century. Between 1904 and 1939, there were 205 forest and brush fires reported in the Territory; these burned approximately 14,780 ha (36,500 a), a yearly average of 420 ha (1,044 a). By contrast, in the period from 1940-76, at least 878 fires occurred, burning a total of 83,660 ha (206,650 a), or an average of 2,320 ha (5,740 a) per year, nearly a six-fold increase over the area burned in the previous 35 years (Schmitt 1977). In the 25-year interval between 1921 and 1945, foresters of Hawai‘i Island recorded only 61 forest fires (Bryan 1947). Forty years later (1986), a total of 73 fires occurred in just one year on Hawai‘i Island (Hawaii State Department of Business and Economic Development 1988), and the total area of forest and shrubland burned in the State exceeded 10,100 ha (25,000 a).

This same pattern of increasing fire size and frequency has been observed in Hawaii Volcanoes National Park, where accurate records of fires have been kept since 1924. The Park supports large stands of relatively dry ‘ōhi‘a forest and native shrublands in a lowland zone between 305 and 1,070 m (1,000-3,500 ft) elevation; below this is a coastal area previously modified by Hawaiians. The ground cover in both these lowland zones is now dominated by alien grasses. Before the establishment of alien grasses, particularly broomsedge, bush beardgrass (Schizachyrium condensatum), and molasses grass (Melinis minutiflora), fires were small and infrequent, with only 27 fires averaging 4 ha (10 a) in size recorded from 1924 to 1967 (National Park Service 1989; J.T. Tunison and J. Leialoha, unpubl. data). By the 1960s, broomsedge and other grasses had invaded the Park (Fosberg 1966), but a large population of feral goats (Capra hircus) kept grasses cropped and maintained the dominance of annual grasses over tall, perennial species (Mueller-Dombois 1981b), at least in the central and western coastal lowlands. When goats were removed from most of the Park in the 1970s, tall perennial grasses such as broomsedge and bush beardgrass came to form a continuous ground cover in formerly open vegetation in that part of the coastal lowlands with sufficient soil. There was a great “increase in biomass and a fuel bed capable of supporting fire” (National Park Service 1989), and the sizes of fires increased two orders of magnitude over those recorded prior to 1970 (Smith 1985). More than 90% of all fires that have occurred in the Park’s coastal lowlands took place after the feral goat removal program began (National Park Service 1989). A similar problem now exists in
western Kaupō Gap of Haleakala National Park on Maui, where the increase in biomass of alien grasses following feral goat removal has resulted in greatly increased potential for wildfire, threatening the ongoing recovery of native trees and shrubs (A.C. Medeiros and L.L. Loope, unpubl. data).

Grasses, particularly those that produce mats of dry material or retain a mass of standing dead leaves, provide fine fuels that allow fires to carry into native forests and shrublands that they have invaded; this vegetation would not otherwise easily burn. Broomsedge is known to be extremely flammable with a very high ratio of surface area to volume, and molasses grass can produce extremely combustible mats greater than 2 m (7 ft) deep (Fujioka and Fujii 1980). During fires observed in Hawaii Volcanoes National Park, broomsedge has been found to burn at very high humidities and fuel moistures (National Park Service 1986a).

In the two decades between 1968 and 1988, 58 fires were recorded in Hawaii Volcanoes National Park, and the average size of fires had increased 50-fold over the previous four decades to 204 ha (500 a). More than half of these fires occurred in the lowland and montane dry zones of the Park, between 305 and 1,100 m elevation (1,000-3,600 ft), an area heavily invaded by broomsedge and bush beargrass (National Park Service 1989). Most recent fires have been caused by human carelessness, but several have been ignited by lightning. The best-documented lightning-ignited fire burned approximately 4,250 ha (10,500 a) in 1986 before being extinguished by Park personnel (Tunison and Leialoha 1988). Lava flows are, of course, another natural ignition source and were the cause of 26% of Park fires from 1924 to 1988 (National Park Service 1989). In upland wet forests, fires rarely carry long distances from lava flow edges (Vogl 1969), and wildfire becomes likely only when flows reach the lowlands infested by alien grasses.

Fire Effects. The effects of fires on native Hawaiian vegetation are largely deleterious. Native woody plants may recover from fire to some degree, but fire tips the competitive balance toward alien species (National Park Service 1989). Although a few native plants, such as koa (Acacia koa), respond favorably to fire by resprouting from suckers, or by producing prolific seedlings, as does 'a'ali'i (Dodonaea viscosa), they do not require fire to survive, and such adaptations may relate to other stress factors or simply be a trait inherited from ancestral stock (Mueller-Dombois 1981a). In numerous studies carried out in Hawaii Volcanoes National Park and elsewhere, fire has generally been shown to adversely affect native woody plants (National Park Service 1989; Smith and Tunison, in press). 'Ohi'a (Metrosideros polymorpha) is the most abundant tree in dry lowland and mid-elevation regions that still support native woody vegetation. Such areas are often heavily invaded by alien grasses and are prone to fires. In several studies of burns in 'ōhi'a woodland, only about 50% of the trees regenerated by resprouting (Parmar and Wampler 1977; Tunison et al., in press). Fire intensity is an important factor in the survival of 'ōhi'a; tolerance and survivability decrease as intensity increases (Smith and Tunison, in press). Small 'ōhi'a are more likely to be killed by fire than are large ones with multiple trunks (Smith et al. 1980), but repeated fires in an area may eventually result in the total loss of 'ōhi'a and inhibit reestablishment of most native woody species (Mueller-Dombois 1981a). Several native tree species of lowland forests, such as sandalwood (Santalum sp.), kōlea (Myrsine lessertiana), and alahe'e (Canthium odoratum), may survive fires if they are not too severe (Warshauer 1974).
Mature rain forests do not seem to be particularly vulnerable to fire, and some common understory plants such as tree ferns or hāpuʻu (Cibotium spp.) are known to have a high fire survival rate. However, in rain forests that have burned, disturbance by fire is usually followed by invasion of alien shrubs and grasses (Smith and Tunison, in press).

Several common native shrubs of the lowlands are capable of surviving low-intensity fires and resprouting from the base, particularly 'ulei (Osteomeles anthyllidifolia), 'a'ali'i, and ʻōhelo (Vaccinium reticulatum) (Warshauer 1974), although regrowth may be slow (Smith and Tunison, in press). Because 'a'ali'i produces many seedlings following fire, its density may actually increase in burned areas (Hughes 1989; Tunison et al., in press). Other native shrubs, particularly pūkiawe (Styphelia tameiameiae), are very susceptible to fire. Burned low-elevation shrublands containing pūkiawe typically show a great decrease in cover or even a total loss of the species, and pūkiawe seedlings are rarely observed in fresh burns (Warshauer 1974; Parman and Wampler 1977). In mid-elevation shrublands of Kaupō, Maui, fire threatens to retard recovery and succession of native woody species following feral goat (Capra hircus) removal (A.C. Medeiros and L.L. Loope, unpubl. data).

Unlike native woody species, many alien grasses recover quickly and increase in cover following fires. This pattern is seen in most fire studies in Hawaii Volcanoes National Park, where fire-adapted grasses such as broomsedge, bush beardgrass, molasses grass, and thatching grass (Andropogon virginicus, Schizachyrium condensatum, Melinis minutiflora, Hyparrhenia rufa) invariably increase in cover following fires (Parman and Wampler 1977; J.T. Tunison and P.K. Higashino, unpubl. data; L.W. Cuddihy, unpubl. data). Hughes (1989) noted a pattern of increased cover of alien grasses and decreased cover of native shrub species that persisted after 18 years in a burned area near Kipuka Nēnē campground.

Fire-adapted grasses such as broomsedge are able to recover quickly because fire stimulates growth from the base of clumps and encourages seed germination (Sorenson 1977). Broomsedge and other alien species such as molasses grass and fountain grass (Pennisetum setaceum) use the C₄ photosynthetic pathway, which allows them to efficiently photosynthesize at a high rate even in hot, dry habitats with low soil nitrogen levels (Sorenson 1977; Hughes 1989; Vitousek, in press).

Urbanization and Development

The loss of original vegetation cover due to the development of human habitations began with the Polynesians, who lived primarily in the coastal areas and lowlands. Far more significant than the development of their living areas and villages were the losses of forest resulting from conversion to agricultural fields and extensive burning, which were part of Hawaiian agricultural practices (Kirch 1982).

The human population of the Hawaiian Islands when first contacted by Europeans in 1778 was probably between 200,000 and 1 million; varying estimates were made in the 18th century (Schmitt 1977; Stannard 1989). This population greatly decreased in the decades following contact; despite the influx of people from Europe and North America, the human population of the Islands did not reach the quarter-million mark again until 1920 (Schmitt 1977), although it had begun to rise as early as 1870 (Fisher 1973). As late as 1853, the population of Hawai‘i was still primarily restricted to the coastal lowlands near fishing and farming sites, and the interiors of the Islands were almost
uninhabited (Coulter 1931). In 1820, the towns of Hilo, Kailua, Lahaina, and Hāna each had populations of about 2,000, and Honolulu was only slightly larger; 33 years later, Honolulu had more than 11,000 people, which included most of the Kingdom's foreigners (Chow 1983). In the 20th century, cities such as Honolulu and Hilo began to grow more rapidly, but it was not until 1930 that the numbers of people living in urbanized areas exceeded the rural population (Schmitt 1977). McEldowney (1979) attributed the increase in the population of Hilo, the second-most populous city in the Hawaiian Islands, to the relocation of sugar plantation labor after nullification of labor contracts during the annexation of the Hawaiian Kingdom. The growth of Honolulu was also influenced by the migration of ex-plantation laborers (Chow 1983).

The primary focus of 20th century urbanization in the Islands has been O'ahu, which in 1980 had 41,960 ha (103,640 a) of urban land, more than half of the State's total (75,160 ha or 185,640 a) (Armstrong 1983). Honolulu has been the population center of the Hawaiian Islands since the late 1800s (Schmitt 1977), when the population of O'ahu finally surpassed that of Hawai'i Island (Chow 1983). In 1980, the city contained nearly 40% of the people in the State (Armstrong 1983). Although most of the valleys and the coastal plain of Honolulu had already been disturbed by activities of pre-European contact Hawaiians, 20th century urbanization and population growth have expanded development to many areas not used by Hawaiians for agriculture, such as ridges, slopes, and the upper reaches of valleys. Several residential subdivisions were developed on Honolulu ridges and slopes by 1920 (e.g., St. Louis Heights, Diamond Head) (Chow 1983). Certainly the development of a modern city has transformed the landscape to a far greater extent than the Hawaiians were capable of doing before European contact. Urbanization of greater Honolulu has not only replaced the land's former vegetative cover with structures, roads, and alien plantings (Wester 1983) but has even obliterated such natural features as Salt Lake (Aliapa'akai), formerly the largest natural lake in the Hawaiian Islands (Cooper and Daws 1985). By 1969, more than 3,240 ha (8,000 a) of land on O'ahu had been converted to streets and highways (Schmitt 1977). Urbanization results in the loss of nearly everything that lived in the area before development. Gagné (1981) pointed out that several native insect species, which were historically collected in areas that became part of the city or suburbs of Honolulu, are undoubtedly extinct today.

For several decades, the fastest growth rates on O'ahu have been in suburban areas on the edge of the central city. This expansion (or urban sprawl) began after World War II and involved such areas as Pearl City and the windward towns of Kailua and Kāne'ohe (Chow 1983). Because of this great increase on windward O'ahu, a tunnel through the Ko'olau Range to connect these communities with Honolulu was necessary by the 1950s, and later a second tunnel was constructed. By the 1970s, a third tunnel and "H-3" freeway were proposed. Construction of the H-3 was opposed by environmentalists who were concerned about the loss of native plants, particularly localized species of Cyrtandra and loulu palms (Pritchardia), in Moanalua Valley, the original route proposed for the Highway (Gagné 1974). More than 10 years later, the proposed route for H-3 had been changed to a corridor from Ha'iku Valley on windward O'ahu through the Ko'olau Mountains to Hālawa Valley on the leeward side of the island. This route also met with resistance from conservationists and biologists, because it would result in the destruction of habitat for the endangered O'ahu creeper (Paroreomyza maculata) and endangered land snails (Achatinella spp.) on Conservation-zoned land in the Ko'olau Mountains. The highway would also destroy vegetation and the stream of the valley floor in Hālawa (Gagné and Montgomery 1986). While H-3, "probably the nation's longest-running highway dispute" (Myers 1976), has been the most
Tourism and Resort Development. Tourism, today the State’s most important industry, began in Hawai‘i in the middle of the 19th century with the first hotel built on the island of Hawai‘i near Kilauea Crater in 1866. By the turn of the century, the focus of tourism and hotel-building had moved to Waikiki on O‘ahu (Morgan 1989). The number of visitors to Hawai‘i grew slowly during the first half of the 20th century, from less than 10,000 in 1922 to more than 100,000 in 1955 (Schmitt 1977). Tourism boomed after World War II, helping to prevent a predicted economic decline (Baker 1961). Statehood provided another tremendous boost to the industry, as did the development of jet travel and the reduction in airline fares (Morgan 1989). Annual visitor numbers began to rise dramatically just before Statehood in 1959, doubling about every five years throughout the 1960s and early 1970s (Schmitt 1977). Within 14 years of Statehood, tourism increased five-fold, and the value of constructed hotels grew 18-fold (Fisher 1973). In 1987, nearly 6 million tourists visited the State; at any given time during the previous year, visitors represented approximately 15% of the State’s population (Morgan 1989). To accommodate this increasing influx of visitors in the last three decades, there has been a boom in hotel building, mostly on O‘ahu and Maui, the two islands that have seen the most urban development of all the Islands (Cooper and Daws 1985). By 1982, almost 58,000 hotel units had been built (Armstrong 1983), and by 1988 this had increased to more than 69,000 (Hawaii State Department of Business and Economic Development 1988).

While many hotels are built in areas already urbanized, new resorts are primarily located on the coast, and their effects reach far beyond the buildings constructed to house tourists. The building of hotels and the creation of resorts in an area leads to increased urbanization, commercial development, and residential subdivision building. This is evident in the former fishing village of Kailua-Kona on the island of Hawai‘i, where tourism and real estate are now the primary commercial activities. Urbanization has increased rapidly there; one indication is the doubling of the number of real estate agents in Kailua (from 200 to 400) in just three years (Kelly 1983). West Hawai‘i has been the fastest growing region on the Island (Culliney 1988), and resort development has also accelerated growth on Maui, Moloka‘i, and Kaua‘i (Chow 1983). The State has used investments to encourage tourist development, particularly on the main Islands other than O‘ahu (Myers 1976). Recently, “huge, upscale resorts” have been built on Lāna‘i and Moloka‘i, where little tourism occurred in the past (Culliney 1988). A harbinger of even greater change on Lāna‘i was the 1970s reclassification of 6,880 ha (17,000 a) of Conservation land to Urban, earmarked for tourist development (Myers 1976).

A recent trend is the creation of destination resorts far from urban areas and other hotels. The first of these was developed in 1961 at Ka‘anapali, near Lahaina on Maui (Cooper and Daws 1985). Some resorts, particularly on islands other than O‘ahu, are constructed in dry, sunny areas that never supported large populations in the past. Construction at remote sites results in increased access to an area and may cause destruction of natural areas miles away from resorts, including unseen damage to marine systems (Culliney 1988). Important remaining lowland systems may be sacrificed to resort development; a recent example is the loss of one-third of the known anchialine pools in the State, when an elaborate resort complex was built at ‘Anaeho’omalu, North Kona, on Hawai‘i Island (Culliney 1988). (Anchialine pools are unusual near-shore

controversial highway project in recent years, it is unlikely to be the last proposed highway or road to severely impact native ecosystems. Pressures to develop and improve transportation are inevitable as population growth and urbanization continue.

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tidal pools with no direct surface connection to the sea. They contain a high percentage of endemic organisms and are often important sites for native waterbirds.) Although a legal appeal was being heard in Circuit court, the developer bulldozed 70% of the 'Anaeho'omalu ponds, destroying habitat for more than 60 species of plants and animals (Conant 1986). The 'Anaeho'omalu site was considered to be of exceptional natural value because of the number and diversity of its pools, which harbored a rich assemblage of invertebrates and fishes, as well as a rare species of eel (Gymnothorax hilonis) (Maciolek and Brock 1974). Another North Kona site with anchialine pools and endangered shore bird habitat was recently spared development when the landowner withdrew a request for rezoning (Mull 1987). Even though development may have been forestalled or delayed at this site, ten more resorts have been planned for the West Hawai'i coast (Mull 1986c).

A massive resort project has also been proposed for the rural Ka'ū District of Hawai'i Island. The project would convert a remote 1,310-ha (3,240-a) parcel currently zoned Conservation and Agriculture into an urban development that would quadruple the existing population of the District (Harada-Stone 1989). Drawing parallels with such densely populated and developed tourist destinations as Bermuda, Culliney (1988) warned that rapid and unbridled tourist development in Hawai'i may lead to great intensification of human population densities in the Islands and "acute environmental woes".

Hawai'i has had a comprehensive land use law with state-wide zoning and "permanent" boundaries since 1961 and was the first state to adopt such a planning tool (Myers 1976). In spite of this, developers have often found it possible to obtain rezoning to reclassify Conservation lands to urban or resort uses. Rezoning has been particularly pronounced on Hawai'i, which in the 1970s led all the other Islands in the amount of land rezoned to Urban use (Chow 1983). Mull (1987) warned of the negative, long-term consequences to native plants, wildlife, and communities when "great land tracts are transferred to urban use."

Even when rezoning is not accomplished, much development can take place on "Conservation" lands through the Conservation District Use application process. Such uses have included tourist attractions on O'ahu and an airport on Hawai'i; in a five-year period (1971-76) no public development on Conservation land was turned down because of an adverse Environmental Impact Statement (Myers 1976).

**Upland Subdivisions and Other Development.** Although the expansion of urban areas and resorts has taken place primarily in the lowlands, often in localities affected by pre-European Hawaiian land uses, the 20th-century development of residential and "agricultural" subdivisions has expanded such disturbance to many upland sites still covered by native vegetation. In just eight years (1960-68), the amount of land in the state classified as Urban doubled, primarily because of undeveloped subdivisions (Schmitt 1977). The focus of the most dramatic subdivision of undeveloped land has been the island of Hawai'i, where between the late 1950s and 1975 approximately 80,000 residential lots were created, primarily for speculation (Cooper and Daws 1985). While some of these subdivisions were developed on former agricultural lands or relatively recent lava flows with little vegetation, others, particularly in the Puna District, were in wet and mesic forests dominated by 'ōhi'a (Metrosideros polymorpha) or other native trees. One of the most flagrant cases of development for purely speculative purposes is that of Royal Gardens, a 730-ha (1,800-a) parcel downslope of the East Rift of Kilauea and east of Hawaii Volcanoes National Park, which has, since 1983, been frequently featured in the news. Royal Gardens was subdivided first in the 1960s and
was heavily promoted on the U.S. Mainland (Cooper and Daws 1985), despite its position in a volcanic hazard zone (Anonymous 1976). This subdivision is directly adjacent to a section of the Park notable for its rich mesic forests, uncommon plant species (Warshauer 1977), and unusually high lowland populations of native birds (Conant 1980). By 1985, much of the subdivision was covered by lava flows from the ongoing Kīlauea eruption, which began in 1983.

Many other Puna subdivisions were developed in native forests with a high diversity of native plant species, but the pre-disturbance cover can often only be gauged by what remains nearby. A survey of Malama-Ki Forest Reserve, adjacent to the Leilani Estates subdivision, showed that a candidate endangered tree species and a recently discovered Cyrtandra in closed lama (Diospyros sandwicensis) forest were present in an area that was previously continuous with the forest of the subdivided area (Clarke et al. 1981). A number of large parcels were subdivided between the villages of Mountain View and Volcano, bordering the large tract that later became the Kāhauale'a Natural Area Reserve. Large subdivisions have also been developed in formerly forested lands of the districts of Kā'u and South Kona; examples are a parcel contiguous to Manukā Natural Area Reserve (The Nature Conservancy of Hawai'i 1987) and an area in the upland forests of Kapu'a, which J.F. Rock considered one of the island's richest botanical sites (Rock 1913).

Most of these subdivided lots on Hawai'i Island have never been cleared or occupied; for example, only 5% of those in Puna had residences in 1983 (Cooper and Daws 1985). Even so, the process of bulldozing roads fragments and degrades existing vegetation and provides avenues for the establishment of alien plants. On Maui, weed introduction into the uplands has been linked to road construction and resurfacing (Loope et al., in press).

Twentieth-century development of upland forests has not been restricted to subdivisions and small agricultural parcels. In the 1940s, foresters unsuccessfully opposed the development of Kulani Prison Honor Camp in what was part of 'Ola'a Forest Reserve. Bryan (1944a, 1944b) decried the road-building and clearing in native wet forest because of the likelihood of weed introductions and the potential for fire. Subsequent recognition of the Kulani area forests as important habitat for several endangered bird species (Scott et al. 1986) and the establishment of adjacent lands as a State Natural Area Reserve serve to underscore the inappropriateness of a large-scale institutional and agricultural compound at this upland site. Between Kūlani Cone and Volcano Village, large-scale upland agricultural development continued into the 1950s, when hundreds of hectares were removed from forest reserve status and sold as farm lots (Mull 1987). Today this incongruous parcel of farm and grazing land is surrounded on three sides by Hawaii Volcanoes National Park and State Natural Area Reserve and serves as a potential source of invasive alien plants.

The various branches of the U.S. military own or control a total area of nearly 98,000 ha (241,920 a) in the Hawaiian Islands, most of it on the islands of O'ahu and Hawai'i (Armstrong 1983). Several O'ahu military reservations cover much of the northern Ko'olau and Wai'anae Mountains, areas that contain sites supporting rare natural communities and plants; some installations are located near existing or proposed State Natural Area Reserves (The Nature Conservancy of Hawaii 1987). The primary military site on the island of Hawai'i is Pōhakuloa Training Area, located near 1,830 m (6,000 ft) elevation in the saddle formed by Mauna Kea, Mauna Loa, and Hualalai. Pōhakuloa is notable as habitat for three endangered plant species (Haplostachys
haplostachya, Lipochaeta venosa, Stenogyne angustifolia) and also supports populations of several candidate endangered plant species and important examples of montane dry forests (Higashino et al. 1977). Fire is one of the greatest threats to rare plants and native vegetation in military training areas such as Pōhakuloa (Wagner et al. 1985), where firing of weapons and large numbers of troops provide potential ignition sources. Other negative effects of military use are the accidental introduction of alien plant species with equipment or personnel (Smith 1989b) and the bulldozing of military roads, which may be useful as firebreaks but also act as corridors for the movement of weeds into stands of native vegetation. On Maui, the military have been implicated as a "significant source of plant introductions" at Haleakalā National Park, where military use during World War II included the transport of materials from O'ahu (Loope et al., in press b). Perhaps the most alarming use the military has made of native forests occurred on Kaua'i, where testing of chemical defoliants, including Agent Orange, occurred in the 1960s (Culliney 1988).

**Geothermal and Hydroelectric Development.** Although Hawai'i has little heavy industry, and most manufacturing occurs on already heavily urbanized O'ahu (Armstrong 1983), the development of geothermal power threatens to bring industrial complexes to Agricultural and Conservation District areas of the Islands, at least on Maui and Hawai'i. Culliney (1988) predicted that "geothermal power production could become the key factor leading to virtually unlimited development." Exploratory geothermal wells were drilled on the active East Rift of Kīlauea on Hawai'i Island as early as 1961, and a successful well (HGP-A) was drilled there in 1975 and is now generating approximately 3 megawatts of energy (Thomas 1985).

In the early 1980s, a large geothermal development was proposed for Kahauale'a, a privately owned parcel on the upper East Rift of Kīlauea, directly adjacent to Hawaii Volcanoes National Park. Most of the more than 10,000 ha (25,000 acres) of land proposed for this industrial development was zoned Conservation and was covered by relatively intact ʻōhi'a (Metrosideros polymorpha) rain forest. The 250-megawatt project was envisioned as a complex of five power plants and up to 70 wells connected by a network of many miles of roadway and piping (Towill 1982). It was estimated that construction would require the clearing of 170 ha (420 a) of forest (Clark 1982). A general estimate of land required for structures and graded clearings in a geothermal complex is 0.1 to 1.2 ha (0.3-3 a) per megawatt (Hawaii State Department of Planning and Economic Development 1982).

In the Environmental Impact Statement prepared for the Kahauale'a project, the loss of land required for the complex was presented as insignificant to plants and wildlife, although it was recognized that development would impact the only known population of a rare fern (Adenophorus periens), a candidate for Federal Endangered Species status. Several species of endangered birds, particularly the Ñú (Psittirostra psittacea) and Hawaiian hawk or ʻio (Buteo solitarius), were also at risk (Towill 1982). Although an estimated 5-10% of Adenophorus periens plants might have been destroyed by construction and clearing, the vigorous population was thought to be capable of surviving such a loss (Clark 1982).

The development of an industrial complex in the upland native rain forest of Kahauale'a was vigorously opposed by conservationists and community associations, who cited the danger of "habitat degradation through an accelerated rate of exotic plant influx" and pointed out the lack of knowledge about the long-term effects of geothermal emissions on native plants and animals (Stemmermann 1983). The developers were
eventually given permission by the Board of Land and Natural Resources to drill exploratory wells. Subsequently, the 1983 Pu‘u 'O'o eruptions covered many of the proposed well and power plant sites before drilling began, some to a depth of 18 m (60 ft). Eventually, the State exchanged Natural Area Reserve and Forest Reserve lands of the middle East Rift for Kahauale'a, and the Governor declared Kahauale'a a Natural Area Reserve (Culliney 1988). While the upper East Rift forests now appear secure from industrialization, the focus of geothermal development has simply moved downrift (Mull 1986d). Forests of Kilauea's middle East Rift may be typically less dense and more disturbed than those at higher elevations, but stands of tall, closed-canopy, highly diverse rain forest containing populations of several rare plant species are found there (Char and Lamoureux 1985).

The East Rift of Kilauea is not the only potential site for geothermal development in Hawai‘i. One assessment identified 20 potential geothermal resource areas on five Islands (Thomas 1985), but only sites with good probability of a high-temperature resource are likely to be developed for electrical energy in the near future. In addition to the three sections of the East Rift (upper, middle, and lower), Hawai‘i Island has potentially exploitable geothermal resources on the Southwest Rift of Kilauea, the Northwest Rift Zone of Hualalai, and the Southwest and Northeast Rift Zones of Mauna Loa. On Maui, the sites with greatest geothermal potential are the East and Southwest Rift Zones of Haleakalā. Except for the Southwest Rift of Kilauea, all these potential geothermal development areas contain Conservation-zoned land. Several of them support significant habitat for endangered bird species and rare plants, particularly the East Rift Zone of Haleakalā (which stretches between Hāna and Haleakalā National Park) and the Northeast Rift of Mauna Loa, which includes the area around Kūlani Cone (Hawaii State Department of Planning and Economic Development 1986). Since 1983, it has been possible to designate geothermal resource subzones in any land use District, including land zoned Conservation (Hawaii State Department of Planning and Economic Development 1986).

In 1987, electric utilities on Hawai‘i Island supplied an average of 66 megawatts of power hourly (Hawaii State Department of Business and Economic Development 1988), and the Island's peak power needs have reached 126 megawatts (Bishop 1989). Despite the relatively modest needs of Hawai‘i Island, the development of geothermal complexes to produce 500 megawatts is envisioned in the near future if an interisland deep-sea cable to transport energy to O‘ahu becomes feasible (Hawaii State Department of Planning and Economic Development 1982). The impacts on existing natural vegetation and native animal habitat, as well as the loss of agricultural land, will increase with the increasing energy-producing capacity of geothermal developments. The losses could be even greater if large-scale geothermal projects stimulate development of local industries to use the geothermal steam directly (Lew 1981) or provide impetus for the development of energy-consumptive, potentially polluting industries such as manganese nodule processing. A single refinery processing manganese ores into cobalt and nickel would cover hundreds of hectares with tailings and waste treatment ponds; proposed sites for refineries include the Puna and Kohala Districts of Hawai‘i Island (Culliney 1988).

Hydroelectric power developments are another potential disturbance in native forests, although their impacts are perhaps less far-reaching than those of geothermal projects. Since 1964, hydropower has provided the state with 78-115 million kwh each year (Hawaii State Department of Business and Economic Development 1988). A few small hydroelectric plants have been in place on Kaua‘i for 50 years, and recently much larger projects have been proposed for valleys on Kaua‘i, Maui, and Moloka‘i (Culliney
Although at present only 2% of the electricity consumed on Hawai'i Island comes from hydroelectric power (Towill 1982), two new hydroelectric projects are planned for streams near Hilo: a 10-megawatt plant on the Wailuku River and a 14.6 megawatt development on nearby Honoli'i stream (Bishop 1989). While the Honoli'i project has generated more controversy for its possible adverse effects on a nearby surfing beach, the Wailuku River plant would impact 47 acres of State-owned Conservation District land (Bishop 1989) in an area notable as habitat for a rare variety of 'ōhi'a (Metrosideros polymorpha var. newellii) and several endangered birds (Mull 1986c).
SUMMARY OF VEGETATION ALTERATION IN THE HAWAIIAN ISLANDS

Pre-European Contact Changes

By the time of Captain James Cook's arrival in the Hawaiian Islands in 1778, the original vegetation of the lowlands had been greatly altered by more than 1,000 years of Hawaiian occupation. Agricultural practices of the Hawaiians were the major cause of environmental change in the Islands. Kirch (1982) expressed the opinion that any lowland area receiving 500 mm (20 in.) or more of annual rainfall would reveal archaeological evidence of Hawaiian agricultural use if examined. In nearly every valley with a permanent stream, the natural vegetation was replaced with irrigated taro (*Colocasia esculenta*) and other plants introduced by Hawaiians. The development of large dryland field systems on the island of Hawai'i (and East Maui) completely cleared the original dry and mesic vegetation over large tracts of the lower leeward slopes. Newman (1972) estimated that as much as 260 km² (100 mi²) of the island of Hawai'i (amounting to 2% of the land area) was "churned up" during preparation of field systems.

Shifting cultivation, using slash and burn techniques, was carried out at least to 460 m (1,500 ft) elevation on windward slopes and in areas near sites of irrigation agriculture. Plants introduced by the Hawaiians largely replaced native plants in succession on fallow and abandoned fields. Dryland cultivation greatly altered the vegetation cover of the islands of Ni'ihau, Kaho'olawe, and Lana'i long before the arrival of Europeans.

Even in lowland areas not actually cultivated, natural vegetation was degraded through the use of fire to encourage thatching grasses (Kirch 1982), firewood gathering, and removal of timber for construction purposes. The forest zone above cultivated areas was used for wild plant products, canoe logs, and for collecting feathers and was invaded to some extent by plants of Polynesian introduction. Only above 760 m (2,500 ft) elevation was the original vegetation essentially untouched by Hawaiians (Kirch 1982). Lowland areas below this upper limit of Polynesian influence where native vegetation has survived to the present and escaped modification are found on rough substrates, steep terrain, or remote coasts of difficult access.

In recent years, evidence for the destruction of lowland vegetation has come from analysis of fossil bird bones and land snails. Olson and James (1982) identified 40 previously unknown extinct species of birds from fossil bone deposits at a number of sites (primarily lowland) on five Hawaiian Islands; this doubled the number of endemic land bird species known from Hawai'i. Additional work on fossilized bird remains from a cave on Maui tripled the number of bird species known to have occurred on that Island (James et al. 1987). Radiocarbon dates on the Maui fossils and both radiocarbon dates and stratigraphic analysis at the previously discovered sites indicated that many of these birds had become extinct since Polynesian occupation of the Islands. Olson and James (1982) also pointed out that the currently understood fossil record is probably incomplete and the "original bird diversity" of the Islands may have been even greater. On O'ahu, deposits of endemic land snails indicate changes in the snail fauna.