DOE/OR/22088--T2

U.S. Fish and Wildlife Service
Pacific Islands Office, Ecological Services

Vegetation component of geothermal EIS studies: Introduced plants, ecosystem stability, and geothermal development

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JUN 16 1995
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Prepared by:

U.S. Fish and Wildlife Service
Hawai'i Research Station
P.O. Box 44
Hawai'i National Park, HI 96718

Submitted to:

Andrea W. Campbell
Project Manager, HGP-EIS
U.S. Department of Energy, Oak Ridge
P.O. Box 2001
Oak Ridge, Tennessee 37831-8739

October 1994

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INTRODUCTION

Background

This paper contributes new information about the impacts from introduced plant invasions on the native Hawaiian vegetation as consequences of land disturbance and geothermal development activities. In this regard, most geothermal development is expected to act as another recurring source of physical disturbance which favors the spread and maintenance of introduced organisms throughout the region. Where geothermal exploration and development activities extend beyond existing agricultural and residential development, they will become the initial or sole source of disturbance to the naturalized vegetation of the area.

Kilauea has a unique ecosystem adapted to the dynamics of a volcanically active landscape. The characteristics of this ecosystem need to be realized in order to understand the major threats to the ecosystem and to evaluate the effects of and mitigation for geothermal development in Puna.

The native Puna vegetation is well adapted to disturbances associated with volcanic eruption, but it is ill-adapted to compete with alien plant species in secondary disturbances produced by human activities. Introduced plant and animal species have become a major threat to the continued presence of the native biota in the Puna region of reference.

Many aspects of the alien invasion situation in Puna parallel those in south Florida, the area in the continental U.S. with the most tropical flora, including shared invasive alien plants such as *Casuarina spp.*, *Schinus terebinthifolius*, and *Melaleuca quinquenervia.* Land disturbing activities, ecosystem alterations, plant introductions from other humid tropical areas of the world, and expanding road networks that facilitate the dispersal of alien organisms are among the elements discussed by J. Ewel (1986) which are common to Puna and elsewhere in Hawaii.

Introduced plants in the native environment

Char and Lamoureux (1985) examined an area of Puna which included and extended beyond the area of the present survey, reporting 255 species of introduced and 200+ native plants. The present survey on a smaller area recorded about 140 of these introduced species and found over 40 additional alien species. There exists a considerable flux of other species which are continually moved into and within the 50,000+ residential and agricultural lots in Puna by lot owners, farmers and horticulturalists. Many of these plants were purposefully introduced for agricultural, horticultural, aesthetic, and forestry uses, and nearly as many have arrived without active intent (Wester 1992). Thus, there is a large reservoir of introduced species expanding within the district. A growing number of these introduced plants disperse into a local native vegetation which has adapted to the volcanically active landscape.

Environmental conditions

Conditions for plant growth are favorable in Puna. The region receives an abundance of moisture, moderate temperatures and contains an array of variously fertile volcanic soils. The variety of these environmental conditions, when coupled with extensive secondary disturbance, favor the naturalization of large numbers of the literally hundreds of alien species introduced into Puna. In addition, these conditions encourage some species not normally fertile in Hawai'i to self propagate. Even transported plant fragments and seeds may find conditions conducive to their establishment.

The Puna landscape is geologically young. Of the Lower East Rift Zone (ERZ) area mapped by Moore and Trusdell in 1991 (which includes most of the area of the three geothermal resource subzones), 75% of the landscape surface is less than 400 years old and 25% of the land surface is less than 200 years old (Figure 1; Moore 1992). Moore and Trusdell also identified in the lower ERZ map area 117 lava flow units produced by 112 eruptions over the 300 square kilometers (116 square miles). These flow units are part of a continuous mosaic of comparable age which comprises the Kilauea land surface (Figure 2; Holcomb 1987). Much of the mosaic's complexity extends along and adjacent to the rift zones of the volcano.

Despite the juvenile nature of the landscape, favorable environmental conditions allow native vegetation to colonize immediately on new lava flows, and forests may be observed on flows that are less than 150 years old. A rapid accumulation of increasingly fertile organic soils (histosols) ensues. Many lava flow areas along the Kilauea ERZ are also periodically enriched with deposits of volcanic ash and cinders.

The temperature range across middle and lower Kilauea approximates that of the subtropical and cooler tropical areas of the world from which many of the plants introduced to Hawai'i originate. Both temperature and rainfall are controlled by the region's topography, with up-slope areas generally being cooler and wetter than down-slope areas. At two sites representing higher and lower elevational portions of the subject area, Mountain View (466 meters or 1530 feet) and Kapoho (20 meters or 65 feet), the records of 20-25 years' mean monthly high and low temperatures (State of Hawai'i, 1970) fall between 27.2 and 13.5 degrees C. (81.0 and 56.3 degrees F.). At each site the maximum diurnal temperature range (10-12 degrees C. or 18-22 degrees F.) is 2-3 times the seasonal range. The elevation-induced temperature differences between the upper Mountain View and coastal Kapoho sites is even less than the seasonal difference.

Median annual rainfall in middle and lower Kilauea ranges between 2000 and 4000 mm. (80 and 160 inches), and is evenly distributed over the year (Figures 3 and 4; State of Hawai'i, 1986). Droughts are uncommon, and Puna is known for the frequent rain showers blowing in from the ocean. Moisture appears to be growth limiting only on the most recent (less than 50-150 years) lava flows and in the lower, drier areas where plant cover and soil accumulation has been minimal.

Moisture is the major environmental gradient in windward Puna, and conditions range from seasonal mesic (with dry seasons usually in the summer) to constantly wet or hygric (Figure 5). Rainfall increases with the elevation of the land surface, although not in direct proportion. Soil moisture retention is generally greater on older lava flow surfaces and on those which have been veneered with rapidly weathering volcanic ash and cinders. The more heavily vegetated areas can be expected to provide more even air moisture and shade conditions required by some species. Thus, the expected clinal increase in moisture contains a mosaic overlay.

Disturbed areas

Although land clearing on east Kilauea has been a recurrent experience since before the advent of the Europeans to Hawai'i, until the late nineteenth and twentieth centuries, the ecological consequences have been somewhat limited. The lower and middle slopes (below about 460 meters or 1500 feet elevation) of Kilauea were subject to partial and periodic anthropogenic disturbance during prehistoric and early historic periods. At least some of the intermediate and older substrates experienced shifting cultivation, in which scattered garden plots were rotated through an area of forest or resultant secondary vegetation. Such plots were cleared, burned to release nutrients, planted to short-term crops, and abandoned to fallow (Kirch 1985). Except for a handful of Polynesian-introduced cultigens and weeds, all species in the regrowth were composed of native species, albeit their composition was an anthropogenically altered secondary vegetation (P.H. McEldowney, pers.comm.). Recognizable signs of former shifting cultivation in Puna forests may be inferred by about 10 Polynesian-introduced plant species (Appendices 1 and 2) and occasional stone mounds and ground modifications. Later Hawaiian cultivation also may have included a few of the early historic plant introductions, some of which have persisted in the forest: e.g., *Psidium guajava, P. cattleianum, Coffea arabica, Syzigium jambos, Persea americana,* and *Paspalum conjugatum.*

In some areas, Hawaiian shifting agriculture was eventually succeeded by Western agriculture, in which larger, fixed cultivated areas such as sugar cane fields tend to be repeatedly utilized. The added roads and borders have supported an increasing number of introduced species, and native plants now play a minor role in the secondary vegetation. Sugar cane, papaya, cattle, orchids, nursery plants, and macadamia nuts are or have been the major Puna crops of this century. The displacement of east Kilauea native vegetation by crops and the additional introductions of alien species have increased to the point of significant adverse consequences to native vegetation. In addition, uncontrolled wildfires have begun to play an enlarging role in the loss of native vegetation outside of cultivated areas. Residential subdivisions now span the elevational range of east Kilauea, further fragmenting the forested areas and introducing alien organisms, land clearing, and fires.

Extensive agricultural clearing of intermediate-aged native forests accelerated in the 1980's as the papaya-growing industry expanded to supply export markets. Papaya disease and the ready availability of leased forest land combined to encourage the common industry practice of clearing virgin forest (disease free) for a single planting, then moving on to clear more forest once the papaya disease depressed yields (Ko 1982). Numerous pieces of land within the remaining forest areas were cleared, coalescing into large tracts with time. Large individual clearings on east Kilauea extend up to 425 meters (1400 feet) elevation, but the major portion lies below 130 meters (400 feet) elevation.

The accelerating expansion by both agricultural and residential activities into Puna native forest vegetation has resulted in a set of circumstances which promotes the spread of introduced species throughout the district. The spread of alien species has directly resulted in the attrition and deterioration of native vegetation in the area. Land clearing activities cause continued loss of native vegetation and creation of freshly disturbed sites. Some of these, plus abandoned cleared areas, maintain synchronously new and maturing weed communities. A patchwork of such cleared weedy lots exists throughout the 56,000 smaller parcels which were subdivided within the region's forests 20-30 years ago. Juxtaposed within these cleared and uncleared lots is a profusion of homesites and small agricultural operations. These disturbed sites harbor a diverse set of introduced plants. Large weed-infested blocks of land have resulted from a sugar plantation's recent closure and when papaya growers repeatedly moved their short-term land use to new forest sites. A large number of arborescent, shrubby and herbaceous weeds are spreading from the smaller to larger vacant lots, and seeds from all disperse into the adjoining landscape. The taller secondary colonizers provide habitat for invading shade-requiring weed species.

Dispersal of introduced species

Accompanying the disturbed sites in Puna are situations which enhance active and passive dispersal of organisms throughout the district. Bulldozers and other earth moving machines are transported from site to site throughout Puna and from other districts, where they come into contact with a variety of introduced species. Many of the cinder cones commonly found in Puna are quarried, and the cinders, soil and fill materials are moved about daily. Road construction provides an initial inoculation of introduced plants from seeds contained in cinders and fill used for construction of the road.

Roads, an essential element of nearly all development in Puna, play a key role in the invasion of alien species into native communities. The unimproved roads which interconnect nearly all the disturbed sites appear to act as the primary conduits of dispersal for most alien plants in the region. Even seeds not especially adapted for hitchhiking will readily adhere to wet vehicle frames for short or long rides through this moist district. Many Puna roads are single lanes, causing passing vehicles to drive periodically onto the weedy shoulders, adding and losing seeds and fragments. Roadsides themselves provide an extensive habitat suitable for most of the reported introduced species.

Weed communities along roads and on disturbed lands are continually being supplemented with intentional and unintentional alien introductions. Throughout Puna, most roadsides are frequent locations for intentional dispersal of many species when they are planted or dumped along with other household and yard refuse. Such releases also occur along remote roads and those with restricted access. Other examples of human dispersal are the off-road plantings of ornamental species frequently in or near agricultural fields and that of weeds infesting illicit marijuana cultivation throughout forests and fields in Puna. Introduced birds, wind, and feral pigs disperse the seeds from weed species of various life forms away from the roads and other source areas.

These dispersal mechanisms are continually spreading roadside weed species intermittently throughout the region. Abutting subdivisions in Puna form an array of roads which describe a reversed "C" extending north of and along the alignment of the East Rift Zone (ERZ), incorporating all the east end of the ERZ, and continuing more intermittently south of the rift zone alignment west to Hawai'i Volcanoes National Park (Figure 6). The land surrounded by this reticulated area contains the last large roadless tract of forest remaining on Kilauea. The other road-dissected areas produce a fragmented landscape covering about two-thirds of windward Kilauea.

NATURAL SUCCESSIONAL ECOLOGY OF KILAUEA

The vegetation of windward Kilauea is neither uniform nor static. Spatial variability and continued change are built into the natural ecology of the area. The driving force behind the vegetation dynamics is the frequent eruptive activity of Kilauea volcano. The younger windward Kilauea surfaces are in some intermediate or early states of primary succession, and only the most recent lava flows are temporarily devoid of plant life. The lava flow surfaces form a mosaic of different substrates, a generalized display of which is shown in Figure 2. Note that the flows originate from the Kilauea summit (upper left central) or from along the linear crests of the East Rift Zone and the Southwest Rift Zone.

Primary succession process

Primary succession on lava flows is the colonization of new lava flow surfaces by plants and animals, and the accrual of species, biomass, soil, nutrients and ecosystem complexity which follows in this time series of community development. Each lava flow surface is an example of a progressing time series of community development. Each of these series began at the time the lava flow or cinder field was deposited.

Almost as soon as a lava flow cools, specially adapted crickets (*Caconemobius fori*) and wolf spiders (*Lycosa* sp.) take up residence in the surface cracks and scavenge detritus or prey upon other arthropods which fly, drift, or blunder into the desiccating open landscape from adjoining forest areas (Howarth 1979). Usually within months, the light rain of detritus, seeds, and spores from adjoining forests will result in the germination and establishment of ferns, bryophytes, shrubs, and, most importantly, 'ohi'a trees (*Metrosideros spp.*). The wetter Puna areas and the rough, cracked lava surfaces provide the localized conditions favoring rapid plant establishment. Drier areas develop growth more slowly.

Pahoehoe flows near the vents are full of small and large voids, cracks, and blisters. Upon cooling, these flows exfoliate an abundance of glass flakes. 'A'a flows have a massive core but a clinkery surface of loose crystalline rock, a mix in size from boulders to fine particles. Sometimes new and older flows are partially veneered with tephra. Finely fragmented lava and cinder material on the flow surfaces and the minerals readily leached from these glassy fragments provide, in humid conditions, a physical soil substitute suitable for these early plant colonizers. These colonizers are adapted to withstand frequent moisture stress and by making efficient use of the limited nitrogen compounds available from rainfall sources and that contributed by cryptogam colonizers which utilize symbiont organisms to fix nitrogen from the air (Vitousek and Walker 1989).

The adaptation of some native species to the restrictive living conditions found on new and younger lava flows favor dominance by native species in the younger primary successional communities when located adjacent to native seed sources.

Over time, more individuals and additional plant species from adjacent forests become established. In this manner, conditions on the new flows change and become more favorable to an increasing number of plants and animals. More plant and animal species join the communities as succession progresses, and some of those better adapted to the harsher, open conditions of open lava flows disappear.

The return of leaves, bark litter, and dead root material to the ground, and its breakdown by soil arthropods and microbes into organic material, provide the main fabric of the thin layer of organic soil and duff. The soil accumulates along with the rapid development of vegetation. Nutrients derived from the lava and air by the early colonizing plants are incorporated into this organic soil and eventually made available to other organisms. In this way, the original colonizing plants produce the organic soil which supports their growth and that of the expanding community. In early succession the soil is deficient in nitrogen, and possibly phosphorus, but over time the amounts and availability of these and other nutrients increase (Vitousek et al. 1992).

Throughout primary succession on windward Kilauea, 'ohi'a remains the dominant plant. The tree's ability to form and shed wind-dispersed seeds in prodigious quantities ensures that it remains the dominant tree in this dynamic landscape. Also, *Metrosideros* trees can serve as perching sites, encouraging and concentrating the addition of bird-dispersed native and alien plants. This has been demonstrated by Vitousek and Walker (1989) for the invasive alien tree *Myrica faya*.

The rain of tiny 'ohi'a seeds is derived from three kinds of *Metrosideros* on windward Kilauea: *M. polymorpha* var. *incana, M. polymorpha* var. *glaberrima*, and *M. polymorpha* var. *macrophylla* (Lani Stemmermann, pers.comm., 1983). *Metrosideros polymorpha* var.*incana*, with pubescent leaves, starts the succession process. *Metrosideros polymorpha* var.*glaberrima*, with glabrous leaves, is added in wetter areas, and may replace var. *incana* as communities mature. In older wetter sites with considerable soil, *Metrosideros polymorpha* var.*macrophylla* tends to achieve dominance. This last kind of 'ohi'a is noted for its characteristic of shedding bark in long large strips, a feature which limits the cumulative epiphyte load on its trunk, including the endangered fern *Adenophorus periens* (Lamoureux et al. 1987).

Flowering plants accrued into the community may have their own suites of arthropods and other organisms accompanying them. Numerous arthropods utilize 'ohi'a as their specific host. In the wetter uplands, numerous epiphytes contribute diversity: ferns, bryophytes, algae and some flowering plants find suitable host trees, adding further complexity and nutrient input.

Moisture is the most important determinant influencing the rate and the nature of vegetation succession on volcanic surfaces. On the wetter slopes of Kilauea, rapid forest development is able to colonize the landscape faster than new flows can cover it. Wet forests also have different species compositions than drier mesic forests, adding to the region's total species diversity. Dry conditions significantly retard the rate of primary succession on lava flows. The importance of moisture is a major factor in explaining why the dry, leeward slopes of Kilauea volcano are only partially vegetated, while windward Kilauea is mostly veneered with vegetation.

Vegetation can cover a new flow very quickly where conditions are favorable. For example, flows from a wet 1840 eruption site (at 365 meters or 1200 feet elevation) have been completely covered for some time by an open-canopy 'ohi'a forest distributed over a ground covering mat of uluhe fern (*Dicranopteris sp.*). In lower elevations with drier conditions (75 meters or 250 feet), the uluhe on the 1840 lava is discontinuous and supplemented by other native understory species scattered about the open surface.

Lava flows terminate the community development and reset the successional clock. In natural situations, new flows are situated within or near native vegetation of varying maturity, from which the rain of organic detritus, seeds and spores begins at once. If the new flow lies within a larger area of new flows (such as on a satellite shield built from a sustained eruption), the inner portions receive a more diffused rain of seeds, and it takes a longer time to accumulate vegetation cover and diversity. If the new flow lies within land anthropogenically cleared of its native vegetation (and now covered with introduced species), the addition of native species may be significantly diminished and delayed, and colonization by a few introduced species may occur.

Temporal and spatial aspects

The eruptive history of Kilauea influences the ecology of the Puna area. Most obvious is that the younger a portion of the landscape is, the less matured is its vegetation, and vice versa. A broad range of ages provides a broad range of community compositions.

A related aspect shaping the vegetation is that the eruptive pace in an area of the ERZ is not constant. Holcomb (1987) has modeled the behavior of Kilauea volcano, and found that eruptive activity alternates between summit dominance and rift zone dominance (Figure 7). These phases may be separated by caldera collapse and violently explosive phreatomagmatic events at the summit. Cycles and subcycles may be as short as 200 years or longer than 1500 years. Lavas emanating from each area tend to be regionally distributed and alternate their encroachment onto the other. For example, the last 500 years, during which about three-fourths of Kilauea's surface was covered, are characterized by an initial period of summit dominated activity and subsequently by rift zone activity (Holcomb 1987).

The 'Ai-la'au series of sustained summit-dominated overflow activity occurred 300-500 years ago (Holcomb, 1987; note that Moore and Trusdell, 1993, dated this area to be 200-400 years old; Figure 1). Flows originate from a vent at the filled summit caldera and have covered 30% of the volcano surface. Lava tubes conducted these flows over long distances. The flows extend to the sea in several directions, including east, within the shallow swale between Mauna Loa and the crest of the Kilauea ERZ. These flows have covered and recovered most of the north flank of Kilauea, including parts of the ERZ, with the dense, degassed lava which issues from the ends of or breaks in the imbedded tube systems. These 'Ai-la'au pahoehoe flows have created a large expanse of gently sloping, mostly uniform tube-fed pahoehoe flows which induce poorly drained soils and support suboptimal plant growth. Over time, varieties of 'ohi'a tree replaced one another (large dead trees standing above younger replacements verify the continuing dynamics) and many other species became incorporated into the community (including some introduced plants). The expanse of the 'Ai-la'au flows lacks the range in age and other ecological features found in abundance within the rift-zone mosaic array, but it does provide a diverse reservoir of species representing its own ecological conditions.

During the subsequent rift zone period of eruptive dominance, a second period of extensive activity, in the 18th century, distributed numerous eruptive vents along the Kilauea ERZ (Holcomb 1987). During this time, much of the rift zone and adjacent slopes were covered by a variety of lava-flow types, commonly from brief effusive eruptions. These eruptions discharged highly vesicular surface-fed (from nearby vents) pahoehoe lavas and 'a'a flows. Both of these lava types promote rapid growth of vegetation and well-drained soils. Explosive eruptions at the summit and Kapoho cone occurred on each end of the ERZ. There also occurred the sustained eruption of Heiheiahulu shield, which provided a large local expanse of dense tube-fed pahoehoe flows. Growth conditions and the recovery of diverse vegetation on such tube-fed lavas are retarded, in contrast to that on the other 18th century lavas.

As ERZ activity continues, more new flows reach into the large forest tract which mantles the 'Ai-la'au flows. This extension of the finer-grained mosaic into the more uniform 'Ai-la'au forest decreases the dispersal distance for uncommon species and, in effect, incorporates more of the northern 'Ai-la'au communities into propagule exchange with the diverse remainder of the successional ecosystem.

As noted by Holcomb (1987), the current increase in ERZ eruptive activity parallels that of the 18th century. Therefore, it is possible that Kilauea has entered a third period of recent excessive eruptive activity which may continue to cover more of the 'Ai-la'au forests with rift zone flows. Table 1 uses information from MacDonald et al. (1983) and data from Hawai'i Volcano Observatory to illustrate the sharp increase in lava flow coverage that has been occurring during the last 40 years. The accelerated rate of forest loss from natural causes is coinciding with the increased anthropogenic forest loss and invasion by foreign organisms.

The numerous lava surfaces of windward Kilauea are not arranged in any specific, set pattern but rather as an indeterminate mosaic of flow pieces (kipuka) of different sizes and ages. Many of these flow pieces are small enough to produce a large number of kipuka of variable ages in close enough proximity to one another that dispersal of organisms is promoted among the successional stages. The flows and kipuka of and adjoining the ERZ tend to be small and contain a wide range of age and environmental conditions. This has resulted in a finer-grained region of the mosaic. The flow pieces of and within the 'Ai-la'au lavas north of the ERZ tend to be large and of limited variety, making this a coarse-grained region.

An important consequence of this mosaic arrangement is that many kipuka are near or abutting both older and younger kipuka. These kipuka are able to receive and provide propagules from and to nearby kipuka of varying degrees of successional development. This is a vital and mutually interdependent process. Because the density of passively dispersed propagules in the seed rain is inversely proportional to the source distance, and positively related to the density and diversity of source plants, the presence of older, adjacent kipuka can greatly accelerate the colonization of species into younger communities. A retardation of community development can be expected if the proximity and abundance of propagule sources is reduced.

Thus, each portion of the successional mosaic is an integral and important part of the whole ecosystem. The survival of this dynamic ecosystem and its maximum biodiversity depends on the maintenance through time of a broad representation of community diversity (pieces of the mosaic).

Some important features of this differentially aged mosaic ecosystem are (a) that forest succession is rapid enough to keep pace with forest loss to lava flows; (b) that the diversity of communities and species is relatively high in any small geographic area (given the community simplicity of any given kipuka); (c) that this is a unique and dynamic region.

Unique nature of the successional ecosystem on Kilauea

The existence of the successional ecosystem on Kilauea is the result of the process of primary succession on recent volcanic surfaces, interacting with the spatial and temporal eruptive aspects of Kilauea, one of the world's most active volcanoes. Volcanic succession in Hawai'i also occurs on somewhat less active Mauna Loa and also on Hualalai and portions of Haleakala volcanoes, both with only limited recent activity. However the high rate of lava effusion distributed across the small size of subaerial Kilauea condenses the volcanic activity and products. This concentration, consequently, produces a considerably higher frequency of surface coverage than on the other Hawaiian volcanoes. The portions of Kilauea along and bordering the two active rift zones are the most volcanically active.

Primary succession provides a vegetated landscape where the pattern of variety reflects the ages and types of the volcanic surfaces. On older volcanoes, lava flow segments supporting maturing successional vegetation tend to lose much of their individual differences and to take on characteristics typical of the flanking vegetation zone. Vegetation zones controlled by elevation and moisture wrap the mountain and are intersected by the youngest of the lava flows. On Kilauea, however, vegetation zonation is expressed as little more than wet windward and dry leeward vegetation. While some elevational differences in forest composition occur over the 1230 meter (4035 foot) range of Kilauea volcano, they are small compared with the differences due to the mosaic of ages and volcanic surface types. On Kilauea, the activity of the volcano, not its topography, is what shapes the area's vegetation, and it strongly overlays and has subjugated climatic control of a zonal vegetation pattern.

Kilauea has been above sea level for about 500,000 years (Moore and Trusdell 1993), and for most of that time primary succession has been occurring on its new substrates. Colonizing plant species generally have been shared with much larger and older Mauna Loa volcano. The increasing growth of Kilauea has separated the latter from its original source area of successional species. Presently, the two adjacent rift zones are about 24 kilometers (15 miles) apart at this time. In addition, like Kilauea, the lower parts of Mauna Loa have been heavily altered by land clearing and invasions of alien species. Kilauea has achieved considerable ecological isolation from the Mauna Loa flows, and it may be in a situation where it maintains its own pool of successional species.

Only a few plants and terrestrial animals have speciated on Kilauea, suggesting that evolutionary replacement of lost colonial plant species may still be quite limited. This is in contrast to Hawai'i's other, older volcanic mountains, which have generated many local endemics (Wagner et al. 1990). Any losses of successional plant species from the Kilauea species pool would be significant, even though they would not likely be extinctions of the species.

Two other associated ecosystems

Two additional ecosystems are embedded within the Kilauea successional ecosystem. Both of these ecosystems are dominated by arthropods rather than by photosynthesizing plants, and each depends on the adjacent plant-dominated ecosystems for its energy source.

The first of these ecosystems is the subterranean *lava tube ecosystem* which exists within the surface or near surface pahoehoe flows which support *Metrosideros* trees (Howarth 1973). A diverse fauna of highly specialized cave organisms live in the dark and damp lava tubes and associated cracks, feeding on penetrating *Metrosideros* roots or on other invertebrates cohabiting the dark zone (Howarth 1981). This ecosystem can exist only as long as contact with living *Metrosideros* roots (the energy source) is maintained and the tubes and cracks remain open, cool, dark and damp. In contrast to successional ecosystem, the lava tube fauna of Kilauea has demonstrated significant speciation and some unique and locally restricted arthropods have been reported (McEldowney and Stone 1991).

The second ecosystem occurs on recent, barren, or sparsely vegetated lava flow surfaces and depends on an aerial drift of organic detritus and arthropods from adjoining vegetated flows and kipuka to provide the energy source (Howarth 1979). Its name, *neogeoaeolian ecosystem*, reflects these conditions. The specialized crickets and spiders which dominate the system scavenge upon detritus and waif arthropods that drift or fly across the flow and are killed or marooned by the harsh surface conditions. These species forage at night and seek shady cracks during the day. This ecosystem is transitory and dependent on a periodic renewal of fresh lava surfaces to colonize. Natural forest succession ameliorates the harsh surface conditions and gradually replaces the simple early successional ecosystem with one of greater complexity.

Natural disturbances to the successional ecosystem

Even though the geologic setting of Kilauea volcano provides considerable volcanic disturbance to vegetation, the native vegetation is adapted to it. Man-induced disturbance which is treated later in this report provides more severe threat to the Kilauea successional ecosystem. Small scale non-volcanic disturbances damage native vegetation without serious consequences. Tree falls, small wind storms and the like may create openings and exposed soil which are colonized by some of the later primary successional species already present in the area, possibly augmented by a few introduced weeds. Episodes of 'ohi'a canopy dieback are another source of natural forest openings that may naturally accompany a succeeding of one variety of *Metrosideros* by another. Other tree and shrub species tend to take advantage of the openings for entry or to increase abundance in the community as well, including a few introduced species. Most other natural disturbances to vegetation on Kilauea are volcanic in origin, examples of which are addressed below.

Earthquakes, ground cracking and faulting occur frequently enough that their effects on the native ecosystems have been observed. Adverse effects are local and inconsequential. Cracks, pit craters, and grabens are frequent accompaniments of subsurface magma movement along the ERZ. These features provide moist and shady microsites which are colonized earlier than adjoining open areas by some plants, and can act as oases of species usually found on older substrates. Since the introduction of the European pig, these locations have also provided refuge from the destructive digging of feral pigs. Such sites serve as important seed and spore source areas for a number of native species now depleted by feral pig foraging.

The "Ka'u Desert" is a permanent fume desert which lies along the upper southwest rift zone and downwind (southwest) of continuous volcanic degassing from the summit, where long-term local conditions exert considerable selection in the colonizing species. An area of acidified rainfall extends about ten kilometers (6.2 miles) downwind of the summit caldera (Harding and Miller 1982). On the shorter time scale, volcanic fumes, primarily sulphur dioxide, can cause forest kills downwind of eruptive vents along the rift zones. Char and Lamoureux (1985) report that fume and tephra erupted from the high fountaining phases (1983-86) of the ongoing ERZ eruption near Pu'u 'O'o vent did have severe effects on the nearby forests and these vent products killed back a significant portion of the largest known population of the endangered epiphytic fern *Adenophorus periens*.

Near-surface intrusions of magma have also been observed to cause forest kill upon occasion. The "Puhimau thermal area" in Hawai'i Volcanoes National Park is one such place. While most of the original vegetation was killed by the high temperatures and associated conditions, certain native and alien plants, including an endangered succulent herb, *Portulaca sclerocarpa*, has become locally common. Another thermal area is at Heiheiahulu, the summit of the 1750 satellite shield next to Upper Kaimu Homesteads.

Explosive eruptions are infrequent, and the phreatic and phreatomagmatic eruptions of Kilauea are generally limited to the summit area and lower elevations of the ERZ. Where magma and a shallow aquifer intersect, and when the super-heated water-saturated rock and magma are opened to atmospheric pressure by caldera collapse or eruptive fracturing, the pressurized products explode upward, disintegrating surrounding rock and magma. The fragments are ejected violently by and with the flashed steam and magmatic gasses in a prolonged series of rapidly repeating explosions. As gravity returns the denser material to the ground, the descending columns are deflected laterally, producing devastating base surge blasts out from the source. Devastated areas can be extensive and slow to recover.

By far, the most frequent type of natural disturbance is coverage of existing flow surfaces with lava flows. These new surfaces replace any existing vegetation, but usually leave the adjoining wet forest intact. The new surface is sterile until dispersal begins the colonization process. While periodic lava and tephra inundation is a common and terminal disturbance to the native successional communities, it serves as a beginning point for primary succession.

The strategy of survival from such volcanic activities has not been one of tolerance to the disturbance itself, but rather one of chance avoidance and by maintaining an adequate number of replicate communities which provide sources of dispersed propagules to maintain the successional process. Maintenance of these replicate communities is critical to the survival of the ecosystem as a whole. This replicated mosaic strategy has allowed the long-term survival of the Kilauea successional ecosystem in spite of extensive natural catastrophes associated with volcanic activity and from hurricanes. After these major but infrequent catastrophes, one can expect some localized disappearance of certain species and a long period of recovery to regain community diversity.

Such natural disasters must be anticipated in the future of the Kilauea successional ecosystem. The natural dynamics of the Kilauea successional ecosystem requires large contiguous tracts of land in order for it to maintain itself. If the areas remaining in native vegetation are not of sufficient size and variety in a portion of the Kilauea ERZ, the integrity and continuity of the natural succession process could be at risk. New lava flows located in areas which have been earlier cleared of forest or otherwise degraded are now adjacent to reservoirs of alien weed species rather than forests of native species. The planning and layout of natural preserve areas needs to accommodate the dynamics of this ecosystem by incorporating large blocks of contiguous native vegetation which covers a broad geographic area and a diversity of substrates and environmental gradients.

STUDY OBJECTIVES

This survey report has been prepared to make available and archive the background scientific data and related information on introduced plants, ecosystem stability and vegetation collected and analyzed during the preparation of the environmental impact statement (EIS) for Phases 3 and 4 of the Hawaii Geothermal Project (HGP). Subsequently, the U.S. Department of Energy (DOE) published a notice in the *Federal Register* on May 17, 1994, (Fed. Regis. 59:25638) withdrawing its Notice of Intent to prepare the HGP EIS. Because the State of Hawaii now says that it is no longer pursuing or planning to pursue the HGP, DOE considers the project to be terminated.

This survey assesses the potential biological impact of geothermal exploration and development in Puna. In addition to potentially providing electricity, geothermal development brings with it disturbance of landscapes, abandonment of disturbed lands, construction and use of roads, transport of heavy equipment from other places, dispersal of introduced species, and degradation of the Kilauea successional ecosystem. In many respects, these negative impacts are similar to those of other development activities in the east Puna area. Because this study was unable to access existing geothermal development in Puna, the project was designed to investigate the effects of similar non-geothermal activities on native vegetation.

The purpose of this survey is to document the patterns and processes of alien plant invasions in Puna, as they relate to disturbances similar to those associated with proposed geothermal development. In addition, this study will assess the characteristics of the alien species found in Puna and evaluate the scale of the weed invasion problem in Puna, particularly with respect to the roles of introduced plants and disturbance in the degradation of native ecosystems on Kilauea.

Given the critical role that primary succession plays in maintaining the native ecosystems of Kilauea, and the ecological consequences of anthropogenic disturbance in Puna, this survey has concentrated on the following aspects:

- The identification of alien plant species established in Puna;
- the documentation of the various environmental conditions and patterns in which alien species are established (to include disturbance history);

- -- the dispersal of alien species throughout Puna and from outside sources; and
- -- the identification of alien species which can disrupt native ecosystem structure or stability.

METHODS

Plant communities were sampled at representative sites throughout middle and lower Puna (Table 2 and Figure 12). These sites were located within or near the three geothermal resource subzones. A total of 2432 observations of native and introduced species of plants were recorded from 96 sites. These represented 611 native species observations (25%) and 1821 introduced species observations (75%). Thirty-four of these sites (35%) were in undisturbed native vegetation and 62 (65%) had been physically disturbed. Physical disturbance usually involved being run over or scraped by heavy equipment (singly, multiply or repeatedly) or being burned by a major wildfire. All roads and roadsides were defined as disturbed.

The sampling procedure involved walking a transect through a vegetation type (or along a roadside) for approximately 50-300 meters and recording all plant species observed. Each species recorded at a site was considered an observation. The length of the traverse was variable. Transects were terminated when a significant distance had passed without adding a new species to the list.

This sampling strategy is better adapted to the geographic variability found in the lower East Rift Zone of Kilauea than the use of set sampling plots. The variability recorded reflects the diversity of environmental and successional conditions found among the sites as well as the localized distributions of alien species newly naturalized to the district.

Additional data, such as estimates of relative abundance were sometimes also taken, but not used in the numerical analysis. Reported field observations relating to relative abundance are herein referred to as "observed".

Even though abundance measures of each species on a site were not consistently recorded, the large number of sampling sites allows the frequency of species occurrences to provide an index of overall abundance. These data can also be used to evaluate the relationship of disturbance to the disruptive alien plants. The total list of introduced species can be viewed as the current set of alien plants that are available for dispersal and colonization in the Puna area. However, new introductions are occurring at a high rate, so there is no expectation that this listing of alien species will remain stable.

Sampling sites were evaluated for elevation, age of the volcanic substrate, and degree of disturbance. Evaluations were based on the pooled numbers of species among all sites in the category for native and for introduced species. The percentage portions of the pool which was native and introduced were also calculated. Since the pooled numbers of species are influenced by the number of sites sampled in each group, percentage proportions were used. The categories were each further divided into classes along an elevation gradient and along a gradient reflecting the age of the lava flow surface. Table 2 diagrams the sample sites with respect to elevation and geochronological groupings, identifies site types, and indicates the number of sites in various groupings.

The pooled numbers of species recorded and the relative proportion (in percent) of native and introduced species provide some indication of the available introduced species present in the various groupings of sample site types. Individual site species lists are considerably smaller than the total number of introduced species observed for each site pool.

The number of introduced plant species at a site provides an indication of the weed pool size available at the site, but it does not in itself indicate the prominence of these alien species within the communities sampled. Different sorts of data are required to make those evaluations, and neither was obtained in this survey.

RESULTS

Plant species observed

A total of 195 introduced and 96 native species of plants were found at the 96 sample sites in lower and middle Puna (Appendix 1 and 2). Introduced species were seen at every site, but their share of a site's plant list was varied. The range of relative prominence of the introduced element in the vegetation cover of the sites was even wider.

Overall patterns

Occurrence of introduced species

Most observations of these introduced plants fall into various groups of site disturbance. Appendix 3 is a sorted list of 195 introduced plants observed and of the 96 sites at which they were reported. The sites are arranged into Disturbed (62) and Undisturbed (34) portions and the species are arranged into groups according to several generalizations about their patterns of occurrence. Of the 195 introduced species, 144 were naturalized at survey sites, and 51 appeared to be dumped or planted at sites.

Group 1. The largest category of the 144 naturally occurring species (91, or 63%) includes those introduced species which are found restricted to only disturbed sites. Overall, these plants were observed infrequently but 20 were observed with at least a 10% frequency (maximum =42%). So far, these species are presently restricted to disturbed sites and do not appear to pose a risk of invasion to undisturbed native vegetation or uncolonized new flows. Dispersal means are mixed in this group, and wind dispersal is common. These weeds are not considered to be biologically problematic as they are not particularly aggressive.

Group 2. Eight species (5.6%) are found commonly naturalized in both disturbed and undisturbed sites. These alien plants include fern, grass, herb, shrub and tree life forms. They are fairly indiscriminate and include the highest site occurrence frequencies (28-75%). Nearly all have wind-dispersed seeds or spores, and one (*Psidium cattleianum*) has fruit-borne seeds widely dispersed by birds and feral pigs. These species all varied in observed abundance, but most are at least common in some undisturbed native communities. Four species appear to be particularly aggressive and disruptive weeds in native communities. The bunchgrass *Andropogon virginicus* displaces small native species and commonly promotes wildfires which are disastrous to native ecosystems. When *Melastoma candida*, *Nephrolepis multiflora* and *P. cattleianum* achieve a high abundance, they displace natives and usurp establishment sites.

Group 3. These 13 (9% of the 144) introduced plants are found predominantly within disturbed sites, but each species is also found in one or a few undisturbed native vegetation sites. Their frequencies of occurrence are moderately high (14-47%). Again, most of the group have wind dispersed propagules, and at least one is bird dispersed. Two, a tree (*Melochia umbellata*) and a tall whip-like shrub (*Desmodium cajanifolium*), are commonly found along roads and within cleared areas, from which they can spread some into undisturbed native communities. Another bunchgrass, *Schizachyrium condensatum*,is like *Andropogon virginicus* with regard to creating a wildfire risk if its density is great enough. Otherwise, most of the other 10 plants in the group do not pose a significant problem to native vegetation.

Group 4. These 23 (16%) aliens naturalize in both disturbed and undisturbed sites, but presently are found fairly infrequently (2-14%) in the Puna area. Of these, seven are trees or shrubs which share the ability to invade undisturbed native vegetation: *Psidium guajava, Clidemia hirta, Schinus terebinthifolius, Clusia rosea, Schefflera actinophylla, Cecropia obtusifolia*, and *Archontophoenix alexandrae*. The first three are also all serious weeds in other Hawaiian vegetation. Of note is that all seven species appear to be primarily bird dispersed, which facilitates their spread into native vegetation. The ornamental plant *Begonia hirtella*, a moderately large perennial succulent herb, appears to be in the early stages of invading native vegetation types throughout the Puna area. The remaining Group 4 species are of little consequence in native communities, including the five Polynesian introduced species.

Group 5. These 6 introduced plants (4.2% of the 144) are infrequently found only in the understory at sites with undisturbed native vegetation. *Setaria palmifolia*, is a tall weedy grass which aggressively invades areas where the natural ground cover has been disturbed by feral pigs (or other factors). It is present in this group only because the occasional roadsides and disturbed places in Puna where it has colonized were not selected in the sampling procedure. It probably more properly belongs in Group 4. Fortunately, no other Group 5 species is known to present any threat to native vegetation. Two of these are Polynesian-cultivated, and another, coffee, was widely cultivated in shaded vegetation during the last century.

Group 6. These 51 species form an artificial grouping of species that have apparently been dumped or planted at a location, rather than showing a natural pattern of occurrence. They are discussed in detail elsewhere in this portion of the report. Man is the primary dispersal agent, but about 16 are known to have additional dispersal means as well. There is real concern that more "deposited" plants will naturalize, as a few have done, and spread aggressively into undisturbed native vegetation. One in particular, *Albizia lebbeck*, is found both as an occasional planting and as a naturalized species in disturbed and undisturbed vegetation. This fast-growing large tree is combining these two dispersal patterns with other traits to become a significant threat to native communities as it spreads through Puna.

The current study is simply a snapshot in time of a dynamic process where some species move between the groups as they progress through the invasion process.

Several widespread species, particularly *Psidium cattleianum, Melastoma candida, Andropogon virginicus* and *Nephrolepis multiflora*, are already well-established within various Puna native vegetation types and are of demonstrated ecological concern. There is real concern that some of the plants with currently limited occurrence may also spread aggressively. Group 4 has the largest amount of such potentially problematic species, plants which usually have demonstrated elsewhere in Hawaii an aggressiveness and ability to invade and disrupt native vegetation. Among all six categories (of the 195 alien plants), 35 appear to be of probable or possible ecological concern (Table 3). This is about 18% of the introduced plants reported in this survey.

Several additional species of concern, including the aggressive *Miconia calvescens*, were seen in Puna during the course of the field work, but were not observed at sample sites.

Lava flow age

In the lava flow age class evaluation, the youngest age class (historic flows) consists of 1955, 1960 and 1977 flows, reflecting relative quiescence on the Kilauea middle and lower ERZ between 1840 and 1955 (Holcomb 1987). Vegetation on these newest flows is sparse.

On undisturbed flows, there is an even split between native and introduced species numbers (Figure 9), even though the observed vegetation cover is predominantly native in all but at the lowest elevation. The diversity of native species tends to increase with lava flow age as more species and microenvironments are added to developing communities. Introduced species show similar increases in numbers with flow age, especially in disturbed situations. Proportionally, however, the percentage of introduced species in disturbed sites remains at 78-88% regardless of surface age (Figure 8). In undisturbed communities there are more native than introduced species, especially in the middle age class.

Disturbed and undisturbed sites

Figures 8 and 9 compare pools (combined sites) of various disturbance categories, broken into the age and elevation classes referred to above. In the undisturbed situations, a distinct trend is evident: the greater the elevation is, the greater are the proportions and actual numbers of native species in sites' floras. For disturbed sites, numerous introduced species are available at most elevations and ages, without apparent pattern. However, for the different age and elevation categories, the proportion of alien species within the disturbed pools is relatively constant (all within 76-88%). This proportional constancy persists despite considerable difference in numbers of native and alien species in each disturbed pool. Also, the numbers of introduced species in disturbed situations is 2.5 to 6.5 times the amount in the undisturbed situations. An extreme example occurs on the 1750 flows, which support extensive *Dicranopteris* cover beneath an open to closed 'ohi'a canopy. The dense *Dicranopteris* cover suppresses diversity and cover of both native and introduced species in undisturbed situations Here, the disturbed pool has 19 times as many alien species and 50% more native species than do the undisturbed flows of the same age.

Types of disturbance

In both recently disturbed and older disturbed situations the pattern is the same: disturbance of native vegetation favors a permanent shift in conditions to favor a much broader range of introduced species and restricted range of native species. The result of disturbance is a vegetation dominated by introduced species.

By examining the distribution of aliens in different disturbance situations, some additional detail becomes apparent. In two comparisons, three generalized categories of sites were evaluated: undisturbed native vegetation, cleared vegetation or lava flow, and roadsides (Figures 10 and 11).

Looking at the elevation gradient evaluation, the higher elevations have more native species and high proportion of natives on sites, as a rule (Figure 11). Across the lava flow age gradient, undisturbed communities nearly always support more native species than introduced (Figure 10). In nearly all sites, the observed dominance favors the native component of the undisturbed vegetation cover.

Once a flow surface is disturbed, the species composition of the secondary vegetation is overwhelmingly of introduced plants. The number of native species declines markedly in both cleared and roadside pools at all elevations. All disturbed site pools have 2-4 times as many introduced species as do the undisturbed site pools. The roadside category areas generally host more alien species than do the adjacent cleared category areas. The largest proportions of site pools in all disturbed areas are overwhelmingly introduced species in each disturbed category as well. This proportional dominance by alien over native species is seen across the elevation and age ranges (Figures 8, 9, 10, 11).

Deposited species

Over 120 observations were of introduced species which had been intentionally deposited at the site as disposed yard cuttings or as transplantation. Examples include those growing out of discarded heaps of trimmed branches and stems, weedy species only known to reproduce vegetatively, cultivated plants uncommon to the region and growing far beyond their known planted or naturalized distributions, and those known only or generally from cultivation. The source of most of the planted or discarded material is thought to be from homesites, with a few from agricultural fields. The 51 deposited species observed at sites were usually ornamentals, and include some fast-growing species which spread rapidly, both in people's yards and in naturalized situations.

About a quarter of these species tend to spread slightly from the point of deposition. Half are not expected to spread at all. The remaining quarter are known to spread much farther, some disruptively, vegetatively or by setting seed. Nearly a third of the 51 species are also capable of non-human dispersal away from the deposition location (these are marked by P* in Appendix 1 and 2). A fourth of the plants noted are arborescent; a fifth are vines; the rest are shrubs and herbs.

These 51 deposited species makes up 26% of the introduced species recorded in this study. Almost half of these species (23) were found deposited at sites only once, but nearly a quarter were seen 5 to 17 times. The deposition of viable plant parts is apparently prevalent throughout the Puna region. Many other additional alien species were seen in such situations outside survey sites.

A wide variety of locations and situations receive deposited plants. Many of our sample sites throughout Puna contained at least one deposited species. Up to 12 such species, comprising up to 30% of the introduced species, were found at a site. Sites include both disturbed and undisturbed situations, those visited by humans frequently and infrequently, and different aged substrates. The common element in each planting or dumping event was proximity to a road.

Most plant depositions in Puna occur along secondary (usually cinder-covered) roads and road edges (Table 4). Groups of species are frequently left along with other refuse and abandoned vehicles, all of which abound along the back roads of Puna. Even relatively remote and restricted-access roads have plants growing which had been dumped and occasionally planted.

Roadsides in agricultural areas and adjacent secondary growth are augmented the most frequently with intentional plantings; while roadsides and adjacent areas which are used as de facto refuse dumps are supplemented mainly with plants which have been casually disposed of. Residential roadsides and abandoned cleared lots receive both inputs, as do most of the roads in Puna. Cumulatively, large numbers of these human-vector dispersal events disperse numerous plant species throughout the portions of windward Kilauea accessible by roads. Passive hitchhiking on vehicles leads to similar patterns for other species.

The occurrence of deposited species in various categories of sites can be seen in Table 4. Collectively, the more heavily disturbed or cleared areas tend to receive more deposited plants than areas less disturbed. Following roads, the cleared sites pool (25 graded or bulldozed situations) has accumulated the next largest number of deposited species. Nine heavily disturbed sites (repeatedly disturbed, such as quarries and agricultural fields) and 8 lightly disturbed sites (single disturbances by heavy equipment, such as widened areas along a little-used jeep track or a firebreak) were also compared. The numbers of depositions (21 and 2, respectively) and their proportions of the two very different sized pools of alien species (19% and 4% of the total number of aliens, respectively) both reflect an influence of frequency of human access on the incidence of intentional and accidental deposition of plants at a site.

Note that the categories of burned forest, firebreak and adjacent roads all are low in total dispersed alien species, that they lack deposited species, and that they experience limited human traffic. The single exception is *Albizia*, several saplings of which were seen colonizing the forest area where the suppressive *Dicranopteris* mat had been burned off. The parent plant may be one of several planted trees 1-2 kilometers (0.6-1.2 miles) away in the Upper Kaimu Homesteads Road area.

About 43 alien species were reported in this survey but not in the more intensive survey by Char and Lamoureux (1985) nine years earlier (Table 5). Twenty-two of the 43 are considered to be deposited species in the current report. This 22 includes three members of the Melastomataceae, a family notorious for invasive members that have been introduced to Hawai'i and elsewhere. This 22 also includes *Clusia rosea*, a widely planted ornamental tree which readily naturalizes and is now too naturally widespread to consider as a deposited species. *Clusia* and *Medinilla magnifica* (on the list of 43) as well as *Schlefflera actinophylla* and *Ficus microphylla* (other common ornamentals which naturalize) all are able to spread beyond the plantings by producing bird-dispersed seeds and sharing the ability to get started as an epiphyte on a host tree in already established forest, native or introduced.

Some alien species have moved into undisturbed communities. Of these, *Casuarina, Tibouchina urvilleana* and *Hedychium gardnerianum* have demonstrated an ability to severely damage native communities. Given that numerous naturalized and spreading species in Puna were started as plantings only a short time ago, these new plantings and their known invasive complement provide an index to the ever increasing threat of human-aggravated invasion by alien plant species.

DISCUSSION

Primary succession on Kilauea

Significance of the Kilauea successional ecosystem

The existence of the successional ecosystem on Kilauea is the result of the process of primary succession on recent volcanic surfaces interacting with the spatial and temporal eruptive aspects of Kilauea, one of the world's most active volcanoes.

The rapid turnover of land surface favors certain attributes in the region's flora, tending to select some kinds of plants over others. Those species that readily disperse are the ones which are found in greatest abundance. If they can tolerate extremes in moisture and restrictive nutrient availability, they may be included in the pioneer vegetation on new surfaces. If other plants grow next to variably aged pieces of the differentially vegetated mosaic, then they may eventually be dispersed to or from some of them. A propensity for dispersal and/or proximity both enhance dispersal to other pieces of the mosaic. Having a fine-grained mosaic (small pieces) enhances short-distance dispersal. Having many replicates increases the chances for surviving volcanic burial. The reciprocals of these relationships discourage rapid succession and diverse communities.

The network of recurrent dispersal events and variety in receiving surfaces ensure continuance in the process of community succession. Continuance in this process keeps the ecosystem intact and maximizes native organism diversity. If the dispersal of native species is curtailed or significant gaps become developed in the successional continuum, then the process is likely to be adversely affected. Should there be attrition and substitutions in the pool of species dispersed, this, too, will affect the process.

The native diversity on Kilauea is found in the accumulation of species within the variously developed successional communities. Collectively, the summary flora of numerous simple communities is far greater than that found in any one or few. Thus, the ecological value of a particular area of vegetated land on Kilauea does not lie simply in the presence of local endemic species or rare and endangered species. A better indicator of ecological value lies in its mosaic of variably aged flow pieces and the range and replication of communities which are represented upon them.

As dispersal of native organisms to younger pieces of the successional mosaic is a vital part of the process, each degree of community development is important in maintaining continuity of successive seed species. Each piece of the mosaic is important, as there is a mutual interdependence. Maintaining replicates of the diverse mosaic pieces is also essential to the process of primary succession. This ecosystem's resistance to destruction by volcanic activity lies in sustaining a diverse array of variably matured natural communities throughout the dynamics of periodic replacement by newly erupted volcanic surfaces. Loss of enough of these components in an area due to extensive inundation by lava and/or displacement by development can lead to a marked drop in native species diversity, and ultimately it can break the successional chain. Such breakdown of the native successional processes has occurred on some of Kilauea.

Invasion of native vegetation by alien species

Some intermediate and older substrates (greater than 250-300 years old) are invaded by numerous exotics, primarily *Melastoma candida* and *Psidium cattleianum*, to the point that a significant part of the shrub and smaller arborescent biomass is composed of these two aliens. Numerous individuals of native species are displaced, but it is unlikely that many (if any) native species are excluded except in extreme situations where the biomass is predominantly introduced. With fewer remaining seed source individuals, the expected dispersal of native species from these areas should be reduced. Nonetheless, the remnant natives still serve an irreplaceable function as the source area and reservoir for dispersing seeds. These dispersed native seeds may well find a more favorable situation for proliferation on the receiving substrate, particularly some release from alien competition. Whereas *Melastoma* and *Psidium* are abundant in some communities, their observed presence on most younger flows is generally limited.

This seed source role is important to maintain even if these new receiving flow surfaces have not yet been erupted. On Kilauea, the wait will be brief. Added to existing forest clearing losses, more anthropogenic removal of such intermediate-aged and older parts of the mosaic would be an incalculable loss to the successional process in that their relative presence has already been and will continue to be diminished by lava inundation. Even heavily invaded native vegetation serves the vital function of harboring seed sources for dispersal and it has ecological value in the Kilauea successional ecosystem. Preserving the remaining native vegetation, invaded or otherwise, is of paramount importance to the continued function of the Kilauea successional ecosystem. Once a species is lost from the Kilauea successional pool, it is not likely to be replaced, given the cumulative anthropogenic impacts to the Kilauea and adjoining Mauna Loa vegetation.

It should be obvious that this reservoir role of standing native seed bank will be better achieved if there are fewer introduced species invading the remaining native vegetation, particularly the more vulnerable intermediate and older flow units. An important conservation and management aim should be to prevent, as much as is possible, the further addition of alien species to the weed pool surrounding the remaining vegetation of Puna. The spread of these plants throughout Puna's road network appears almost inevitable; and from there follows invasion by a few into the adjoining forest. It is the case for most alien species in Puna that, generally, the alien species are not displacing native communities as much as they are joining them. However, if the communities are physically disturbed, then the secondary vegetation is composed mostly of introduced species, both in numbers and in biomass.

Another consideration for invasions of introduced nitrogen fixing plants and other infrequent incipient, disruptive species relates to making evaluations for their local eradication. Whether an invasion of each nitrogen fixing species into an undisturbed native community will lead to the same outcome as physical disturbance remains to be seen, but the observed early indications are worrisome. There should be made a serious assessment for selected species' eradication before their local populations become unmanageable.

Secondary succession on Kilauea: consequences of disturbance

Roads

The important role that roads and roadsides play in the distribution of plant species can be seen in several aspects. Roads and roadsides are significant habitat for introduced species. They have considerable cumulative land area and geographic extent. Individually, a road will have a small land area, but this is important ecologically because the edges of that area forms extensive linear interactive interfaces with adjoining vegetation, including native communities. Many roads and roadsides penetrate otherwise little-modified native communities, facilitating the access of roadside weeds to large areas of native vegetation (Ewel 1986).

While they span quite a range in environmental conditions, the roadside habitats have their own characteristics. They tend to have an abundance of compacted moisture-retaining fine mineral material at the surface, which can make a moist root environment even in Puna's drier areas (Wester and Juvik 1983). The crushed cinder base typical of Puna roads is rich in most nutrients except nitrogen, and the powdered volcanic composition of crushed cinder facilitates the rapid release of these nutrients. Roads sometimes are better lighted than the surrounding area. The combination makes many exposed roadside surfaces an ideal seed bed for many alien plants. The same conditions appear not to be favorable for many native plants, as only 26 native species were found (sparingly) along roads, 27% of all natives reported here. The strip of favorable habitat for weeds provided by a road may penetrate inhospitable habitat fostering the roadside migration of weeds and connecting with other habitats favorable to weed establishment (Wester and Juvik 1983).

Of all habitats in Puna, roads tend to be recipient of the most concentrated dispersal of the largest numbers of alien plants (162, or 94% of all the introduced plant species found in this survey were found along roads). The largest grouping of deposited plants is from the roads category, emphasizing the role humans play in utilizing roads to actively spread plants. Additional passive dispersal along roads by vehicles is obviously considerable. Consequently, roadsides are also the greatest reservoir of alien plant species, many of which are able to disperse out from the roadside. The roadside communities are diverse and dynamic due to this large amount of dispersal, as species are added to the pool, turn over in composition, and experience a saltatory spread along the lengths of the roads. Given the above, it is inevitable that the presence of a road in an area will result in the spread of introduced species along it. No evidence to the contrary was seen on this survey.

There is repeated indication that numerous exotic species become established infrequently along roads, and that they enter the native vegetation from this edge. These include some plants whose presence in native vegetation is inconsequential, and others which can be variably disruptive. From the relatively stable roadside distributions, they can move (by seed or vegetatively) into adjoining habitats, both native and disturbed vegetation. Examples include: *Melochia umbellata, Cecropia obtusifolia, Buddleia asiatica, Pluchia symphytifolia, Desmodium cajanifolium, Conyza bonariensis, Polygala paniculata, Drymaria cordata, Chamaesyce hirta, Juncus spp., Tibouchina urvilleana, Emilia sonchifolia.* The species of greatest concern are those which, once spread by man, are able to further disperse away from the roadside, such as: *Albizia lebbeck, Clidemia hirta, Casuarina equisetifolia, Spathodea campanulata, Pennisetum setaceum*, and *Setaria palmifolia*. Table 3 lists 35 species of probable or possible ecological concern.

It is likely that the now widespread and intrusive *Melastoma candida* got started as above from a roadside or residence. Once established in many native communities (young and old substrates both), it has been able to spread widely, attaining much higher observed densities on older flow surfaces than younger. Some areas of middle and lower Puna native vegetation are still free of this aggressive shrub, and the continuing invasion from reservoirs on roadsides and disturbed vegetation can be seen (such as at lower Nanawale Forest Reserve).

A few species have only spread little from roadsides into native vegetation and that adjoining it at the time and places of this survey's observation. They may have the potential to spread much more; consequently, they should be watched. These include: *Derris elliptica, Melaleuca quinquenervia, Persea americana, Ficus microcarpa, Hedychium coronarium, Epipremnon pinnatum, Philodendron sanguineum, Philodendron sp., Melinis minutiflora, Clerodendrum philippinum, Wedelia trilobata, Dissotis rotundifolia, Heterocentron sp., Anthurium sp., Brachiaria mutica. Persea* was seen to be spreading readily within two examples of lower, older (500+ years) substrate at Malama Ki (100 meters or 330 feet elevation) and Keahialaka (225 meters or 740 feet elevation) into which it had been planted. *Hedychium coronarium* was observed to be setting seed adjacent to Ala'ili Road at Kamaili Homesteads (350 meters or 1150 feet elevation), a behavior which has made *H. gardnerianum* such an aggressive forest pest at higher elevations. *Melaleuca* was spreading from a roadside into a previously burned area at Waikahekahe Iki, 415 meters (1360 feet) elevation.

Cleared areas

Cleared vegetation and flow surfaces nearly always are recolonized primarily with introduced species, some of which achieve dominance in the vegetation cover. Any native components in the disturbed sites examined are very minor in numbers and in cover. Even if the alien species are ignored, the native species colonizing cleared sites usually comprise only a small portion of the native species in the adjoining undisturbed areas of vegetation. Where native vegetation has been partially cleared, the original primary vegetation and the adjacent newer secondary vegetation are very much different.

Among the few exceptions observed is a location where a bulldozer crossed a portion of the 1955 Kehena 'a'a flow. In the flattened tracks which the machine had left now grow the same simple mixture of colonizing native and introduced plants as on the undisturbed flow, but the abundance of the widespread introduced *Arundina graminifolia* and *Andropogon virginicus* on the tracks was observed to be considerably greater than on the undisturbed 'a'a. The physical nature of the disturbed 'a'a seemed little different other than being compacted.

Generally, when native vegetation is even just lightly disturbed by heavy equipment, the recovering secondary vegetation is predominantly alien in composition and in cover dominance. As seen in Table 4, the numbers of introduced species colonizing lightly disturbed categories are relatively few compared with those in the heavier disturbance categories. In lightly disturbed situations, the machinery usually exposes soil which, in an undisturbed state, would be interstitial within the upper 'a'a clinkers or concentrated in cavities and depressions on a pahoehoe flow. The surface soil excavated at recently cleared (or burned) flow surfaces is exposed to view and settlement. This exposure may facilitate the establishment of small-seeded, easily dispersed alien plants which otherwise might not have the energy reserves in their small seeds or tolerance to minimal illumination to grow up to light from the cryptic soil below a stony undisturbed or vegetated flow surface.

Where disturbance has been heavy, and usually recurrent, the introduced species pool is much larger, but still only 81% as large as the roads pool (Table 4). These sites include abandoned agricultural fields, quarries, heavily graded sites, cleared house lots within native forest, and an abandoned geothermal well drilling site. Compared observations at fresh and older cleared house sites (close to one another) suggest a considerable turnover in alien species composition as the secondary weed communities mature. As above, native species make up a small part of the species lists and a considerably smaller portion of the secondary vegetation cover, even when surrounded by native-dominated vegetation.

Degradation of the Kilauea successional ecosystem

<u>Attrition and replacement of seed sources</u>

Some land clearing on east Kilauea has been a recurrent process since the colonization by pre-contact Hawaiians (P.H. McEldowney, pers.comm.). Until recent decades, however, the extent and ecological consequences have been concentrated on intermediate and older flow surfaces. The permanent displacement of native vegetation by crops and the additional introductions of alien species have increased to the point of significant adverse result to native vegetation. Accompanying the cumulative settlement of the mostly-vacant lots, uncontrolled wildfires have begun to play an increasing role in the loss of native communities on windward Kilauea as well. Humans ignite most fires, and the spread of alien grasses in recent decades has increased the size and frequency of wildfires (Smith and Tunison 1992). Residential subdivisions now span the elevational range of windward Kilauea, mostly to the north, east and southeast, further displacing and fragmenting the forested areas. Growing of orchids and orchards, quarrying, and residential construction have also moved onto sparsely vegetated recent flows.

The problem of attrition of seed sources from extensive clearing is one which accelerated in the 1980's as the papaya industry expanded to meet export markets. Papaya disease and availability of leased forest land encouraged the common practice of clearing virgin (disease free) forest for a single planting, then moving on to more forest once the papaya disease depressed yields. Numerous pieces of land within the remaining forest areas were cleared, with time, coalescing into large tracts over more and more of east Kilauea. Large clearings extend up to 1400 feet (425 meters) elevation, but the major tracts lie below 400 feet (120 meters) elevation.

As native vegetation is cleared and replaced by alien-dominated communities, any young flows in the vicinity may experience a decrease in quantities and diversity of dispersed seeds and spores in the "seed rain" at the same time as the rain of propagules from an enlarging number of introduced species is increasing. This is a serious problem for *Metrosideros* with minute wind-dispersed seeds. Drake (1993) reports that they tend to germinate soon after shedding, retain viability for only a short time and are not adapted to becoming incorporated into a persistent "seed bank" in the soil. Instead, they are adapted to providing a periodic rain of seeds, dispersing them aerially to new volcanic substrates (which have buried the pre-existing soil). This pattern of recurring dispersal is paralleled with other plants colonizing new flows, even if they depend on animal vectors or gravity to disperse the seeds to the flow surface.

The attrition of native propagule stocks can be seen in an example in the lowest end of the Kilauea East Rift Zone near Kapoho. The expansive low elevation 1960 and 1955 Ki'i flows have left large areas of bare lava and cinder fields, and surrounding agriculture and residential uses have replaced much of the nearby native forest. Plant life on the 1960 flow is sparse and composed of few species, mostly introduced. Not only are local seed sources for colonizing native species reduced, the 1960 flow extends upwind (during the prevailing tradewinds) to the shoreline, further exacerbating the situation for native wind-dispersed colonizers such as *Metrosideros*. The very sparsely distributed (about 4-12/hectare) young trees on the observed open 1960 lava flow are fairly evenly split between *Metrosideros polymorpha* and the introduced tree *Cecropia obtusifolia*.

Alteration of natural succession by alien species

Also colonizing the 1960 Kapoho flows, waves of the alien tree *Casuarina equisetifolia* are advancing across portions of a relatively bare flow surface, and at even higher density (at 43-61 meters or 140-200 feet elevation) across areas of the flow which have been veneered by cinders thrown out by the nearby vent. In another recently erupted area at intermediate elevation (245-305 meters or 800-1000 feet), the introduced tree *Albizia lebbeck* is invading the native dominated vegetation which has been colonizing the 1955 'a'a flow at Kehena. Here, the native seed sources are sufficient to foster the rapidly developing vegetation, but an adjacent grove of *Albizia* is supplying seeds which are also establishing on the new flow. The presence of each young *Albizia* tree is enhancing the growth of immediately surrounding species, mostly exotic.

Both *Albizia* and *Casuarina* are reported to be nitrogen fixers (Smith, 1985), utilizing this ability to enhance their own establishment on the flow and at the same time altering the whole natural primary succession process. Vitousek (1992) notes that a nitrogen-fixing plant can be at a competitive advantage when invading a nitrogen-limited primary successional community. He also suggests that an invasion of such a nitrogen-fixing species may elevate available nitrogen in the invaded area and thereby make it more amenable to invasion by other species, many of which will be aliens.

This phenomenon was first described for another exotic tree, *Myrica faya*, which is invading primary successional communities near the summit and upper ERZ on Kilauea (Vitousek, et al., 1987). In doing so, *Myrica* is able to achieve more rapid growth than *Metrosideros*, and it also turns the immediate area from nitrogen deficient (all other nutrients are reported sufficient) to having a net surplus of nitrogen, a major ecosystem alteration (Lewin, 1987). These local areas of the flow having full nutrient availability in an otherwise restrictive nutrient-limiting early successional community opens opportunities for more introduced species to invade, risking further community disruption. Such invasions become self-compounding, as an enlarging number of species increases the probability that more species of plants and animals will find suitable niche opportunities (Howarth, 1981).

Invasion of a nitrogen fixing organism early in primary succession can begin premature invasion by a considerable variety of introduced organisms, this at a time in successional development when there are few native species already established in the simple initial colonial community. The continued succession process following this enrichment of nutrient status and species composition is more akin to secondary succession than to primary. Once this transition occurs, the chances for native species to gain a prominent role in the continued community development are nil.

Edge effects

A transitional edge habitat is created and maintained along the vegetated margins of roads, clearings, pipelines and powerlines. This edge connects the lighted and desiccating open environment with the adjoining community's conditions. Where the edge transects a forest, most of the native forest organisms find the edge conditions exclusive, while a few, such as *Pipturus albidus*, *Pycreus polystachyos*, and *Sphenomeris chinensis* find them ideal for colonization. These sometimes join various introduced plants to form a perennial edge community of plants and animals assembled by chance and shared propensities for secondary succession. Like roadside communities throughout Puna, such a disturbance community has the possibility to receive and maintain alien species, a few of which can be expected to be capable of spreading into the forest.

As is observed for roads in general, many alien species use the edge habitat as conduits for spread through native habitats. The mobile aliens adventive within the edge communities then transect and interconnect native communities. The naturally characteristic and protective isolation inherent in a kipuka (an older piece of the mosaic) is lost once it is interconnected. While vulnerable to invasion by their relative successional maturity, older kipuka naturally tend to be shielded by the surrounding younger flows bearing communities less prone to exotic invasion. Currently, the more isolated an older kipuka is, the more likely it will be relatively uninvaded.

Where an open edge habitat runs through a rainforest situation (as in the Kilauea Middle East Rift or Kamaili Geothermal Resource Subzones, for example), it forms a pronounced separation between the forest portions, acting as a barrier for many native organisms. The barrier provided by the road or clearing and its edge differs with both the extent of the opening or road, and also with the kind of organism considered, running from nearly complete for many to nearly transparent for others.

One major effect of this barrier is to act as a selective filter restricting the array of organisms dispersing and moving from one side to the other. Considering the vital function which dispersal plays within the Kilauea successional ecosystem in the continuous movement into and within the various pieces of the successional mosaic, such an inhibition of dispersal will affect the functioning of the ecosystem on both sides of the barrier. This, in turn, will seriously fragment the vegetation mosaic and attenuate natural community development. Where roads interconnect or form a network, as in the extensive subdivisions of Puna, there is a formidable fragmentation of the forest. Only the most vagile organisms are unimpaired.

Ecosystem breakdown

The lush successional vegetation of windward Kilauea is in dynamic balance with the active volcano. On the drier leeward (southwest) side of the mountain, the successional process is naturally slower, and hence, the vegetation cover has been only partial. The natural primary succession of leeward Kilauea has been interrupted and replaced by weed succession controlled by alien organisms in all but the most inhospitable locations. Such transition has resulted from the native vegetation of leeward Kilauea being subjected to sustained trauma from introduced ungulate browsing (until recently) and 30 years of wildfires promoted and sustained by the concomitant, extensive spread of alien grasses which had colonized the browsed landscape. The grasses and other exotic plants adapted to browsing and fires have now come to dominate the vegetation by surviving the changing nature and frequency of disturbance, and by replacing most of the receding nonresistant native plant cover. The mesic summit and adjoining areas are suffering equivalent trauma from the proliferation of nitrogen fixing *Myrica faya*, flammable alien grasses and consequent weeds.

There is concern that the more resistant and intact wet windward Kilauea communities may suffer similarly where there is cumulative forest loss and replacement of native organisms by aliens. The same outcome might befall other areas altered by different ecosystem perturbations, with or without physical trauma. The earlier mentioned attenuation and transformation of primary succession on the 1960 Kapoho flows may be an example of interruption of the natural chain of succession at a formative early time. The portions of the same flow (and the bottom of the 1750 flow at Malama Ki) which are invaded by *Casuarina equisetifolia* and the area of the 1955 Kehena flow which is invaded by *Albizia lebbeck* are also areas of serious concern. These sites are generally lacking in physical disturbance, but appear to be severely altered in composition and process by only the addition of the single species which inserts its nitrogen-fixing role.

Geothermal development and native ecosystems

Geothermal resource subzones

Regulations restrict the exploration for geothermal resources and the placement of surface infrastructure to three Geothermal Resource Subzones which straddle the ERZ of Kilauea (Figure 12).

Kapoho Geothermal Resource Subzone. This subzone runs from near sea level to approximately 215 meters (700 feet) elevation. About a third to half of the area is covered with 1955 and 1960 lavas, extending along most of the elevation range of the subzone. These are covered with an open, low stature forest in the upper, wetter portion, and are nearly barren closest to the coast. In between, the pioneer vegetation is a variable, mostly low, open to sparse scrub. Nearly all of the older vegetation has been cleared for agriculture, as well as some of the recent flow area. About seven older erupted cones support forest, but at least some introduced species are common within their vegetation. The best preserved native vegetation may be on older substrate at the subzone's highest elevation cone cluster at Pu'ulena and the adjacent still-forested area. A bit of forest remains along the north central boundary, between Halekamahina cone and the Halepua'a section of Nanawale Forest Reserve, growing at +/- 90 meters (300 feet) elevation on 1790 lava. Another swath of good forest remains at Oneloa at around 100+ meters (350 feet) elevation, on 1790 and 1650 flows. Scattered patches of modified forest or native plants are relictual. Considering that the landscape is covered with much more introduced vegetation than native, the remaining native vegetation and individual plants retain high value as seed sources for the large area of new flows.

Kamaili Geothermal Resource Subzone. This subzone extends from about 180 to nearly 425 meters (600 feet to 1400 feet) elevation. There is a diverse mosaic of flow ages, ranging from older ash soil surfaces to younger flows from 1750, 1790, 1840, 1955 and 1961. At least half the area still supports native vegetation. Most of the northern Kaohe area was cleared for timber and cane about 90 years ago, and some of the central homesteads east and southeast of Pu'u Iilewa have been opened up more recently. Unlike the Kapoho area, there are still few roads into much of the Kamaili forests.

Middle East Rift Geothermal Resource Subzone. This subzone extends from 365 to 610 meters (1200 to 2000 feet) elevation. The mosaic straddling the ERZ is of many pieces and ages. The most recent flows, from 1983, reach far into the intermediate age 'Ai-la'au flows which mantle the north flank of east Kilauea. The 1750

Heiheiahulu shield, 1961, 1963 and 1977 flows also ride over much older surfaces. The whole subzone is uncleared except for a recent road to a now-abandoned geothermal drill site. The surrounding areas are all natural surfaces as well, as this subzone is within the largest remaining forest tract on windward Kilauea (including the former Wao Kele O Puna Natural Area Reserve).

Disturbance and geothermal development.

Physical disturbance. Examples of the types and geographic layouts of a geothermal development scenario can be seen in the EIS for the proposed Kahauale'a geothermal project along the Kilauea ERZ (Towill 1982). Most types of physical disturbance created by geothermal exploration, development and operations are nearly the same as the most severe disturbances from agriculture, residential, quarry and related activities which were observed elsewhere in Puna. The geothermal activities with similar degrees of ground disturbance include the construction and use of roads, and the clearance of sites for staging areas, ponds, sumps and power plant facilities. The consequences from such disturbance to vegetation can be expected to be the same: the site conditions are permanently shifted to favor a much broader range of introduced species, a restricted range in native species, and an overwhelming preponderance of introduced species in the cover of the secondary vegetation. This assessment should apply whether or not the heavily disturbed site is within mostly native vegetation or introduced vegetation, and the generalization should apply at all elevations along the ERZ.

Other kinds of activities associated with geothermal may cause either a heavy disturbance as above or may be less disruptive. Examples include the construction and use of powerlines and pipelines which are located within or alongside a heavily disturbed roadway, rather than within areas of native vegetation. Even if these items and survey lines are carefully placed within native vegetation, there will still result some physical disturbance, an increase in light levels and dryness, possible repeated clearing or trimming of vegetation, and the inadvertent introduction of weed species. Minimally, an edge effect can be expected as a result of the clearing.

The spatial and temporal aspects of such geothermal related disturbance may vary considerably with the nature, scale and location of geothermal activities. For example, exploration for geothermal resources involves the repeated drilling of wells, and, therefore, it is likely to create nearly the same adverse impacts to native vegetation as might a full-scale geothermal project, given a requirement for roads, cleared sites for drilling and staging, sumps and reservoirs. Exploration may also be extensive and protracted, as was proposed for Kahauale'a (Towill 1982), and as is implied by the cumulative areas of the three geothermal resource subzones of the Kilauea ERZ (Fig. 12).

The effects upon native vegetation will be catastrophic and permanent at the network of sites and roads. The consequences beyond the physically disturbed sites are varied and more subtle. They should include, at least, (1) invasion of some introduced species from the considerable marginal length of all the roads and cleared areas (i.e., roads and edges can act as conduits and points of embarkation for many alien species), (2) the long-term degraded native vegetation next to the edge along these margins, (3) the physical fragmentation of the tract of native vegetation by the roads and clearings.

Barriers. A reticulate, dendritic or even a simple linear geothermal exploration or development pattern within native vegetation will cause adverse restrictions to normal plant dispersal and faunal movements at the edges of roads and clearings. The road/clearing and its edges form a differential barrier which curtails the natural process of dispersal and infilling for many organisms. This flow of organisms and propagules is one of the paramount aspects of the successional ecosystem on Kilauea. Differentially impaired dispersal across the edges of the road and clearing network may well cause local disfunction of the successional ecosystem, and the long term implications in sustaining diversity and the successional process in the area are of critical concern. There can be no way to compensate for these constraints on a biota which is obligatorily so spatially and temporally transient. The total perimeter of the roads and clearings rather than their cumulative area is a better index of their extent as a separator or barrier.

Abandonment of geothermal sites. Any geothermal exploration and development project is expected to have well sites periodically abandoned due to lack of drilling success or well degradation. Also abandoned are their associated staging areas, sumps and access roads. The surfaces of these areas are highly disturbed, at least partially compacted, and possibly locally contaminated with geothermal brines, drilling muds, machinery lubricants, sodium hydroxide and other industrial chemicals. While this not the most hospitable plant environment, observations of abandoned quarry areas and a small geothermal drill site indicate that following cessation of disturbance, there will be colonization of the sites by various introduced species and the maintenance of an alien-dominated vegetation. Such a vegetation will be a permanent source of alien species on that disturbed surface, and it will likely continue to add species to its pool of alien plants. Even if the drill site is successful, after testing and attachment of the well to the fluid grid, there will still be portions of highly altered land surface which will no longer be in active use or maintenance. These, too, are almost certain to become reservoirs of introduced species.

When a geothermal project is abandoned, it is highly likely that the complete area of disturbance will be left to accumulate and culture introduced species, much as have abandoned agricultural fields. Any development-related landscaping or weed control can be expected to be similarly abandoned.

Continuous operations. A successful geothermal project is quite likely to expand to meet the needs of possible increased electrical output, decreased production well yields, inadequate injection well or brine disposal pond capacity, replacement well drilling, accessory geothermal related activities, and the like. Thus, continued expansion and new land clearing, or at least continued disturbance, can be expected. Concomitant with development, use, and expansion of a geothermal project is the continued ingress of vehicles and equipment, any of which is a possible vector for organisms not yet present at the site. This risk of new species introductions is greatest when equipment, portable buildings, shipping and storage containers are brought from another site, especially one overseas.

This same sort of accidental introduction and dispersal of alien species has accounted for about half of the alien plant species introductions to Hawai'i (Wester 1992). One example was documented for the upgrading of the Haleakala Highway on Maui, during which fill materials were brought in from elsewhere on the island and some heavy equipment was brought from the mainland U.S. by the contractor. A total of 20 plant species were introduced to and established along the roadside, including two species not previously introduced anywhere in the Hawaiian Islands (Loope et al. 1992).

Other possible consequences of geothermal development

Lava tube dependence. The lava tube communities are a second layer of unique ecosystem existing beneath the pahoehoe flows of Kilauea and other Hawaiian volcanoes. Their total dependence upon the *Metrosideros* forests overlying them, via the tree root link, makes the tubes share the same fate of the forests should the trees be adversely affected by geothermal development. Given the local endemism and individual uniqueness of their biotas on Kilauea (McEldowney and Stone 1991), those lava tubes are particularly likely to be impacted by geothermal development in areas where they both occur.

Interactive Alien Introductions. Some alien organisms may have interactive impacts upon native ecosystems should they be dispersed into native communities by geothermal development. Movement of fill material sometimes results in the establishment of ant colonies at the site of fill emplacement. Such colonies may derive significant benefit from alien orchids and other low growing nectar source plants which tend to colonize the edges of roadsides. Ants are notorious in Hawai'i for decimating the local arthropod fauna, including groups of insects which may be involved in pollinating native plants or feeding native birds. Certain wasps have been spread by the transport of building materials or containers, and have had similar impacts on native invertebrates. Alien slugs and snails can be dispersed on equipment, materials and vehicles into rainforest situations, where a seedling bank of native plants might be available and particularly vulnerable (as has happened many times between residential areas). Introduced nematodes can also be spread with soil, landscape plantings, etc., and these organisms have been detrimental to some native plants.

These sorts of introductions and adverse consequences are almost inevitable whenever as much intrusion, material transport and traffic into native communities occurs as would with geothermal exploration and development activities. Precautions such as inspections and cleaning can be proposed as mitigation, but the actual proper performance and effectiveness of such is highly questionable. A more realistic assessment is to expect the aforementioned types of interactive introductions to occur, despite required mitigation, as a predictable consequence of geothermal activities in native communities. The only realistic partial mitigation of this problem could come with regular surveys of disturbed areas by botanists and invertebrate biologists to constantly look for newly introduced organisms that came in via the development. Even with surveys, most invertebrates would probably escape detection and eradication.

Accidents, Pollination, and Seeding Failure. The reproductive nature of the three kinds of *Metrosideros* colonizing Kilauea involves the periodic release of large numbers of wind-dispersed seeds to take advantage of ever present establishment opportunities, an attribute which keeps it competitive with wind-dispersing aliens. Carpenter (1976) has noted the importance of bird pollination in maximizing viable seed production in *Metrosideros*. Should a large area be deprived of pollination, then a subsequent reduction in dispersal of viable seeds in that portion of the Kilauea successional ecosystem could retard colonization by the tree, and such opportunities might be taken instead by introduced plants. Similar assumptions can be made for other native plants requiring plant or insect pollination which might be interfered with by geothermal activities.

Sustained release of significant concentrations of hydrogen sulfide gas (a prominent, odiferous and poisonous component of geothermal fluids) could discourage visitations to *Metrosideros* by its pollinating birds. This could occur over large areas, given a large source and the daily reversals and swings of the prevailing winds in Puna (Towill 1982, Metz 1989). Any insect or bird pollination involving aromatic flower chemical attractants or stimuli could be similarly interrupted. Excessive noise may produce similar results for birds.

A geothermal well blowout (an uncontrolled, sustained atmospheric release of geothermal well fluids from a damaged or leaking geothermal well) could be a source of both deterrents. There is a distinct possibility that an intrusive volcanic dike could intersect a well or well field and cause sustained multiple well blowouts, given that both dikes and geothermal well bores cohabit the same Kilauea ERZ subsurface locations and depths. Strong seismic events or fault activation from ERZ intrusive deformation could also be sources of subsurface or surface damage to geothermal wells. Even undamaged wells might be required to vent fluids (partially treated or not) due to loss of load at or away from the geothermal power plants. Such a situation could result from volcanic activity, earthquake, tsunami, severe wind storm, utility grid malfunction, or power plant malfunction. Area-wide and even island-wide blackouts have been occurring on Hawai'i Island for years from various causes, each a severance of load from power supply.

Site rehabilitation and planting of native vegetation

Whenever native communities on Kilauea have suffered significant physical disturbance, these have been replaced by secondary communities bearing an overwhelming dominance of introduced plants and animals. No examples are documented or are known of any successful replacement or rehabilitated native communities on Kilauea. Given the examples and patterns seen in disturbed native communities, very few of the native species in the area will recolonize the disturbed area, and the abundance and variety of fast-colonizing introduced species will displace and out-compete the natives. Accordingly, it can be reasonably stated and assumed that once a native community on Kilauea has been significantly disturbed physically or by fire, it is lost to alien species. The loss is permanent unless the site is covered by a new lava flow and sufficient propagule sources exist nearby to sustain primary succession.

The only examples of rehabilitation of disrupted native communities which have had any success have been those in which gross physical disturbance was not a factor. In these, the most disruptive introduced organisms were locally eradicated, generally the alien ungulates (primarily feral goats, cattle, sheep or pigs; Loope and Scowcroft, 1985). Eradication of alien arthropods from native ecosystems has not been achieved, only localized reductions. Removal of selected disruptive alien plant species has usually proven to be even more difficult, and the expenses involved have very much limited the size of the geographic areas so treated (Tunison and Zimmer 1992). Therefore, the prospects of keeping a cleared, formerly native community free of introduced organisms to aid in recolonization by natives are doubtful, and most likely would be prohibitively expensive to attempt. The land cleared of native vegetation should be considered lost to the native successional ecosystem.

On the other hand, careful monitoring and removal of potentially disruptive or invasive introduced plants and animals from disturbed sites within native vegetation is a feasible and desirable activity, although to be successful it will entail a regular and long-term commitment of effective effort and funds. Such a program is necessary in order to reduce the significant biological threat to native communities which cleared sites in their midst do present.

One possible way to reduce the long-term expenses, and to increase the effectiveness of a program to reduce invasion risk of cleared land, is to plant and maintain a dense, non-invasive cover crop over the cleared land. Such a crop species should be arborescent to be able to suppress arborescent invaders, it should be demonstrated not to invade the neighboring communities, it should be easily cultivated by seeds (which are capable of thorough cleansing), it should be self-sustaining, it should be fast growing and resilient to pests, and it should be dense enough to suppress weed growth beneath it. An excellent candidate species which meets all the listed criteria is the kukui tree (*Aleurites moluccana*), a Polynesian introduced tree which already occurs in all three geothermal resource subzones. It frequently grows on heavily disturbed sites such as abandoned agricultural sites and on talus slopes. It is presumed to have persisted in Hawai'i for over 1500 years since the Polynesians settled these islands. Kukui is frequently found in long abandoned forest or coastal sites, but it has not spread appreciably into the adjoining vegetation. Very few alien species are found beneath the trees in any given area, so its role as a weed suppressant is effective. The plant, in effect, forms a persistent and protective vegetation scab over the disturbed land it covers.

Cumulative ecological degradation and geothermal siting

Like large-scale agricultural and residential development, geothermal exploration and development brings considerable physical disturbance and ecological turmoil to whatever location it occurs. Generally, the more extensive and intensive the activity, the greater the cumulative and recurrent disturbance and the ecological disruption. The maximum ecological disruption is associated with the replacement of native communities by development and secondary successional communities and with the introduction of alien species into an area. Other impacts can also be expected, depending on the location of the geothermal development site relative to native vegetation and other biological resources.

Where geothermal development is sited on previously cleared land, there is no direct loss of native vegetation. If the surrounding areas are also devoid of native communities, the chances for degradation of nearby native communities are further limited. Much of the Kapoho Geothermal Resource Subzone appears to fall within this previously degraded geographic context. The main risks would be of introducing organisms not already present or common in the area, and of nurturing a diverse set of secondary introduced species which could disperse outward.

However, in these lower elevation areas, the threats to remaining native habitats by vegetation removal and by collective accumulation of introduced organisms is enormous. The amount of undisturbed land surface is limited. Proper documentation of these areas, proper monitoring and selective control of some of the introduced elements in the area's total biota, and proper siting of geothermal exploration and operations (and other land clearing) away from the remnant native communities could result in minimal impact to the remaining elements of the native biota within the Kapoho Geothermal Resource Subzone.

In roadless tracts of relatively undisturbed native vegetation, the introduction of geothermal exploration or development is expected to be disruptive, and potentially overwhelming to the native biota. In these areas, the geothermal activities and impacts would be the sole or major anthropogenic disturbance in the area. The expected disruptive consequences to ecosystem function have been discussed above. In the Middle East Rift and Kamaili Geothermal Resource Subzones, the native biota is already faced with an increasing suite of introduced organisms dispersing into the area, especially in the lower elevations. Detrimental changes have been occurring, but the Kilauea successional ecosystem is still functioning over much of the ERZ.

The upper ERZ area is now suffering from significant losses of diversity and of mosaic replicates due to the upsurge in eruptive activity. The Kamaili area is just as vulnerable to the same losses in the near future. The timing for increased disturbance and forest loss in these areas from anthropogenic sources of any type could not be worse. Therefore, to introduce any further degree of geothermal exploration or development will add an enormous destabilization to the ecosystem in the Middle East Rift and undisturbed sections of the Kamaili Geothermal Resource Subzone areas. The nearly roadless nature of the Middle East Rift Geothermal Resource Subzone and the limited extent of roads in the Kamaili Geothermal Resource Subzone are key to their long-term stability. Any additional clearing of native vegetation in these two areas will result in further breakdown of the stability of the native ecosystem in this area and cumulative loss of component species.

CONCLUSIONS AND RECOMMENDATIONS

Two major ecological processes, one ancient and native in nature (primary lava flow succession) and one foreign in nature (secondary succession following human-caused disturbance), are each creating different, non-compatible kinds of vegetation on contemporary Kilauea volcano. In the first, native seed sources, considerable seed dispersal, and a variety of native communities on a variably aged mosaic of lava flows are the key elements of the Kilauea successional ecosystem. These elements interact in the orderly creation of a native vegetation cover on recurrent new land surfaces of a dynamic volcano landscape.

In the second process, introduced seed sources, human-enhanced seed dispersal, and man's frequent disruption of vegetated land surfaces are the key elements in contemporary secondary succession. This second process is a consequence of man's recurrent disruptive land-disturbing activities and introductions of alien species into the region, both of which have increased considerably in the last few decades.

The native vegetation is adapted to co-exist with and to colonize the considerable coverage of its parts by eruption. However, most native species are ill-adapted to compete with introduced weed species in the colonization of the enormous amounts of disturbed land which humans have recently produced in the natural Kilauea landscape. Additionally, the two processes are interacting to the detriment of the native one. Both depend on recurrent dispersal of seeds from species preadapted to colonize open substrates and to join developing communities. An increasing variety of introduced seeds and spores are readily dispersing throughout more and more of Kilauea. Because of the parallels in the key elements of the two successional processes, a growing set of alien species is joining and changing the native primary succession process.

The result threatens the entire process of vegetation formation on new lava flows on the wet windward side of Kilauea volcano. Agricultural, residential, geothermal development, and other activities are all expanding into the remaining native vegetation, exacerbating the intrusion of invasive alien organisms. The last significant tracts of native Kilauea vegetation may be replaced or degraded by human-caused disturbances and introduced species in the near future. These two factors are also adversely affecting primary succession processes on new lava flows as well. As the amount of native forest diminishes throughout the Puna area, so too do the available source pools for seeds and spores of native plants and for native invertebrates. All are needed for colonizing new and developing communities.

The drier leeward side of Kilauea volcano has already had the majority of its communities eliminated and much of the moist summit areas are also degrading rapidly. All that remains of a functioning Kilauea successional ecosystem is found in the Puna wet and moist forests. This extensive degradation and clearing of Puna's native vegetation is happening during a period of elevated eruptive output and extensive natural forest loss.

Summary of ecological points

Kilauea has a unique ecosystem adapted to the dynamics of a volcanically active landscape. The characteristics of this ecosystem needs to be understood in order to evaluate the additional impacts from geothermal development in the Puna region.

The volcano's frequent eruptions create spatial variability and new substrates which are integral components of Kilauea's natural history. This primary succession process provides a vegetated landscape on the fresh volcanic surfaces, where the mosaic pattern of variety reflects the ages and types of the surfaces. Each piece of the mosaic continues to mature over time; none is static. Nor is the landscape fixed, as frequent eruptions continually rearrange the mosaic.

Recent lava surfaces characteristically have little soil, frequent moisture stress, and limited nutrient availability. The earliest colonizing plants are usually native species adapted to the harsh conditions. From the rain of seeds and spores falling into moist crevices on the flow surface, a scattering of plants take hold. Gradually, more individuals and additional plant species disperse from adjacent forests and help to form a sparse organic soil. In this manner, the site conditions on the new flow are made favorable for an increasing number of plants and animals. Throughout the community development on windward Kilauea, the native 'ohi'a tree remains the dominant plant and the primary link between the Kilauea lavas and the living landscape. In nearly all sites, the undisturbed early to intermediate vegetation cover is predominantly composed of native plants.

While periodic lava and tephra inundation is an inevitable and terminal disturbance to the native successional communities, it serves as a beginning point for the replacement primary succession. The strategy of survival from such volcanic activities has not been one of resistance to the disturbance itself, but rather one of chance avoidance and colonization. The successional mosaic must maintain an adequate reserve of replicate communities to provide widespread sources of dispersing propagules and to continue the colonization and succession process. Older flow pieces (kipuka) contribute different species than younger kipuka. Maintenance of these varied and replicated communities and their member species is critical to ecosystem survival. Each differentially developed portion of the successional mosaic is an integral and important part of the whole ecosystem. The functioning of the ecosystem and its full biodiversity has depended on maximizing, through time, representation of the community variety (different mosaic pieces).

In natural situations, new flows are formed within or near native vegetation of varying maturity, from which the rain of organic detritus, seeds, and spores begins at once. Continuance of this process keeps the mosaic ecosystem intact and maximizes the diversity of native organisms. If the dispersal of native species is curtailed or significant gaps develop in the successional continuum, then the process will be adversely affected. Should there be species attrition and substitutions by alien organisms in the pool of species dispersed, this, too, will affect the process.

Where lava flows through or next to areas cleared of forest or otherwise degraded, then these newly formed lava flows are situated next to alien plant reservoirs instead of the natural native plant sources. A few alien plants have also recently demonstrated their potential not only to dominate secondary succession, but to disrupt the primary succession process as well.

The natural primary successional process can be abruptly terminated wherever physical disturbance to the native community occurs. Once a flow surface is disturbed, the secondary vegetation which then develops on the disturbed surface is overwhelmingly composed of introduced plants. Without exception, the disturbance of native vegetation favors a permanent shift in conditions which favor introduced species at the expense of native species. These disturbed areas become diverse collections of introduced species and act as reservoirs for the dispersal of seeds. This loss can be regained when a new lava flow covers the introduced vegetation and restarts the primary successional process, if adequate native plant propagule sources exist in adjacent forests.

The greatest variety and abundance of introduced plant species on Kilauea is found along roadsides. Roadsides are extensive in Puna, interconnecting 56,000 developed and vacant lots and all agricultural fields in the district. In addition to providing a continuous favorable habitat for alien plants, roads are the main conduit of dispersal of these species. Man is the major vector for dispersing these aliens, both passively as hitchhikers and actively as he dumps and transplants them along the roadways. Species new to the district are continually establishing along and escaping from the roadsides. Wind and birds are the additional means of dispersing weeds from the roadsides and secondary vegetation sites to and within other disturbed and undisturbed areas.

Some of the introduced species which have become naturalized in secondary communities are able to invade undisturbed native vegetation. Invasions by some aggressive alien species into native communities can diminish native populations and change the nature of the community. As long as a variety of native species remains, however, any vegetation community still has important value as a seed source for native species in the succession process.

The displacement of native vegetation by agriculture and the additional introductions of alien species have increased to the point of significant adverse impact to native vegetation. With the spread of introduced fire-adapted grasses, uncontrolled wildfires have begun to play an increasing role in the loss of native communities on windward Kilauea as well. Residential subdivisions span the elevational range of windward Kilauea, mostly to the north, east and southeast, further fragmenting the forested areas and introducing more exotic species.

The key to conservation of the native vegetation of Kilauea, is preserving the natural successional process on lava flows. As dispersal of native organisms to younger flows in the successional mosaic is a critical part of the process, each degree of ecosystem development is important to maintain a continuity of successive native seed species. Each piece of the mosaic is important, as there is a mutual interdependence. Maintaining replicates of the diverse mosaic pieces is also essential. Loss of enough of these components in an area due to extensive inundation by lava and/or displacement by development can lead to a marked drop in native species diversity, and ultimately it can break the successional chain. Such a breakdown of the native successional processes has occurred on drier leeward Kilauea and portions of lower windward Kilauea.

The ecological value of a particular area of vegetated land on Kilauea is not defined by the presence of rare and endangered species, but more by its role in the successional mosaic. It is only by maintaining the array and integrity of variably matured communities over time, that the process of primary succession on Kilauea can be maintained with native communities.

Preventing or reducing future loss of native vegetation is an essential conservation goal, as such loss will accelerate the current decline of the Kilauea successional ecosystem. If the areas remaining in native vegetation are not of sufficient size and variety in a portion of the Kilauea ERZ, the integrity and continuity of the natural succession process could be at risk. Development should instead be located on some of the abundant supply of previously cleared land. Likewise, further extensions of roads into native vegetation should be avoided.

Long-term planning for the Puna region needs to take into account the effects of past anthropogenic activities and future volcanic events. An intent to maintain the native successional ecosystem will require the preservation of large tracts of contiguous native vegetation over a broad geographic area and across environmental gradients.

Another important conservation and management aim should be to prevent, as much as is possible, the further introduction of more alien species into the Puna area. The spread of these plants throughout Puna's road network appears almost inevitable; and from there follows invasion by some species into the adjoining forest. The alien species currently found in Puna are already causing severe alterations to disturbed and undisturbed native communities. Continued introductions will further degrade the successional ecosystem. Additionally, if the communities are physically disturbed, then the resulting secondary vegetation is composed mostly of introduced species, both in numbers and in biomass.

Recommendations to reduce impacts of geothermal activities

<u>Geothermal exploration and development activities should be located only on lands previously cleared of native vegetation.</u> When native vegetation on Kilauea is cleared, it is invariably and permanently recolonized by alien species. All types and examples of native vegetation are important to the functioning of the Kilauea successional ecosystem in an area, and none should be singled out for clearing because it is successionally young or because it contains introduced species in abundance.

<u>The adverse effects of geothermal activities on native communities will not be limited to the area of clearing.</u> The effects of clearing, such as the introduction of alien weeds and pests, microclimate change, and accessibility extend well into surrounding vegetation.

<u>Prevent any geothermal-related addition of more alien species to any area of Puna.</u> All equipment, vehicles, materials and structures brought to Puna for use in geothermal exploration and development projects should be thoroughly and effectively cleansed of any soil and potentially seed bearing material. All areas of activity should be regularly inspected by biologists familiar with introduced organisms, especially

those found in Puna, in order to detect and immediately eradicate any not already common in Puna.

A competent and consistent capability should be established and maintained by the geothermal industry to monitor, detect and eradicate introduced organisms newly adventive to areas of active and abandoned geothermal activities. The monitoring should be frequent enough to discover and eradicate organisms before they are able to spread at all. There needs to be a high skill level and reliability of the staff or contractors hired to perform this function.

Preserve the remaining roadless areas on windward Kilauea. Avoid extending roads and powerlines into native vegetation. The remaining roadless portions of the Kilauea successional ecosystem are already threatened by introduced species and at the same time they are subject to continued replacement by new lava flows.

The "restoration" of cleared or degraded native vegetation is not a viable technique to mitigate the loss of native vegetation. It is inappropriate and contrary to the findings of this report to expect untried restoration techniques to simulate native habitats in order to offset the loss of other areas to development. Restoration techniques must be proven prior to their proposal for mitigation. In order to prevent abandoned cleared areas from becoming major sources of weed seeds, it is preferable and, almost certainly, more cost-effective to plant kukui tree groves to act as a protective cover and weed suppressant.

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Table 1. Kilauea East Rift Zone lava flow coverage rate during the last two centuries.

TIME		AREA COVERED			COVER RATE	
Time Period	No. Yrs.	km2	ha	ac	ha/yr	ac/yr
1800 - 1950	150	16.6	1,660	4,100	11	27
1951 - 1975	25	104.7	10,470	28,370	419	1,140
1976 - 1993	18	95.1	9,510	23,500	528	1,310

Sources: MacDonald et al. (1983) and Hawai'i Volcano Observatory.

Table 2. Diagram indicating sample site designation, type and distribution within elevational and geochronological groupings.

AGE GROUP (LAVA FLOW AGES)	ELEVATION SL--200 FT SL--61 M	201--600 FT 61--183 M	601--1000 FT 183--305 M	1001--1200 FT 305--366 M	1201--1600 FT 366--488 M	2750 FT 838 M	SUBTOTALS
1977--1955 (1977, 1960, 1955)	AN/CF, AO/PF, AP/CC AT/PR, BW/AF, CB/AF CC/AR, CD/CR [4 UND, 4 DIST]	S_/CR, T_/AF, V_/AR W_/AF [2 UND, 2 DIST]	A_/RS, C_/AF, J_/AR K_/AF, L_/GF, P_/AR Q_/AF, R_/CR [3 UND, 5 DIST]	O_/AF, BH/AR [1 UND, 1 DIST]	AC/AF, AD/AR, BA/AF BB/GF, BC/CR, BE/GF BG/CR, BI/QS, BK/BF [4 UND, 6 DIST]		[14 UND, 18 DIST]
1954--1790 (1790, 1840)		AH/AF, AI/CR, AK/AF AL/CR, AM/AF, BT/AF BU/CR, BV/CR [4 UND, 4 DIST]		CS/CR, CM/PF, CN/PL DJ/CR [1 UND, 3 DIST]			[5 UND, 7 DIST]
1789--1701 (1750*)			W_/CR, Y_/SF, Z_/BF BN/GF, DL/CR, DM/AR [1 UND, 5 DIST]	BO/GF, BQ/UF, BR/BF DN/AR, DT/AF [2 UND, 3 DIST]	DO/AR, DP/AR, DR/BD DS/BF [4 DIST]		[3 UND, 12 DIST]
1700--1451 (1650, 1500, 1450*)	AS/PR [1 DIST]	DB/CR, DC/AF, DK/BD [1 UND, 2 DIST]	E_/CR [1 DIST]	DA/CR, DD/PR [2 DIST]	AE/AF, CG/GF, CH/PF CI/CR, CJ/BD [2 UND, 3 DIST]	G_/CR, H_/BD, I_/ PF [1UND, 2 DIST]	[4 UND, 11 DIST]
1450--860 (1090, 860*)	BY/AF, BZ/AR [1 UND, 2 DIST]	AJ/CR [1 DIST]	D_/CR, M_/AF, N_/GF AA/SF, AB/GF, CP/PF [3 UND, 3 DIST]	F_/CR, CK/PF, CL/CR DE/BD, DF/AR, DG/AF DH/QS, DI/PR, DV/CR DW/GF [2 UND, 8 DIST]	AG/GF, BM/SF, CO/SF [2 UND, 1 DIST]		[8 UND, 14 DIST]
SUBTOTALS	[5 UND, 6 DIST]	[7 UND, 9 DIST]	[7 UND, 14 DIST]	[6 UND, 17 DIST]	[8 UND, 14 DIST]	[1 UND, 2 DIST]	[34 UND, 62 DIST]

Total of 96 sample sites, 34 undisturbed [UND] + 62 disturbed [DIST] flow surfaces. Noted by: (site designation) / (site type).
DISTURBED site types: roads (CR, AR, PR), cleared (GF, BD), burned (BF), quarry (QS), compacted (RS), deep cinder deposit (CC), miscellaneous (PL).
UNDISTURBED site types: 'a'a flow (AF), pahoehoe flow (PF), deep soil (SF), undesignated (UF).
Lava flow ages are given to an exact or approximate year of eruption, except those marked with an *, which are mid-points in a broader time period.
Age data are from Moore and Trusdell (1991) and Moore (1992). Individual dates may have multiple eruptions or eruptions from more than one location.

Table 3. Introduced plants of concern which appear to spread from roadsides and disturbed sites into undisturbed vegetation.

FAMILY	SPECIES	DISPERSAL*	LIFE FORM
FERNS			
Thelypteridaceae	*Macrothelypteris torresiana*	W	large herb
DICOTS			
Anacardiaceae	*Schinus terebinthifolius*	B	tree
Araliaceae	*Schefflera actinophylla*	B	tree
Asteraceae	*Pluchea symphytifolia*	W,H	shrub
Asteraceae	*Wedelia trilobata*	D,F,V	mat herb
Bignoniaceae	*Spathodea campanulata*	D,W	tree
Buddleiaceae	*Buddleia asiatica*	H,W	shrub
Casuarinaceae	*Casuarina equisetifolia*	D,W	tree
Cecropiaceae	*Cecropia obtusifolia*	W,B?	tree
Clusiaceae	*Clusia rosea*	B	tree
Fabaceae	*Albizia lebbeck*	D,W	tree
Fabaceae	*Derris elliptica*	D,V	woody vine
Fabaceae	*Desmodium cajanifolium*	H,W	shrub
Lauraceae	*Persea americana*	D	tree
Melastomataceae	*Clidemia hirta*	B,H	shrub
Melastomataceae	*Medinilla magnifica*	D,B	shrub/tree
Melastomataceae	*Melastoma candida*	B	shrub/tree
Melastomataceae	*Tibouchina herbacea*	H,B?,F	shrub
Melastomataceae	*Tibouchina urvilleana*	D,F,V,?	shrub/tree
Moraceae	*Ficus microcarpa*	D,B	tree
Myrtaceae	*Melaleuca quinquenervia*	D,W	tree
Myrtaceae	*Psidium cattleianum*	B,U,H	shrub/tree
Myrtaceae	*Psidium guajava*	B,U,H	shrub/tree
Rosaceae	*Rubus elliptcus*	D,W	shrub
Sterculiaceae	*Melochia umbellata*	W	tree
Ulmaceae	*Trema orientalis*	B	tree
MONOCOTS			
Arecaceae	*Archontophoenix alexandrae*	D,B	palm tree
Araceae	*Epipremnon pinnatum*	D,V	vine
Commelinaceae	*Commelina diffusa*	D,V,F	viny herb
Poaceae	*Melinis minutifolia*	H,W,F	mat grass
Poaceae	*Pennisetum setaceum*	W,H	grass
Poaceae	*Setaria palmifolia*	H	grass
Zingiberaceae	*Hedychium coccineum*	D,V	large herb
Zingiberaceae	*Hedychium coronarium*	D,V,B?	large herb
Zingiberaceae	*Hedychium gardnerianum*	D,V,B	large herb

* Dispersal means. B = bird, D = deposited by man, H = hitchhiker (especially on vehicles), W = wind, V = vegetative extension, F = fragmentation, U = ungulate.

Note 1. Miconia calvescens (Melstomataceae) is not included in this listing only because it was observed outside a reporting site.

Note 2. Many (27) of the 35 plants in this listing are dispersed by humans, and most by an additional means.

Table 4. Introduced species, including deposited species, which are reported in various categories of sites.

CATEGORY	NO. INTRO. SPP. IN CATEGORY	% OF TOTAL INTRO. SPP. IN CATEGORY	NO. OF DEPOSITED SPP. IN CATEGORY	% DEPOSITED SPP. OF TOTAL INTRO.	NO. OF SITES IN CATEGORY
Combined Sites	195	100	51	26	96
Undisturbed	62	32	12	6	29
Lightly Disturbed	46	25	2	1	8
Heavily Disturbed	109	56	21	11	9
Non-Road Disturbed	132	68	23	12	25
Combined Roads	162	83	40	21	38
Cinder Roads	149	76	36	19	23
Paved Roads	76	39	8	4	4
A'a Roads	66	34	5	3	12
Quarry Sites	57	31	7	4	2
Abandoned Agricultur	61	29	10	5	2
De Facto Dumps	50	26	14	7	2
Burned Forest*	24	12	1#	0.5	2
Bulldozed Firebreak*	29	15	0	0	2
Roads Next to Burn*	44	44	0	0	2
Forest Next to Burn*	3	2	0	0	1

Note 1. The total number of introduced species is 95. This number is used as a denominator for category comparisons.

Note 2. Deposited species are those which have been planted or dumped at sites, including species which also self-disperse.

* All 4 categories are near each other. All 4 are 1750AD Metrosideros forest with dense a Dicranopteris groundcover.

\# While listed as a deposited species, these individuals were apparently self-dispersed from planted individuals nearby.

Table 5. Introduced plant species (46) reported by this survey but not by Char and Lamoureux (1985).

FAMILY	SPECIES	NO. OF SITES OBSERVED	DEPOSITED*
FERN			
Lygodiaceae	Lygodium japonicum	1	+
DICOTS			
Apocynaceae	Catharanthus roseus	1	+/-
Asclepiadaceae	Hoya sp.	1	+
Asteraceae	Lapsana communis	1	-
Asteraceae	Synedrella nodiflora	1	-
Begoniaceae	Begonia sp.	1	+
Campanulaceae	Hippobroma longifolia	1	-
Clusiaceae	Clusia rosea	4	-
Convolvulaceae	Ipomoea cairica	1	-
Euphorbiaceae	Chamaesyce hyssopifolia	7	-
Fabaceae	Crotalaria lanceolata	3	-
Fabaceae	Crotalaria sp.	1	-
Fabaceae	Derris elliptica	3	+
Fabaceae	Desmodium incanum	27	-
Fabaceae	Fabaceae, vine**	1	-
Fabaceae	Macroptilium atropurpureum	3	-
Fabaceae	Macroptilium sp.	1	-
Malvaceae	Hibiscus sp.	1	+
Melastomataceae	Dissotis rotundifolia	1	+
Melastomataceae	Medinilla magnifica	1	+/-
Melastomataceae	Melastomataceae, shrub	1	-
Melastomataceae	Tibouchina herbacea	10	-
Melastomataceae	Tibouchina longifolia	1	+?
Moraceae	Ficus macrophylla	1	+
Myrtaceae	Eucalyptus robusta	1	+
Scrophulariaceae	Lindernia antipoda	1	-
Scrophulariaceae	Buchnera pusilla	1	-
Urticaceae	Pilea microphylla	1	-
Verbenaceae	Clerodendrum philippinum	2	+
MONOCOTS			
Agavaceae	Dracaena fragrans	1	+
Agavaceae	Dracaena marginata	1	+
Araceae	Homalomena rubescens	1	+
Araceae	Monstera sp.	1	+
Araceae	Philodendron radiatum	1	+
Araceae	Philodendron sanguineum	2	+
Araceae	Philodendron scandens	2	+

Araceae	Philodendron sp. 1**	2	+
Araceae	Philodendron sp. 2	1	+
Cyperaceae	Rhynchospora caduca**	6	-
Eriocaulaceae	Eriocaulon sp.	1	-
Poaceae	Cenchrus echinatus	1	-
Poaceae	Digitaria insularis	1	-
Poaceae	Digitaria violascens**	19	-
Poaceae	Eragrostis cilianensis	9	-
Poaceae	Eragrostis elongata	1	-
Zingiberaceae	Hedychium coccineum	1	+

* + = species believed deposited at site in Puna by human action; - = species disperses without human intent; +/- = species disperses by either means.

** This species might be confused with one reported by Char and Lamoureux (1985), as identification of either is incomplete.

Note 1. Miconia calvescens (Melastomataceae) is not included in this listing because it was observed outside a reporting site.

Note 2. Bamboo species seen in both surveys are not included in this listing. because of difficulty in identifying sterile plants.

Appendix 1. Species listing by family, with other data.

FAMILY	SPECIES	ORIGIN	DEPOSITED	OCCURRENCE
FERNS				
Adiantaceae	*Adiantum raddianum*	A		1
Aspleniaceae	*Asplenium lobulatum*	NI		3
Aspleniaceae	*Asplenium nidus*	NI		2
Athyriaceae	*Athyrium sandwichianum*	NE		4
Blechnaceae	*Blechnum occidentale*	A		2
Blechnaceae	*Sadleria cyatheoides*	NE		17
Blechnaceae	*Sadleria pallida*	NE		3
Dennstaeditiaceae	*Microlepia strigosa*	NI		1
Dicksoniaceae	*Cibotium chamissoi*	NE		10
Dicksoniaceae	*Cibotium glaucum*	NE		17
Dicksoniaceae	*Cibotium hawaiense*	NE		1
Elaphoglossaceae	*Elaphoglossum alatum*	NE		6
Elaphoglossaceae	*Elaphoglossum crassifolium*	NE		5
Elaphoglossaceae	*Elaphoglossum hirtum*	NE		1
Gleicheniaceae	*Dicranopteris sp.*	NI		31
Grammitaceae	*Adenophorus periens*	NE		1
Grammitaceae	*Adenophorus pinnatifidus*	NE		3
Grammitaceae	*Adenophorus tamariscinus*	NE		4
Grammitaceae	*Adenophorus tripinnatifidus*	NE		4
Grammitaceae	*Grammitis hookeri*	NE		2
Grammitaceae	*Xiphopteris saffordii*	NE		1
Hemionitidaceae	*Pityrogramma calomelanos*	A		29
Hymenophyllaceae	*Callistopteris baldwinii*	NE		1
Hymenophyllaceae	*Gonocormus minutus*	NI		2
Hymenophyllaceae	*Mecodium recurvum*	NE		2
Hymenophyllaceae	*Sphaerocionium lanceolatum*	NE		3
Hymenophyllaceae	*Vandenboschia cyrtotheca*	NE		4
Lindsaeaceae	*Sphenomeris chinensis*	NE		15
Lycopodiaceae	*Lycopodium cernuum*	NI		15
Lycopodiaceae	*Lycopodium phyllanthum*	NE		10
Lycopodiaceae	*Lycopodium venustulum*	NI		2
Lygodiaceae	*Lygodium japonicum*	A	P	1
Nephrolepidaceae	*Nephrolepis cordifolia*	NI		3
Nephrolepidaceae	*Nephrolepis multiflora*	A		79
Ophioglossaceae	*Ophioglossum pendulum*	NE		8
Polypodiaceae	*Phymatosorus scolopendria*	A		29
Polypodiaceae	*Pleopeltis thunbergiana*	NI		8
Polypodiaceae	*Polypodium pellucidum*	NE		3
Psilotaceae	*Psilotum complanatum*	NI		1
Psilotaceae	*Psilotum nudum*	NI		19
Pteridaceae	*Pteris vittata*	A		9

Appendix 1. Species listing by family, with other data.

FAMILY	SPECIES	ORIGIN	DEPOSITED	OCCURRENCE
Selaginaceae	*Selaginella arbuscula*	NE		1
Thelypteridaceae	*Christella parasitica*	A		18
Thelypteridaceae	*Cyclosorus sandwicensis*	NE		1
Thelypteridaceae	*Macrothelypteris torresiana*	A		8
Vittariaceae	*Vittaria elongata*	NI		3
DICOTS				
Anacardiaceae	*Mangifera indica*	A	P	4
Anacardiaceae	*Schinus terebinthifolius*	A		3
Apiaceae	*Centella asiatica*	A		9
Apocynaceae	*Alyxia olivaeformis*	NE		2
Apocynaceae	*Catharanthus roseus*	A	P*	1
Aquifoliaceae	*Ilex anomala*	NI		4
Araliaceae	*Schefflera actinophylla*	A		2
Araliaceae	*Tetraplasandra hawaiiensis*	NE		2
Asclepiadaceae	*Hoya sp.*	A	P	1
Asteraceae	*Ageratina riparia*	A		9
Asteraceae	*Ageratum conyzoides*	A		32
Asteraceae	*Ageratum houstonianum*	A		3
Asteraceae	*Bidens pilosa*	A		15
Asteraceae	*Conyza bonariensis*	A		12
Asteraceae	*Conyza canadensis*	A		2
Asteraceae	*Crassocephalum crepadioides*	A		7
Asteraceae	*Dubautia scabra*	NE		4
Asteraceae	*Emilia fosbergii*	A		20
Asteraceae	*Emilia sonchifolia*	A		15
Asteraceae	*Erechtites valerianifolia*	A		7
Asteraceae	*Gnaphalium sandwicensium*	NE		1
Asteraceae	*Lapsana communis*	A		1
Asteraceae	*Pluchea symphytifolia*	A		57
Asteraceae	*Sonchus oleraceus*	A		8
Asteraceae	*Synedrella nodiflora*	A		1
Asteraceae	*Vernonia cinerea*	A		8
Asteraceae	*Wedelia trilobata*	A		5
Asteraceae	*Youngia japonica*	A		1
Balsaminaceae	*Impatiens wallerana*	A	P*	7
Begoniaceae	*Begonia hirtella*	A		9
Begoniaceae	*Begonia sp.*	A	P	1
Bignoniaceae	*Spathodea campanulata*	A	P*	1
Brassicaceae	*Cardamine flexuosa*	A		1
Buddleiaceae	*Buddleia asiatica*	A		36
Campanulaceae	*Clermontia hawaiiensis*	NE		1
Campanulaceae	*Clermontia parviflora*	NE		3

Appendix 1. Species listing by family, with other data.

FAMILY	SPECIES	ORIGIN	DEPOSITED	OCCURRENCE
Campanulaceae	*Hippobroma longifolia*	A		1
Caricaceae	*Carica papaya*	A	P	2
Caryophyllaceae	*Drymaria cordata*	A		3
Casuarinaceae	*Casuarina equisetifolia*	A	P*	9
Cecropiaceae	*Cecropia obtusifolia*	A		13
Celastraceae	*Perrottetia sandwicensis*	NE		1
Clusiaceae	*Calophyllum inophyllum*	PO		1
Clusiaceae	*Clusia rosea*	A		4
Clusiaceae	*Hypericum mutilum*	A		4
Convolvulaceae	*Ipomoea cairica*	A		1
Convolvulaceae	*Ipomoea indica*	A		2
Cuscutaceae	*Cuscuta sandwichiana*	NE		1
Ebenaceae	*Diospyros sandwicensis*	NE		7
Epacridaceae	*Styphelia tameiameiae*	NE		11
Ericaceae	*Vaccinium calycinum*	NE		1
Ericaceae	*Vaccinium reticulatum*	NE		4
Euphorbiaceae	*Aleurites moluccana*	PO		6
Euphorbiaceae	*Antidesma platyphyllum*	NE		3
Euphorbiaceae	*Chamaesyce hirta*	A		12
Euphorbiaceae	*Chamaesyce hyssopifolia*	A		7
Euphorbiaceae	*Chamaesyce thymifolia*	A		2
Euphorbiaceae	*Manihot esculenta*	A	P	2
Euphorbiaceae	*Phyllanthus debilis*	A		7
Fabaceae	*Abrus precatorius*	A		1
Fabaceae	*Acacia koa*	NE	P	1
Fabaceae	*Albizia lebbeck*	A	P*	16
Fabaceae	*Chamaecrista nictitans*	A		33
Fabaceae	*Crotalaria assamica*	A		5
Fabaceae	*Crotalaria lanceolata*	A		3
Fabaceae	*Crotalaria pallida*	A		4
Fabaceae	*Crotalaria sp.*	A		1
Fabaceae	*Derris elliptica*	A	P	3
Fabaceae	*Desmodium cajanifolium*	A		28
Fabaceae	*Desmodium incanum*	A		27
Fabaceae	*Desmodium sandwicense*	A		22
Fabaceae	*Desmodium triflorum*	A		33
Fabaceae	*Dioclea wilsonii*	NI		1
Fabaceae	*Fabaceae, vine*	A		1
Fabaceae	*Indigofera suffruticosa*	A		1
Fabaceae	*Macroptilium atropurpureum*	A		3
Fabaceae	*Macroptilium sp.*	A		1
Fabaceae	*Mimosa pudica*	A		39

Appendix 1. Species listing by family, with other data.

FAMILY	SPECIES	ORIGIN	DEPOSITED	OCCURRENCE
Fabaceae	*Mucuna gigantea*	NI		1
Gesneriaceae	*Cyrtandra lysiosepala*	NE		1
Gesneriaceae	*Cyrtandra paludosa*	NE		2
Gesneriaceae	*Cyrtandra sp.*	NE		1
Goodeniaceae	*Scaevola chamissoniana*	NE		1
Goodeniaceae	*Scaevola kilaueae*	NE		2
Goodeniaceae	*Scaevola sericea*	NI		2
Hydrangaceae	*Broussaisia arguta*	NE		3
Lamiaceae	*Hyptis pectinata*	A		14
Lamiaceae	*Plectranthus parviflorus*	NI		1
Lauraceae	*Persea americana*	A	P	11
Lythraceae	*Cuphea carthagenensis*	A		12
Malvaceae	*Hibiscus sp.*	A	P	1
Malvaceae	*Malvastrum coromandelianum*	A		2
Malvaceae	*Sida rhombifolia*	A?		6
Melastomataceae	*Clidemia hirta*	A		9
Melastomataceae	*Dissotis rotundifolia*	A	P	1
Melastomataceae	*Heterocentron subtriplinervium*	A		10
Melastomataceae	*Medinilla magnifica*	A	P*	1
Melastomataceae	*Melastoma candidum*	A		51
Melastomataceae	*Melastomataceae, shrub*	A		1
Melastomataceae	*Tibouchina herbacea*	A		10
Melastomataceae	*Tibouchina longifolia*	A	P?	1
Melastomataceae	*Tibouchina urvilleana*	A	P*	1
Melstomataceae	*Pterolepis glomerata*	A		4
Menispermaceae	*Cocculus trilobus*	NI		18
Moraceae	*Ficus macrophylla*	A	P	1
Moraceae	*Ficus microcarpa*	A	P*	5
Myrsinaceae	*Myrsine lessertiana*	NE		11
Myrsinaceae	*Myrsine sandwicensis*	NE		1
Myrtaceae	*Eucalyptus robusta*	A	P	1
Myrtaceae	*Melaleuca quinquenervia*	A	P*	3
Myrtaceae	*Metrosideros macrophyllum*	NE		6
Myrtaceae	*Metrosideros polymorpha*	NE		49
Myrtaceae	*Psidium cattleianum*	A		32
Myrtaceae	*Psidium guajava*	A		13
Myrtaceae	*Syzygium cumini*	A		1
Myrtaceae	*Syzygium jambos*	A	P	5
Nyctaginaceae	*Pisonia umbellifera*	NI		1
Onagraceae	*Ludwigia octovalvis*	PO		2
Oxalidaceae	*Oxalis corniculatum*	A		4
Passifloraceae	*Passiflora edulis*	A		1

Appendix 1. Species listing by family, with other data.

FAMILY	SPECIES	ORIGIN	DEPOSITED	OCCURRENCE
Passifloraceae	*Passiflora foetida*	A		3
Polygalaceae	*Polygala paniculata*	A		47
Polygonaceae	*Polygonum capitatum*	A		9
Piperaceae	*Peperomia hypoleuca*	NE		5
Piperaceae	*Peperomia leptostachya*	NI		1
Piperaceae	*Peperomia sp.*	NE		3
Piperaceae	*Piper methysticum*	PO		2
Plantaginaceae	*Plantago major*	A		4
Rosaceae	*Osteomeles anthyllidifolia*	NI		2
Rosaceae	*Rubus ellipticus*	A		1
Rosaceae	*Rubus rosifolius*	A		21
Rubiaceae	*Bobea elatior*	NE		1
Rubiaceae	*Coffea arabica*	A		1
Rubiaceae	*Coprosma menziesii*	NE		6
Rubiaceae	*Coprosma ochracea*	NE		1
Rubiaceae	*Gouldia terminalis*	NE		2
Rubiaceae	*Hedyotis centranthoides*	NE		1
Rubiaceae	*Hedyotis corymbosa*	A	P*	3
Rubiaceae	*Morinda citrifolia*	PO		1
Rubiaceae	*Paederia scandens*	A		14
Rubiaceae	*Psychotria hawaiiensis*	NE		17
Rubiaceae	*Spermacoce assurgens*	A		44
Rutaceae	*Pelea clusiifolia*	NE		1
Rutaceae	*Pelea sp.*	NE		1
Scrophulariaceae	*Buchnera pusilla*	A		1
Scrophulariaceae	*Castilleja arvensis*	A		18
Scrophulariaceae	*Lindernia antipoda*	A		1
Scrophulariaceae	*Lindernia crustacea*	A		4
Scrophulariaceae	*Torenia asiatica*	A		5
Solanaceae	*Solanum nigrum*	N?		1
Sterculiaceae	*Melochia umbellata*	A		28
Sterculiaceae	*Waltheria indica*	N?		5
Thymelaeaceae	*Wikstroemia phillyreifolia*	NE	P	5
Ulmaceae	*Trema orientalis*	A		11
Urticaceae	*Pilea microphylla*	A		1
Urticaceae	*Pipturus albidus*	NE		30
Verbenaceae	*Clerodendrum philippinum*	A	P	2
Verbenaceae	*Lantana camara*	A		2
Verbenaceae	*Stachytarpheta jamaicensis*	A		33
Verbenaceae	*Verbena littoralis*	A		1
MONOCOTS				
Arecaceae	*Archontophoenix alexandrae*	A		3

Appendix 1. Species listing by family, with other data.

FAMILY	SPECIES	ORIGIN	DEPOSITED	OCCURRENCE
Arecaceae	*Cocos nucifera*	PO		5
Agavaceae	*Cordyline fruticosa*	PO		15
Agavaceae	*Dracaena fragrans*	A	P	1
Agavaceae	*Dracaena marginata*	A	P	1
Araceae	*Anthurium sp.*	A	P+	1
Araceae	*Colocasia esculenta*	PO		1
Araceae	*Epipremnon pinnatum*	A	P	4
Araceae	*Homalomena rubescens*	A	P	1
Araceae	*Monstera deliciosa*	A	P	2
Araceae	*Monstera sp.*	A	P	1
Araceae	*Philodendron radiatum*	A	P	1
Araceae	*Philodendron sanguineum*	A	P	2
Araceae	*Philodendron scandens*	A	P	2
Araceae	*Philodendron sp. 1*	A	P	2
Araceae	*Philodendron sp. 2*	A	P	1
Commelinaceae	*Commelina diffusa*	A	P	17
Cyperaceae	*Bulbostylis capillaris*	A		1
Cyperaceae	*Cyperus halpan*	A		12
Cyperaceae	*Fimbristylis dichotoma*	NI		3
Cyperaceae	*Kyllinga brevifolia*	A		6
Cyperaceae	*Machaerina angustifolia*	NI		23
Cyperaceae	*Machaerina mariscoides*	NI		17
Cyperaceae	*Pycreus polystachyos*	NI		34
Cyperaceae	*Rhynchospora caduca*	A		6
Cyperaceae	*Rhynchospora rugosa*	NI		4
Cyperaceae	*Scleria testacea*	NI		1
Dioscoreaceae	*Dioscorea pentaphylla*	PO		6
Eriocaulaceae	*Eriocaulon sp.*	A		1
Iridaceae	*Crocosmia x crocosmiiflora*	A	P	1
Juncaceae	*Juncus planifolius*	A		1
Juncaceae	*Juncus tenuis*	A		3
Musaceae	*Musa sp.*	A	P	2
Orchidaceae	*Arundina graminifolia*	A		60
Orchidaceae	*Phaius tankarvillei*	A		4
Orchidaceae	*Spathoglottis plicata*	A		57
Pandanaceae	*Freycinetia arborea*	NI		12
Pandanaceae	*Pandanus tectorius*	N?		6
Poaceae	*Andropogon glomeratus*	A		49
Poaceae	*Axonopus fissifolius*	A		17
Poaceae	*Brachiaria mutica*	A		3
Poaceae	*Cenchrus echinatus*	A		1
Poaceae	*Coix lachryma-jobi*	A	P	3

Appendix 1. Species listing by family, with other data.

FAMILY	SPECIES	ORIGIN	DEPOSITED	OCCURRENCE
Poaceae	*Cynodon dactylon*	A		1
Poaceae	*Digitaria ciliaris*	A		5
Poaceae	*Digitaria fuscescens*	A		5
Poaceae	*Digitaria insularis*	A		1
Poaceae	*Digitaria setigera*	NI		6
Poaceae	*Digitaria violascens*	A		19
Poaceae	*Eleusine indica*	A		9
Poaceae	*Eragrostis brownei*	A		2
Poaceae	*Eragrostis cilianensis*	A		9
Poaceae	*Eragrostis elongata*	A		1
Poaceae	*Hyparrhenia rufa*	A		7
Poaceae	*Isachne distichophylla*	NE		5
Poaceae	*Melinis minutiflora*	A		35
Poaceae	*Oplismenus hirtellus*	A		15
Poaceae	*Panicum maximum*	A		1
Poaceae	*Panicum repens*	A		7
Poaceae	*Paspalum conjugatum*	A		24
Poaceae	*Paspalum dilatatum*	A		8
Poaceae	*Paspalum scrobiculatum*	N?		24
Poaceae	*Paspalum urvillei*	A		4
Poaceae	*Pennisetum purpureum*	A		4
Poaceae	*Pennisetum setaceum*	A		1
Poaceae	*Rhynchelytrum repens*	A		7
Poaceae	*Saccharum officinarum*	A		1
Poaceae	*Sacciolepis indica*	A		37
Poaceae	*Schizachyrium condensatum*	A		62
Poaceae	*Setaria gracilis*	A		9
Poaceae	*Setaria palmifolia*	A		1
Poaceae	*Sporobolus africanus*	A		13
Poaceae	*bamboo 1*	A	P	2
Poaceae	*bamboo 2*	A	P	1
Poaceae	*bamboo 3*	A	P	1
Xyridaceae	*Xyris complanata*	A		3
Zingiberaceae	*Alpinia purpurata*	A	P	1
Zingiberaceae	*Hedychium coccineum*	A	P	1
Zingiberaceae	*Hedychium coronarium*	A	P*	6
Zingiberaceae	*Hedychium flavescens*	A	P	2
Zingiberaceae	*Hedychium gardnerianum*	A	P*	1
Zingiberaceae	*Zingiber zerumbet*	PO		4
CRYPTOGAMS				
lichen	*Stereocaulon volcani*	N		18
moss	*Rhacomitrium*	N		12

Appendix 1. Species listing by family, with other data.

FAMILY	SPECIES	ORIGIN	DEPOSITED	OCCURRENCE

SPECIES. The total number of species listed is 291: 96 NE + NI (native) and 195 A + PO (alien or historically introduced). The nomenclature of flowering plants generally follows that of Wagner, et al. (1990).

ORIGIN. NE = endemic native, NI = indigenous native, PO = Polynesian introduction, A = alien or historic introduction.

DEPOSITED. Deposited species are those which are planted or dumped at sites, including species that self-disperse (noted by an *).

OCCURRENCE. This is the number of sites at which the species was recorded of the total 96 sites.

Appendix 2. Species listing, by species, with other data.

SPECIES	FAMILY	ORIGIN	DEPOSITED	OCCURRENCE
Abrus precatorius	Fabaceae	A		1
Acacia koa	Fabaceae	NE	P	1
Adenophorus periens	Grammitaceae	NE		1
Adenophorus pinnatifidus	Grammitaceae	NE		3
Adenophorus tamariscinus	Grammitaceae	NE		4
Adenophorus tripinnatifidus	Grammitaceae	NE		4
Adiantum raddianum	Adiantaceae	A		1
Ageratina riparia	Asteraceae	A		9
Ageratum conyzoides	Asteraceae	A		32
Ageratum houstonianum	Asteraceae	A		3
Albizia lebbeck	Fabaceae	A	P*	16
Aleurites moluccana	Euphorbiaceae	PO		6
Alpinia purpurata	Zingiberaceae	A	P	1
Alyxia olivaeformis	Apocynaceae	NE		2
Andropogon virginicus	Poaceae	A		62
Anthurium sp.	Araceae	A	P+	1
Antidesma platyphyllum	Euphorbiaceae	NE		3
Archontophoenix alexandrae	Arecaceae	A		3
Arundina graminifolia	Orchidaceae	A		60
Asplenium lobulatum	Aspleniaceae	NI		3
Asplenium nidus	Aspleniaceae	NI		2
Athyrium sandwichianum	Athyriaceae	NE		4
Axonopus fissifolius	Poaceae	A		17
bamboo 1	Poaceae	A	P	2
bamboo 2	Poaceae	A	P	1
bamboo 3	Poaceae	A	P	1
Begonia hirtella	Begoniaceae	A		9
Begonia sp.	Begoniaceae	A	P	1
Bidens pilosa	Asteraceae	A		15
Blechnum occidentale	Blechnaceae	A		2
Bobea elatior	Rubiaceae	NE		1
Brachiaria mutica	Poaceae	A		3
Broussaisia arguta	Hydrangaceae	NE		3
Buchnera pusilla	Scrophulariaceae	A		1
Buddleia asiatica	Buddleiaceae	A		36
Bulbostylis capillaris	Cyperaceae	A		1
Callistopteris baldwinii	Hymenophyllaceae	NE		1
Calophyllum inophyllum	Clusiaceae	PO		1
Cardamine flexuosa	Brassicaceae	A		1
Carica papaya	Caricaceae	A	P	2
Castilleja arvensis	Scrophulariaceae	A		18
Casuarina equisetifolia	Casuarinaceae	A	P*	9

Appendix 2. Species listing, by species, with other data.

SPECIES	FAMILY	ORIGIN	DEPOSITED	OCCURRENCE
Catharanthus roseus	Apocynaceae	A	P*	1
Cecropia obtusifolia	Cecropiaceae	A		13
Cenchrus echinatus	Poaceae	A		1
Centella asiatica	Apiaceae	A		9
Chamaecrista nictitans	Fabaceae	A		33
Chamaesyce hirta	Euphorbiaceae	A		12
Chamaesyce hyssopifolia	Euphorbiaceae	A		7
Chamaesyce thymifolia	Euphorbiaceae	A		2
Christella parasitica	Thelypteridaceae	A		18
Cibotium chamissoi	Dicksoniaceae	NE		10
Cibotium glaucum	Dicksoniaceae	NE		17
Cibotium hawaiense	Dicksoniaceae	NE		1
Clermontia hawaiiensis	Campanulaceae	NE		1
Clermontia parviflora	Campanulaceae	NE		3
Clerodendrum philippinum	Verbenaceae	A	P	2
Clidemia hirta	Melastomataceae	A		9
Clusia rosea	Clusiaceae	A		4
Cocculus trilobus	Menispermaceae	NI		18
Cocos nucifera	Arecaceae	PO		5
Coffea arabica	Rubiaceae	A		1
Coix lachryma-jobi	Poaceae	A	P	3
Colocasia esculenta	Araceae	PO		1
Commelina diffusa	Commelinaceae	A	P	17
Conyza bonariensis	Asteraceae	A		12
Conyza canadensis	Asteraceae	A		2
Coprosma menziesii	Rubiaceae	NE		6
Coprosma ochracea	Rubiaceae	NE		1
Cordyline fruticosa	Agavaceae	PO		15
Crassocephalum crepadioides	Asteraceae	A		7
Crocosmia x crocosmiiflora	Iridaceae	A	P	1
Crotalaria assamica	Fabaceae	A		5
Crotalaria lanceolata	Fabaceae	A		3
Crotalaria pallida	Fabaceae	A		4
Crotalaria sp.	Fabaceae	A		1
Cuphea carthagenensis	Lythraceae	A		12
Cuscuta sandwichiana	Cuscutaceae	NE		1
Cyclosorus sandwicensis	Thelypteridaceae	NE		1
Cynodon dactylon	Poaceae	A		1
Cyperus halpan	Cyperaceae	A		12
Cyrtandra lysiosepala	Gesneriaceae	NE		1
Cyrtandra paludosa	Gesneriaceae	NE		2
Cyrtandra sp.	Gesneriaceae	NE		1

Appendix 2. Species listing, by species, with other data.

SPECIES	FAMILY	ORIGIN	DEPOSITED	OCCURRENCE
Derris elliptica	Fabaceae	A	P	3
Desmodium cajanifolium	Fabaceae	A		28
Desmodium incanum	Fabaceae	A		27
Desmodium sandwicense	Fabaceae	A		22
Desmodium triflorum	Fabaceae	A		33
Dicranopteris sp.	Gleicheniaceae	NI		31
Digitaria ciliaris	Poaceae	A		5
Digitaria fuscescens	Poaceae	A		5
Digitaria insularis	Poaceae	A		1
Digitaria setigera	Poaceae	NI		6
Digitaria violascens	Poaceae	A		19
Dioclea wilsonii	Fabaceae	NI		1
Dioscorea pentaphylla	Dioscoreaceae	PO		6
Diospyros sandwicensis	Ebenaceae	NE		7
Dissotis rotundifolia	Melastomataceae	A	P	1
Dracaena fragrans	Agavaceae	A	P	1
Dracaena marginata	Agavaceae	A	P	1
Drymaria cordata	Caryophyllaceae	A		3
Dubautia scabra	Asteraceae	NE		4
Elaphoglossum alatum	Elaphoglossaceae	NE		6
Elaphoglossum crassifolium	Elaphoglossaceae	NE		5
Elaphoglossum hirtum	Elaphoglossaceae	NE		1
Eleusine indica	Poaceae	A		9
Emilia fosbergii	Asteraceae	A		20
Emilia sonchifolia	Asteraceae	A		15
Epipremnon pinnatum	Araceae	A	P	4
Eragrostis brownei	Poaceae	A		2
Eragrostis cilianensis	Poaceae	A		9
Eragrostis elongata	Poaceae	A		1
Erechtites valerianifolia	Asteraceae	A		7
Eriocaulon sp.	Eriocaulaceae	A		1
Eucalyptus robusta	Myrtaceae	A	P	1
Fabaceae, vine	Fabaceae	A		1
Ficus macrophylla	Moraceae	A	P	1
Ficus microcarpa	Moraceae	A	P*	5
Fimbristylis dichotoma	Cyperaceae	NI		3
Freycinetia arborea	Pandanaceae	NI		12
Gnaphalium sandwicensium	Asteraceae	NE		1
Gonocormus minutus	Hymenophyllaceae	NI		2
Gouldia terminalis	Rubiaceae	NE		2
Grammitis hookeri	Grammitaceae	NE		2
Hedychium coccineum	Zingiberaceae	A	P	1

Appendix 2. Species listing, by species, with other data.

SPECIES	FAMILY	ORIGIN	DEPOSITED	OCCURRENCE
Hedychium coronarium	Zingiberaceae	A	P*	6
Hedychium flavescens	Zingiberaceae	A	P	2
Hedychium gardnerianum	Zingiberaceae	A	P*	1
Hedyotis centranthoides	Rubiaceae	NE		1
Hedyotis corymbosa	Rubiaceae	A	P*	3
Heterocentron subtriplinervium	Melastomataceae	A		10
Hibiscus sp.	Malvaceae	A	P	1
Hippobroma longifolia	Campanulaceae	A		1
Homalomena rubescens	Araceae	A	P	1
Hoya sp.	Asclepiadaceae	A	P	1
Hyparrhenia rufa	Poaceae	A		7
Hypericum mutilum	Clusiaceae	A		4
Hyptis pectinata	Lamiaceae	A		14
Ilex anomala	Aquifoliaceae	NI		4
Impatiens wallerana	Balsaminaceae	A	P*	7
Indigofera suffruticosa	Fabaceae	A		1
Ipomoea cairica	Convolvulaceae	A		1
Ipomoea indica	Convolvulaceae	A		2
Isachne distichophylla	Poaceae	NE		5
Juncus planifolius	Juncaceae	A		1
Juncus tenuis	Juncaceae	A		3
Kyllinga brevifolia	Cyperaceae	A		6
Lantana camara	Verbenaceae	A		2
Lapsana communis	Asteraceae	A		1
Lindernia antipoda	Scrophulariaceae	A		1
Lindernia crustacea	Scrophulariaceae	A		4
Ludwigia octovalvis	Onagraceae	PO		2
Lycopodium cernuum	Lycopodiaceae	NI		15
Lycopodium phyllanthum	Lycopodiaceae	NE		10
Lycopodium venustulum	Lycopodiaceae	NI		2
Lygodium japonicum	Lygodiaceae	A	P	1
Machaerina angustifolia	Cyperaceae	NI		23
Machaerina mariscoides	Cyperaceae	NI		17
Macroptilium atropurpureum	Fabaceae	A		3
Macroptilium sp.	Fabaceae	A		1
Macrothelypteris torresiana	Thelypteridaceae	A		8
Malvastrum coromandelianum	Malvaceae	A		2
Mangifera indica	Anacardiaceae	A	P	4
Manihot esculenta	Euphorbiaceae	A	P	2
Mecodium recurvum	Hymenophyllaceae	NE		2
Medinilla magnifica	Melastomataceae	A	P*	1
Melaleuca quinquenervia	Myrtaceae	A	P*	3

Appendix 2. Species listing, by species, with other data.

SPECIES	FAMILY	ORIGIN	DEPOSITED	OCCURRENCE
Melastoma candidum	Melastomataceae	A		51
Melastomataceae, shrub	Melastomataceae	A		1
Melinis minutiflora	Poaceae	A		35
Melochia umbellata	Sterculiaceae	A		28
Metrosideros macrophyllum	Myrtaceae	NE		6
Metrosideros polymorpha	Myrtaceae	NE		49
Microlepia strigosa	Dennstaeditiaceae	NI		1
Mimosa pudica	Fabaceae	A		39
Monstera deliciosa	Araceae	A	P	2
Monstera sp.	Araceae	A	P	1
Morinda citrifolia	Rubiaceae	PO		1
Mucuna gigantea	Fabaceae	NI		1
Musa sp.	Musaceae	A	P	2
Myrsine lessertiana	Myrsinaceae	NE		11
Myrsine sandwicensis	Myrsinaceae	NE		1
Nephrolepis cordifolia	Nephrolepidaceae	NI		3
Nephrolepis multiflora	Nephrolepidaceae	A		79
Ophioglossum pendulum	Ophioglossaceae	NE		8
Oplismenus hirtellus	Poaceae	A		15
Osteomeles anthyllidifolia	Rosaceae	NI		2
Oxalis corniculatum	Oxalidaceae	A		4
Paederia scandens	Rubiaceae	A		14
Pandanus tectorius	Pandanaceae	N?		6
Panicum maximum	Poaceae	A		1
Panicum repens	Poaceae	A		7
Paspalum conjugatum	Poaceae	A		24
Paspalum dilatatum	Poaceae	A		8
Paspalum scrobiculatum	Poaceae	N?		24
Paspalum urvillei	Poaceae	A		4
Passiflora edulis	Passifloraceae	A		1
Passiflora foetida	Passifloraceae	A		3
Pelea clusiifolia	Rutaceae	NE		1
Pelea sp.	Rutaceae	NE		1
Pennisetum purpureum	Poaceae	A		4
Pennisetum setaceum	Poaceae	A		1
Peperomia hypoleuca	Piperaceae	NE		5
Peperomia leptostachya	Piperaceae	NI		1
Peperomia sp.	Piperaceae	NE		3
Perrottetia sandwicensis	Celastraceae	NE		1
Persea americana	Lauraceae	A	P	11
Phaius tankarvillei	Orchidaceae	A		4
Philodendron radiatum	Araceae	A	P	1

Appendix 2. Species listing, by species, with other data.

SPECIES	FAMILY	ORIGIN	DEPOSITED	OCCURRENCE
Philodendron sanguineum	Araceae	A	P	2
Philodendron scandens	Araceae	A	P	2
Philodendron sp. 1	Araceae	A	P	2
Philodendron sp. 2	Araceae	A	P	1
Phyllanthus debilis	Euphorbiaceae	A		7
Phymatosorus scolopendria	Polypodiaceae	A		29
Pilea microphylla	Urticaceae	A		1
Piper methysticum	Piperaceae	PO		2
Pipturus albidus	Urticaceae	NE		30
Pisonia umbellifera	Nyctaginaceae	NI		1
Pityrogramma calomelanos	Hemionitidaceae	A		29
Plantago major	Plantaginaceae	A		4
Plectranthus parviflorus	Lamiaceae	NI		1
Pleopeltis thunbergiana	Polypodiaceae	NI		8
Pluchea symphytifolia	Asteraceae	A		57
Polygala paniculata	Polygalaceae	A		47
Polygonum capitatum	Polygonaceae	A		9
Polypodium pellucidum	Polypodiaceae	NE		3
Psidium cattleianum	Myrtaceae	A		32
Psidium guajava	Myrtaceae	A		13
Psilotum complanatum	Psilotaceae	NI		1
Psilotum nudum	Psilotaceae	NI		19
Psychotria hawaiiensis	Rubiaceae	NE		17
Pteris vittata	Pteridaceae	A		9
Pterolepis glomerata	Melstomataceae	A		4
Pycreus polystachyos	Cyperaceae	NI		34
Rhacomitrium	moss	N		12
Rhynchelytrum repens	Poaceae	A		7
Rhynchospora caduca	Cyperaceae	A		6
Rhynchospora rugosa	Cyperaceae	NI		4
Rubus ellipticus	Rosaceae	A		1
Rubus rosifolius	Rosaceae	A		21
Saccharum officinarum	Poaceae	A		1
Sacciolepis indica	Poaceae	A		37
Sadleria cyatheoides	Blechnaceae	NE		17
Sadleria pallida	Blechnaceae	NE		3
Scaevola chamissoniana	Goodeniaceae	NE		1
Scaevola kilaueae	Goodeniaceae	NE		2
Scaevola sericea	Goodeniaceae	NI		2
Schefflera actinophylla	Araliaceae	A		2
Schinus terebinthifolius	Anacardiaceae	A		3
Schizachyrium condensatum	Poaceae	A		49

Appendix 2. Species listing, by species, with other data.

SPECIES	FAMILY	ORIGIN	DEPOSITED	OCCURRENCE
Scleria testacea	Cyperaceae	NI		1
Selaginella arbuscula	Selaginaceae	NE		1
Setaria gracilis	Poaceae	A		9
Setaria palmifolia	Poaceae	A		1
Sida rhombifolia	Malvaceae	A?		6
Solanum nigrum	Solanaceae	N?		1
Sonchus oleraceus	Asteraceae	A		8
Spathodea campanulata	Bignoniaceae	A	P*	1
Spathoglottis plicata	Orchidaceae	A		57
Spermacoce assurgens	Rubiaceae	A		44
Sphaerocionium lanceolatum	Hymenophyllaceae	NE		3
Sphenomeris chinensis	Lindsaeaceae	NE		15
Sporobolus africanus	Poaceae	A		13
Stachytarpheta jamaicensis	Verbenaceae	A		33
Stereocaulon volcani	lichen	N		18
Styphelia tameiameiae	Epacridaceae	NE		11
Synedrella nodiflora	Asteraceae	A		1
Syzygium cumini	Myrtaceae	A		1
Syzygium jambos	Myrtaceae	A	P	5
Tetraplasandra hawaiiensis	Araliaceae	NE		2
Thunbergia fragrans	Acanthaceae	A		6
Tibouchina herbacea	Melastomataceae	A		10
Tibouchina longifolia	Melastomataceae	A	P?	1
Tibouchina urvilleana	Melastomataceae	A	P*	1
Torenia asiatica	Scrophulariaceae	A		5
Trema orientalis	Ulmaceae	A		11
Vaccinium calycinum	Ericaceae	NE		1
Vaccinium reticulatum	Ericaceae	NE		4
Vandenboschia cyrtotheca	Hymenophyllaceae	NE		4
Verbena littoralis	Verbenaceae	A		1
Vernonia cinerea	Asteraceae	A		8
Vittaria elongata	Vittariaceae	NI		3
Waltheria indica	Sterculiaceae	N?		5
Wedelia trilobata	Asteraceae	A		5
Wikstroemia phillyreifolia	Thymelaeaceae	NE	P	5
Xiphopteris saffordii	Grammitaceae	NE		1
Xyris complanata	Xyridaceae	A		3
Youngia japonica	Asteraceae	A		1

Appendix 2. Species listing, by species, with other data.

SPECIES	FAMILY	ORIGIN	DEPOSITED	OCCURRENCE

SPECIES. The total number of of species listed is 291: 96 NE + NI (native) and 195 A + PO (alien or introduced). Nomenclature of flowering plants generally follows that in Wagner et al. (1990).

ORIGIN. NE = endemic native, NI = indigenous native, PO = Polynesian introduction, A = alien or historic introduction.

DEPOSITED. Deposited species have been planted or dumped at sites, including species which also naturalize by. self-dispersal (such plants noted by an *).

OCCURRENCE. This is the number of sites at which the species was recorded of the 96 sites surveyed.

Appendix 3. List of introduced plants found in the Puna study area, grouped horizontally by site within disturbance categories (D = Disturbed; U = undisturbed), and vertically by occurrence category (OR: A = Alien species; PO = Polynesian introduction).

Appendix 3. List of introduced plants found in the Puna study area, grouped horizontally by site within disturbance categories (D = Disturbed, U = Undisturbed), and vertically by occurence category. (OR: A = alien species; PO = Polynesian introduction)

GROUP 1 - Introduced species found naturalized only in disturbed sites

OR	SPECIES NAME	# PLOTS 96 COUNT	PERCENT
A	Spermacoce assurgens	44	46
A	Mimosa pudica	39	41
A	Sacciolepis indica	37	39
A	Melinis minutiflora	34	35
A	Desmodium triflorum	33	34
A	Pityrogramma calomelanos	29	30
A	Desmodium incanum	27	28
A	Desmodium sandwicen	22	23
A	Digitaria violescens	19	20
A	Castilleja arvensis	18	19
A	Axonopus fissifolius	17	18
A	Bidens pilosa	15	16
A	Hyptis pectinata	14	15
A	Sporobolus africanus	13	14
A	Cyperus halpan	12	13
A	Cuphea carthagenensis	12	13
A	Trema orientalis	11	11
A	Heterocentron subtrip.	10	10
A	Eragrostis ciliianensis	9	9
A	Centella asiatica	9	9
A	Polygonum capitatum	9	9
A	Setaria gracilis	9	9
A	Tibouchina herbacea	9	9
A	Eleusine indica	9	9
A	Pteris vittata	9	9
A	Macrothelypteris torresia	8	8
A	Ageratina riparia	8	8
A	Paspalum dilatatum	8	8
A	Sonchus oleraceus	8	8
A	Rhynchelytrum repens	7	7
A	Hyparrhenia rufa	7	7
A	Panicum repens	7	7
A	Phyllanthus debilis	7	7
A	Chamaesyce hyssopifol	7	7
A	Erechtites valerianifolia	7	7
A	Sida rhombifolia	6	6
A	Rhynchospora caduca	6	6
A	Kyllinga brevifolia	6	6
A	Digitaria setigera	6	6
A	Digitaria ciliaris	5	5
A	Digitaria fuscescens	5	5
A	Crotalaria assamica	5	5
A	Plantago major	4	4
A	Paspalum urvillei	4	4
A	Pterolepis glomerata	4	4
A	Pennisetum purpureum	4	4
A	Crotalaria pallida	4	4
A	Lindernia crustacea	4	4
A	Hypericum mutilum	4	4
A	Oxalis corniculatum	4	4
A	Crotalaria lanceolata	3	3
A	Juncus tenuis	3	3
A	Ageratum houstonianum	3	3
A	Xyris complanata	3	3
A	Brachiaria mutica	3	3
A	Macroptilium atropurpure	3	3
A	Passiflora foetida	3	3
PO	Ludwigia octovalvis	2	2
A	Ipomoea indica	2	2
A	Lantana camara	2	2
A	Chamaesyce thymifolia	2	2
A	Conyza canadensis	2	2
A	Eragrostis brownei	2	2
A	Malvastrum coromandel	2	2
A	Hippobroma longifolia	1	1
A	Syzygium cumini	1	1
A	Crotalaria sp	1	1
A	Fabaceae	1	1
A	Digitaria insularis	1	1
A	Lindernia antipoda	1	1
A	Cenchrus echinatus	1	1
A	Cardamine flexuosa	1	1
PO	Colocasia esculenta	1	1
PO	Morinda citrifolia	1	1
A	Abrus precatorius	1	1
A	Passiflora edulis	1	1
A	Cynodon dactylon	1	1
A	Panicum maximum	1	1
A	Bulbostylis capillaris	1	1
A	Macroptilium sp.	1	1
A	Scrophulariaceae	1	1
A	Eriocaulon sp.	1	1
A	Lapsana communis	1	1
A	Eragrostis elongata	1	1
A	Verbena littoralis	1	1
A	Rubus ellipticus	1	1
A	Ipomoea cairica	1	1
A	Juncus planifolius	1	1
A	Indigofera suffruticosa	1	1
A	Pilea microphylla	1	1
A	Pennisetum setaceum	1	1
A	Synedrella nodiflora	1	1
A	Melastomataceae	1	1
A	Youngia japonica	1	1

GROUP 2 - Introduced species found naturally frequently in both disturbed and undisturbed sites

OR	SPECIES NAME	# PLOTS 96 COUNT	PERCENT
A	Nephrolepis multiflora	78	81
A	Pluchea symphytifolia	56	58
A	Andropogon virginicus	62	65
A	Arundina graminifolia	60	63
A	Spathoglottis plicata	56	58
A	Melastoma candidum	51	53
A	Psidium cattleianum	32	33
A	Phymatosorus scolopen	28	29

GROUP 3 - Introduced species found naturalized predominantly in disturbed sites

OR	SPECIES NAME	# PLOTS 96 COUNT	PERCENT
A	Polygala paniculata	47	49
A	Schizachyrium condensa	49	51
A	Buddleia asiatica	36	38
A	Chamaecrista nictitans	33	34
A	Stachytarpheta jamaicen	33	34
A	Ageratum conyzoides	32	33
A	Desmodium cajanifoliu	28	29
A	Melochia umbellata	27	28
A	Rubus rosifolius	21	22
A	Paspalum conjugatum	23	24
A	Emilia fosbergii	20	21
A	Christella parasitica	18	19
A	Emilia sonchifolia	15	16

GROUP 4 - Introduced species found naturalized infrequently in both disturbed and undisturbed sites

OR	SPECIES NAME	# PLOTS 96 COUNT	PERCENT
PO	Cordyline fruticosa	16	17
A	Oplismenus hirtellus	15	16
A	Paederia scandens	14	15
A	Cecropia obtusifolia	13	14
A	Psidium guajava	12	13
A	Chamaesyce hirta	12	13
A	Conyza bonariensis	12	13
A	Clidemia hirta	9	9
A	Begonia hirtella	8	8
A	Vernonia cinerea	8	8
A	Crassocephalum crepid	7	7
A	Thunbergia fragrans	6	6
PO	Dioscorea pentaphylla	6	6
PO	Aleurites moluccana	6	6
PO	Cocos nucifera	5	5
A	Torenia asiatica	5	5
A	Clusia rosea	4	4
A	Phaius tankervilleae	4	4
A	Schinus terebinthifolius	3	3
A	Archontophoenix alexand	3	3
A	Drymaria cordata	3	3
PO	Piper methysticum	2	2
A	Schefflera actinophylla	2	2

GROUP 5 - Introduced species found naturalized only in undisturbed forest sites

OR	SPECIES NAME	# PLOTS 96 COUNT	PERCENT
PO	Zingiber zerumbet	4	4
A	Blechnum occidentale	2	2
A	Coffea arabica	1	1
PO	Calophyllum inophyllum	1	1
A	Adiantum raddianum	1	1
A	Setaria palmifolia	1	1

GROUP 6 - Deposited species, planted or dumped in both disturbed and undisturbed sites

OR	SPECIES NAME	# PLOTS 96 COUNT	PERCENT
A	Commelina diffusa	16	17
A	Albizia lebbeck	15	16
A	Persea americana	11	11
A	Casuarina equisetifolia	9	9
A	Impatiens wallerana	7	7
A	Hedychium coronarium	6	6
A	Wedelia trilobata	5	5
A	Ficus microcarpa	5	5
A	Syzygium jambos	5	5
A	Mangifera indica	4	4
A	Epipremnum pinnatum	4	4
A	Osmis elliptica	3	3
A	Coix lachryma-jobi	3	3
A	Philodendron sp. 1	2	2
A	Philodendron sanguineu	2	2
A	Carica papaya	2	2
A	Manihot esculenta	2	2
A	Musa sp.	2	2
A	Hedychium flavescens	2	2
A	Bamboo 1	2	2
A	Melaleuca quinquenervia	2	2
A	Dracaena marginata	2	2
A	Clerodendrum philippinu	2	2
A	Hedyotis corymbosa	2	2
A	Monstera deliciosa	2	2
A	Philodendron scandens	2	2
A	Lygodium japonicum	2	2
A	Cissus rotundifolia	1	1
A	Hibiscus sp.	1	1
A	Hoya sp	1	1
A	Dracaena fragrans	1	1
A	Hedychium coccineum	1	1
A	Bamboo 3	1	1
A	Ficus macrophylla	1	1
A	Eucalyptus robusta	1	1
A	Homalomena rubescen	1	1
A	Bamboo 2	1	1
A	Medinilla magnifica	1	1
A	Anthurium sp.	1	1
A	Philodendron radiatum	1	1
A	Catharanthus roseus	1	1
A	Saccharum officinarum	1	1
A	Philodendron sp. 2	1	1
A	Spathodea campanulata	1	1
A	Begonia sp.	1	1
A	Monstera sp.	1	1
A	Tibouchina urvilleana	1	1
A	Heterocentron sp	1	1
A	Hedychium gardnerianu	1	1
A	Crocosmia x crocosmiifl	1	1
A	Alpinia purpurata	1	1

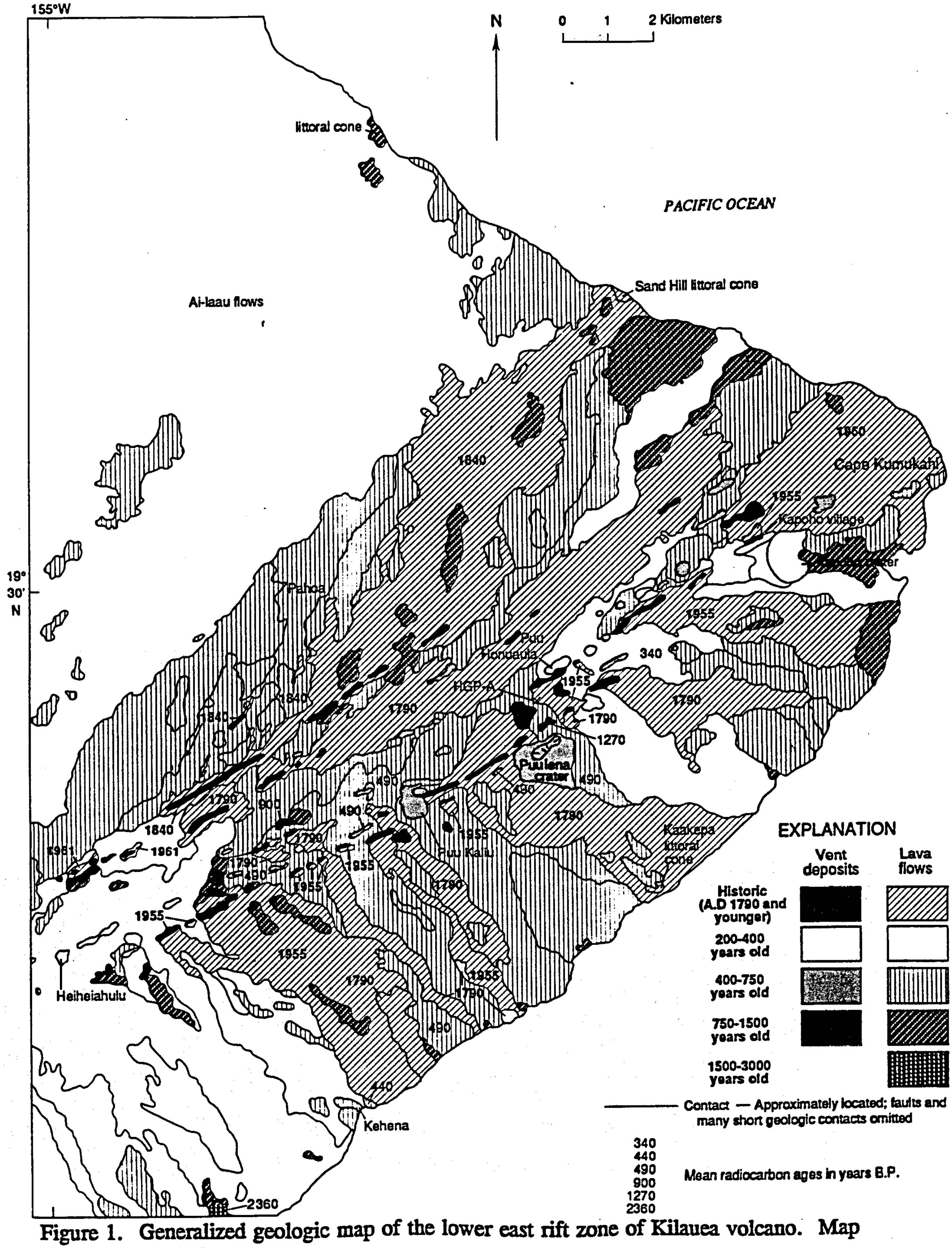

Figure 1. Generalized geologic map of the lower east rift zone of Kilauea volcano. Map from Moore (1992).

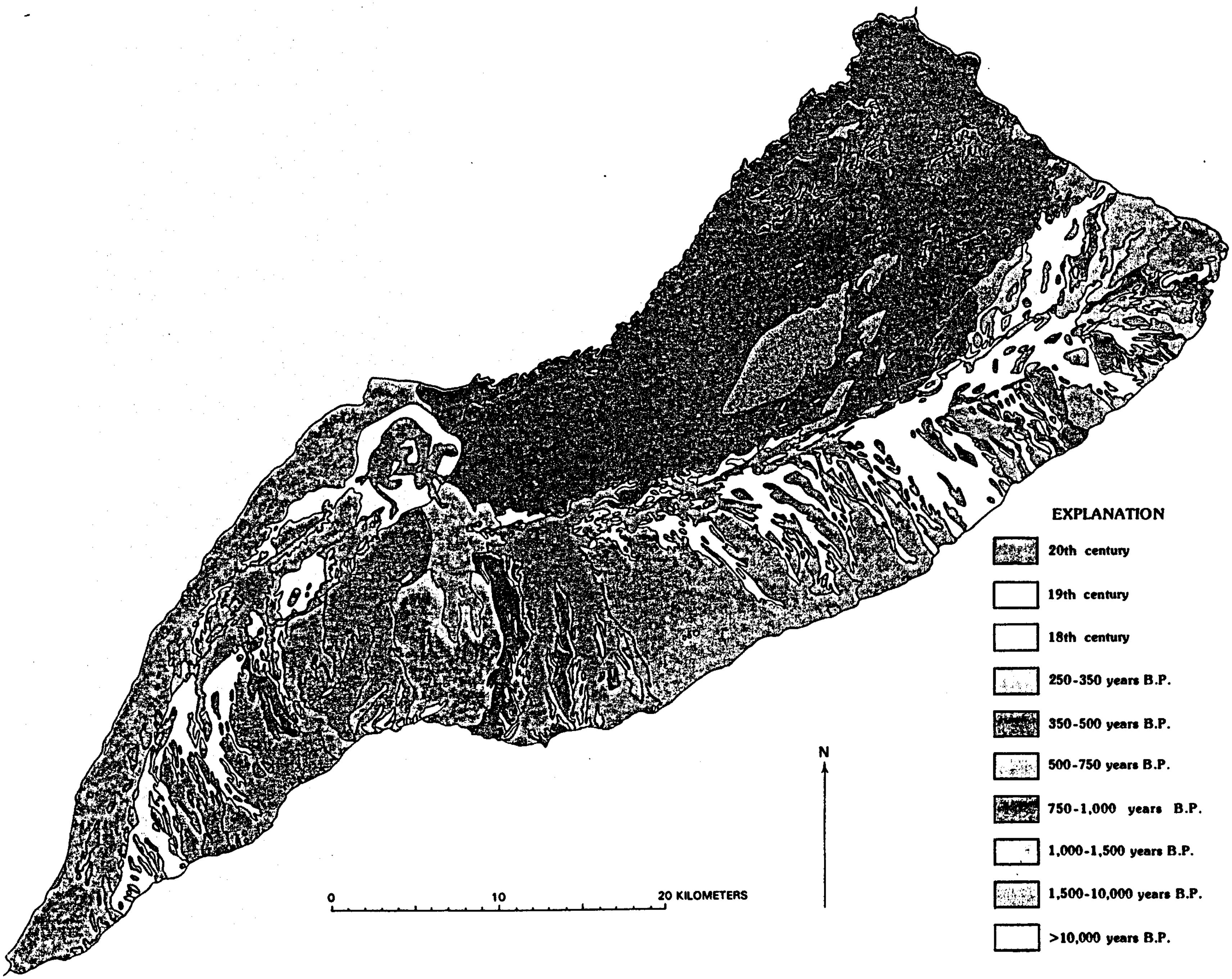

Figure 2. Stratigraphic map of Kilauea, showing approximate ages of surficial lava flows. Map from Holcomb (1987).

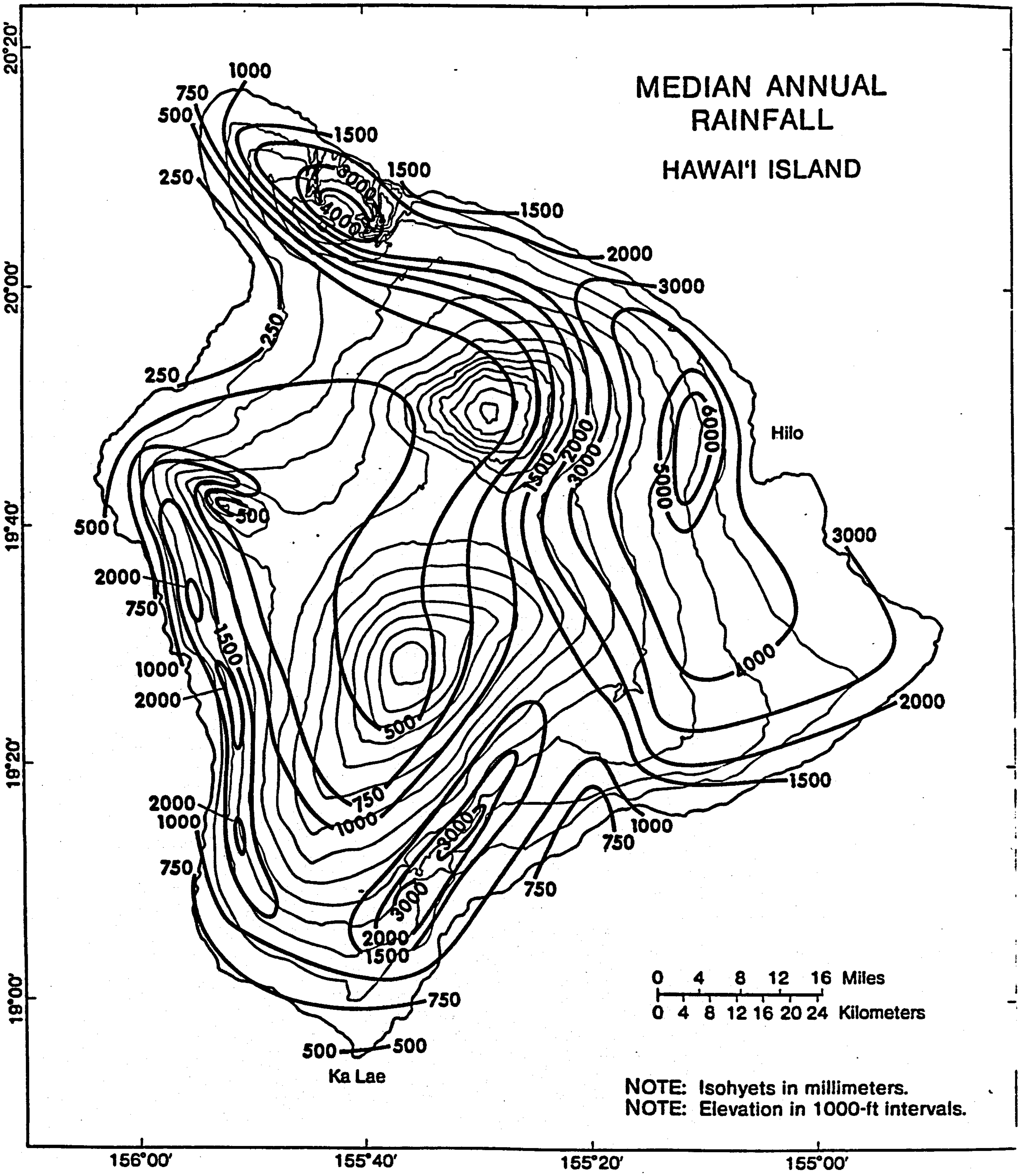

Figure 3. Median annual rainfall, Hawai'i Island. Map from State of Hawai'i (1980).

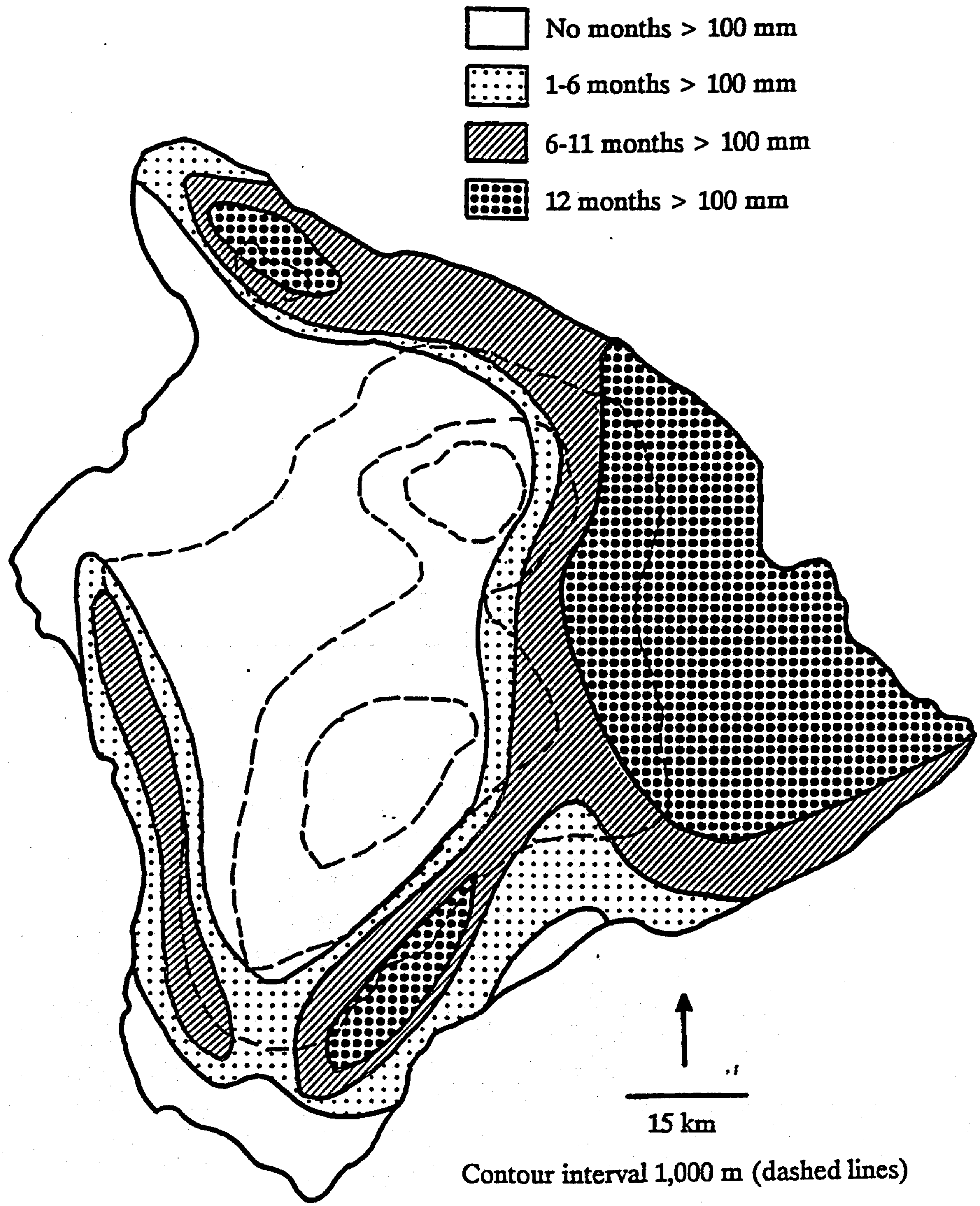

Figure 4. Annual rainfall distribution over the island of Hawai'i.

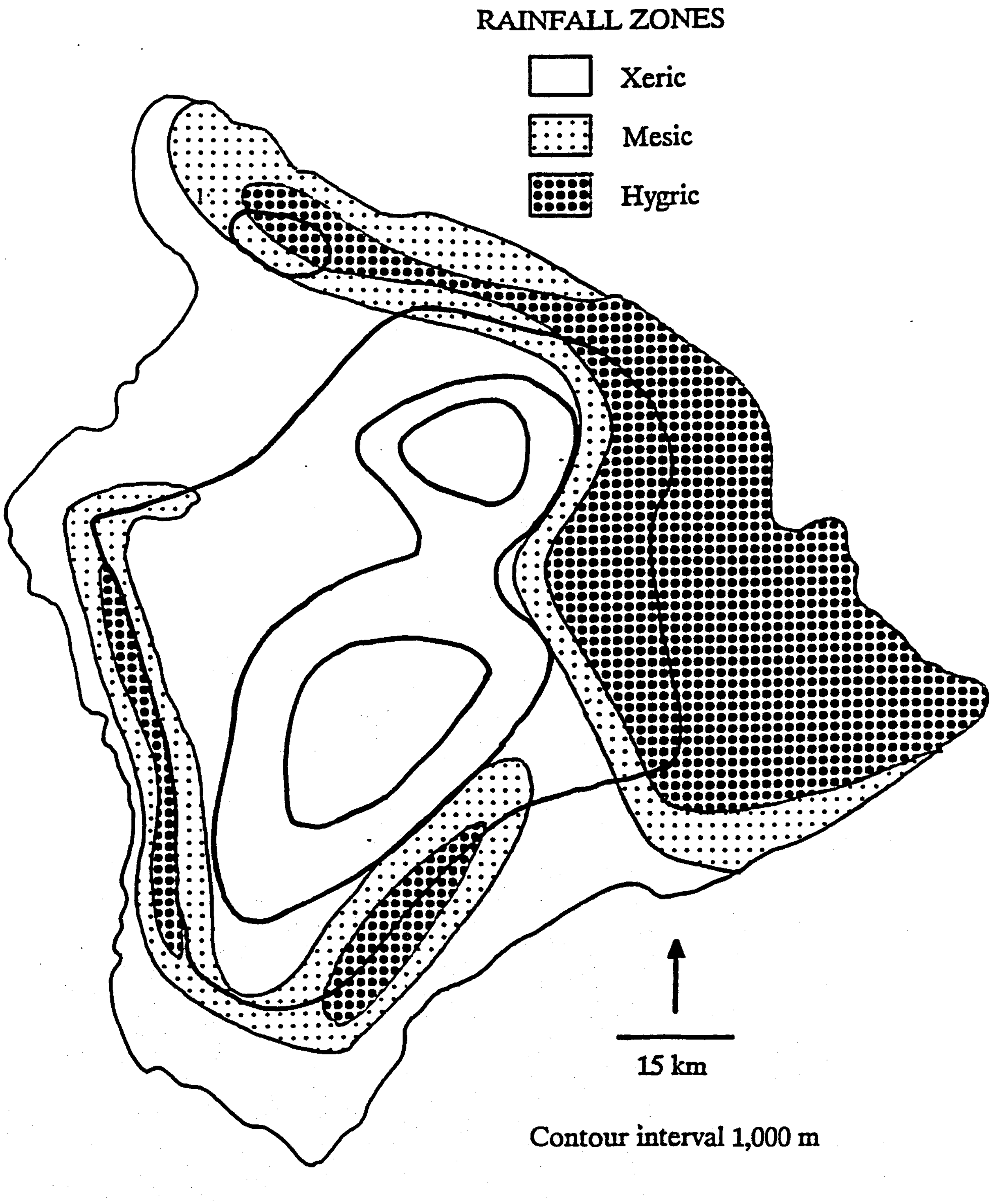

Figure 5. Rainfall zones on the island of Hawai'i.

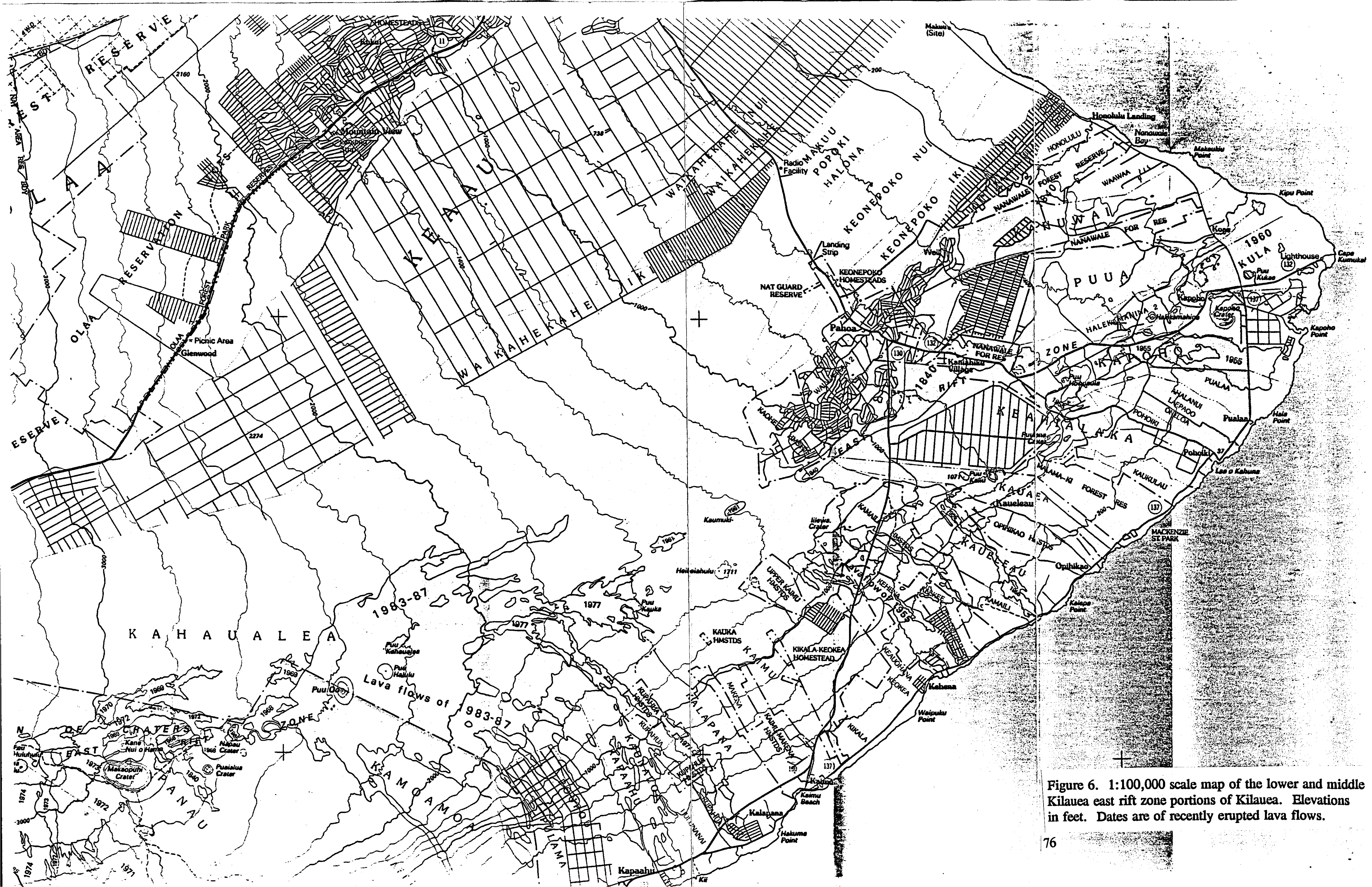

Figure 6. 1:100,000 scale map of the lower and middle Kilauea east rift zone portions of Kilauea. Elevations in feet. Dates are of recently erupted lava flows.

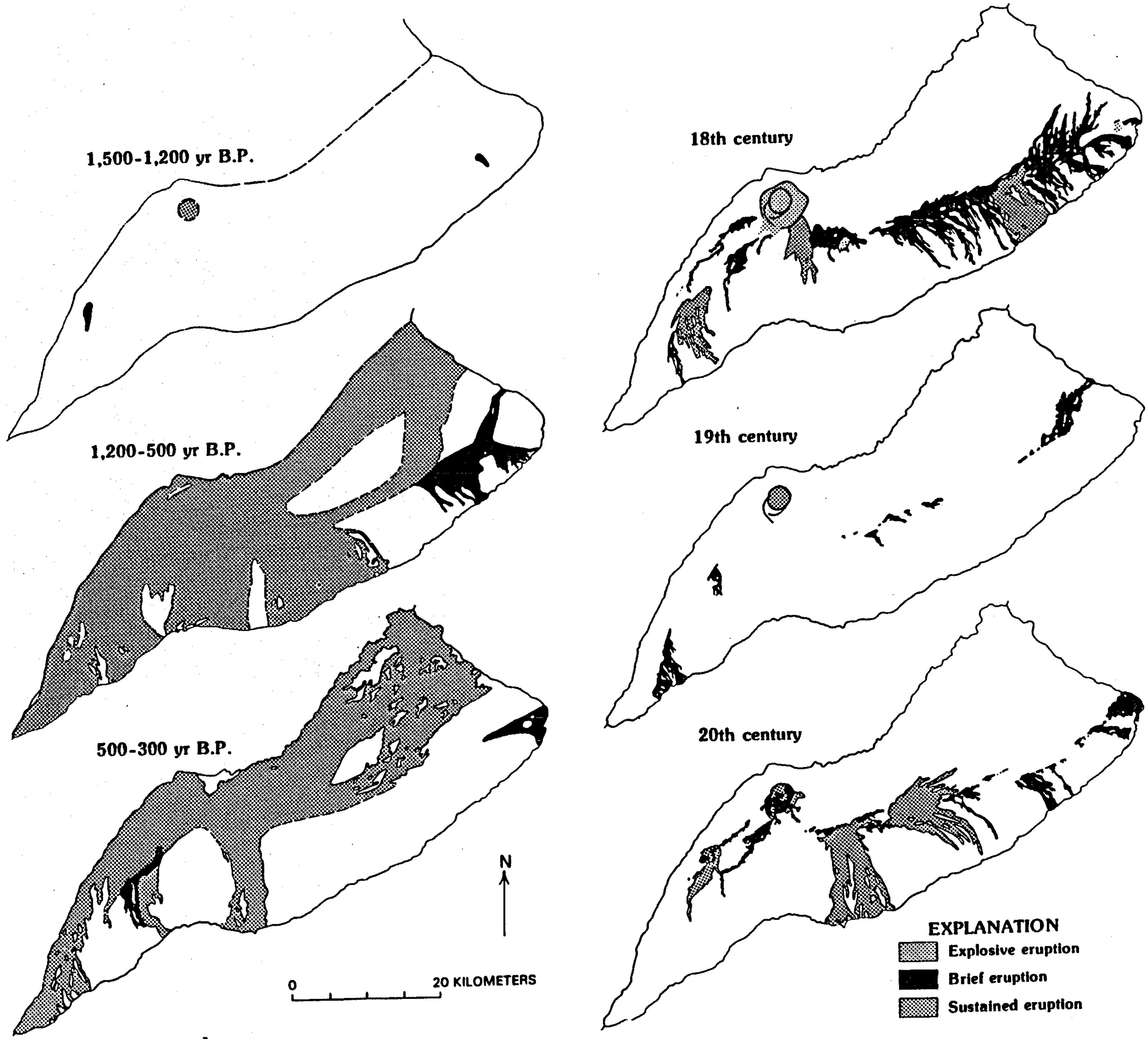

Figure 7. Series of maps summarizing Kilauea's eruptive history during the last 1,500 years. Map from Holcomb (1987).

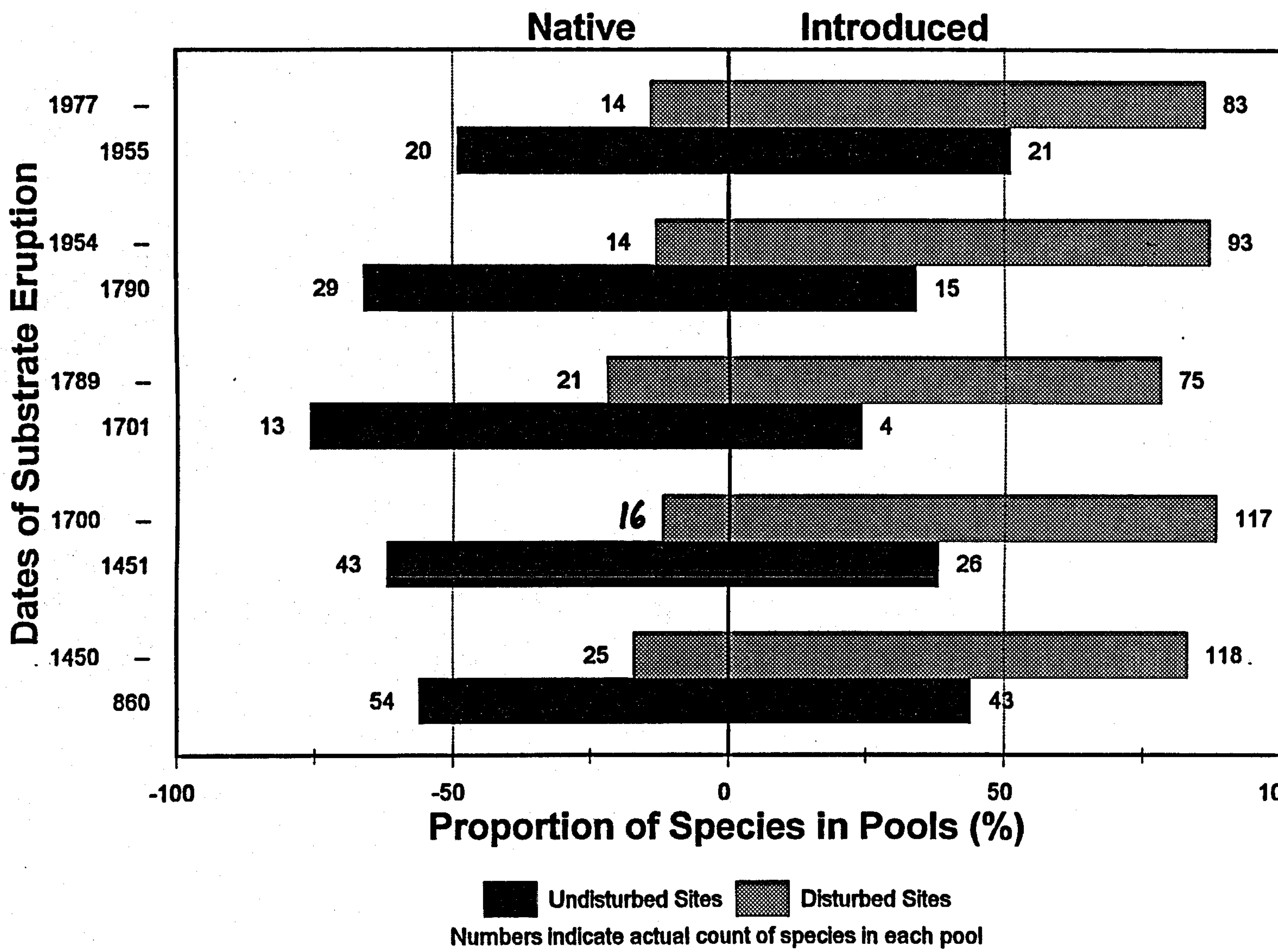

Figure 8. Comparison of disturbed and undisturbed pools of native and alien plant species, by age class (dates of substrate eruption).

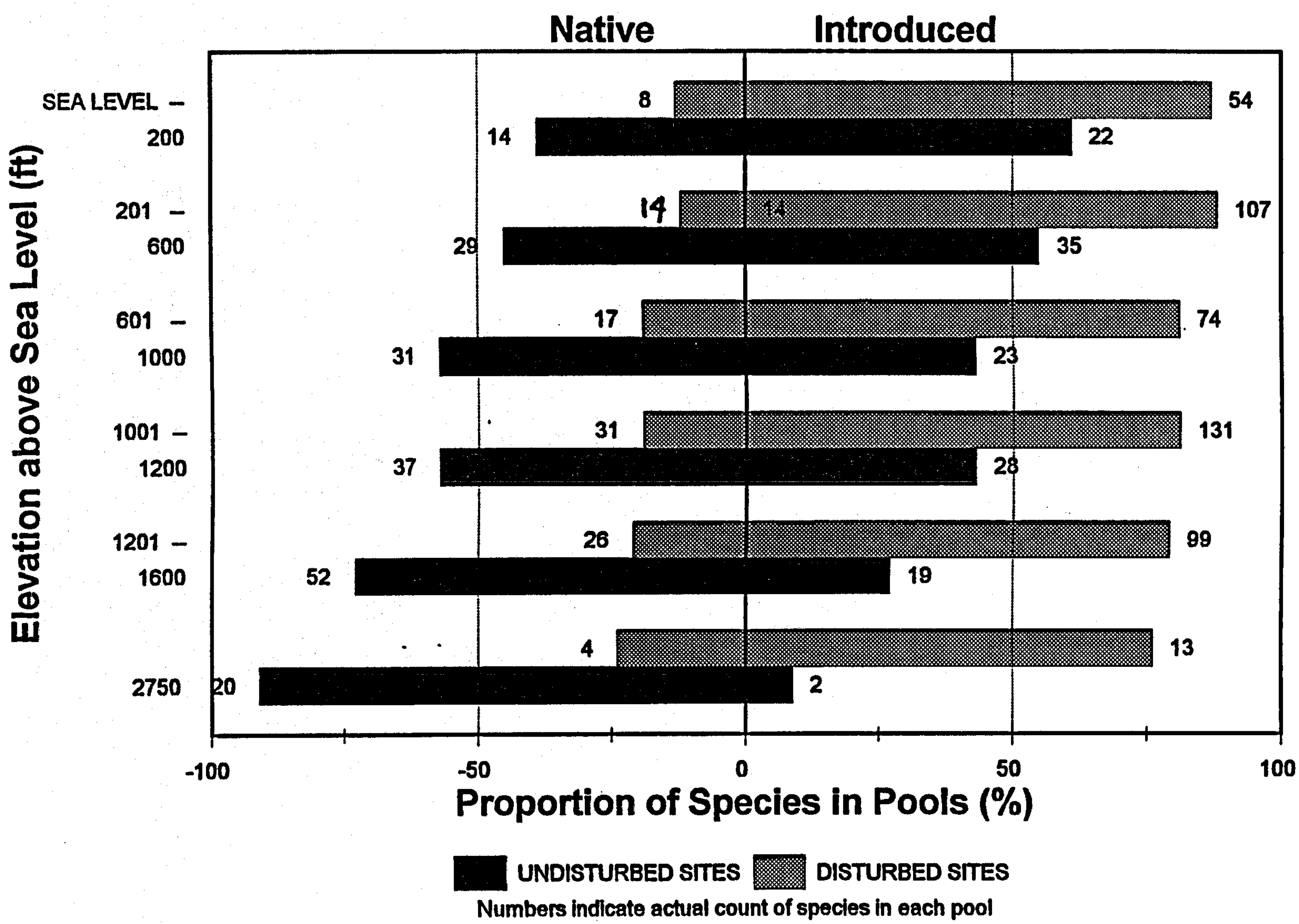

Figure 9. Comparison of disturbed and undisturbed pools of nativeand alien plant species, by elevation class.

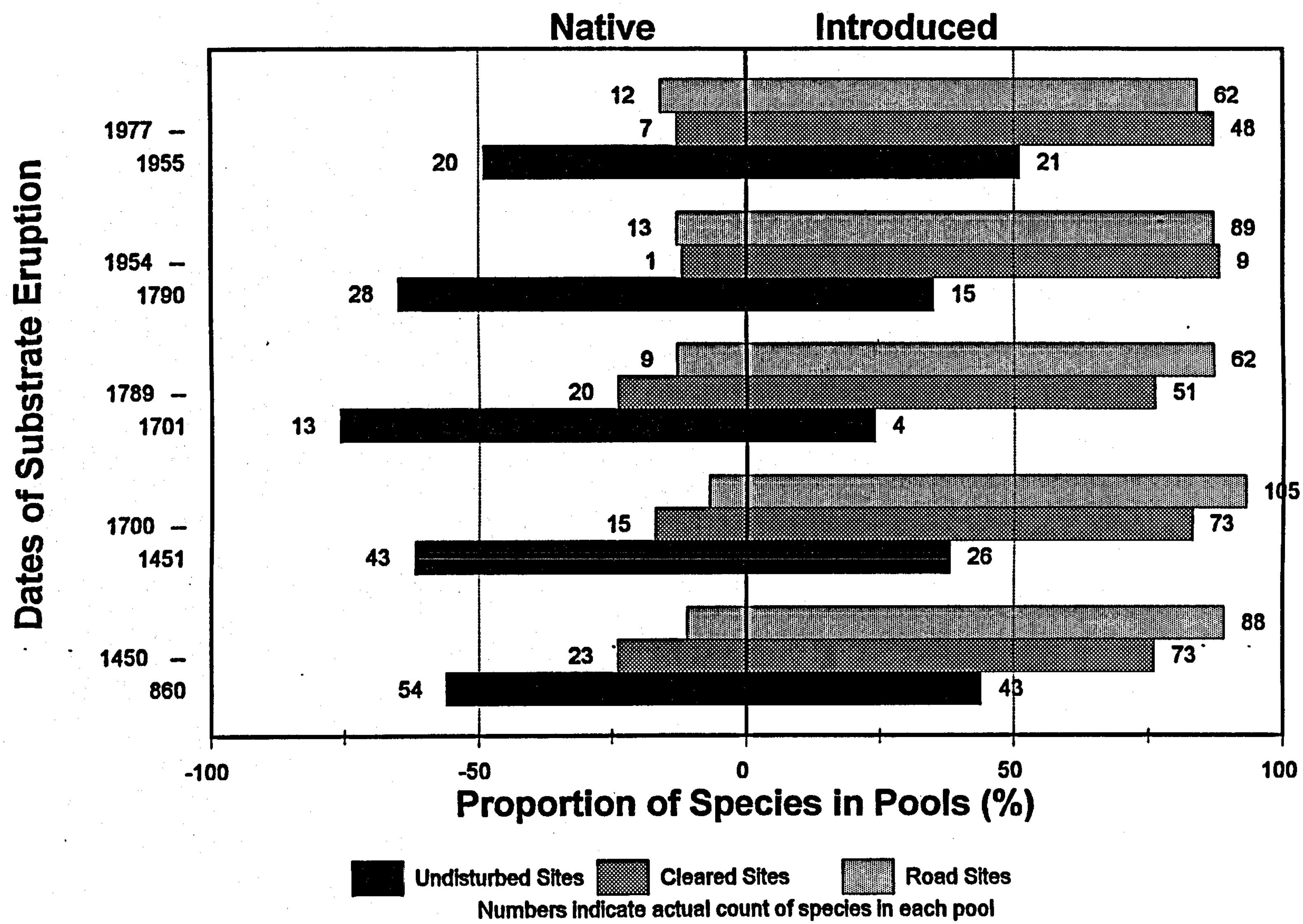

Figure 10. Comparison of species pools in disturbed road sites and cleared sites with species pools in undisturbed sites, by age class.

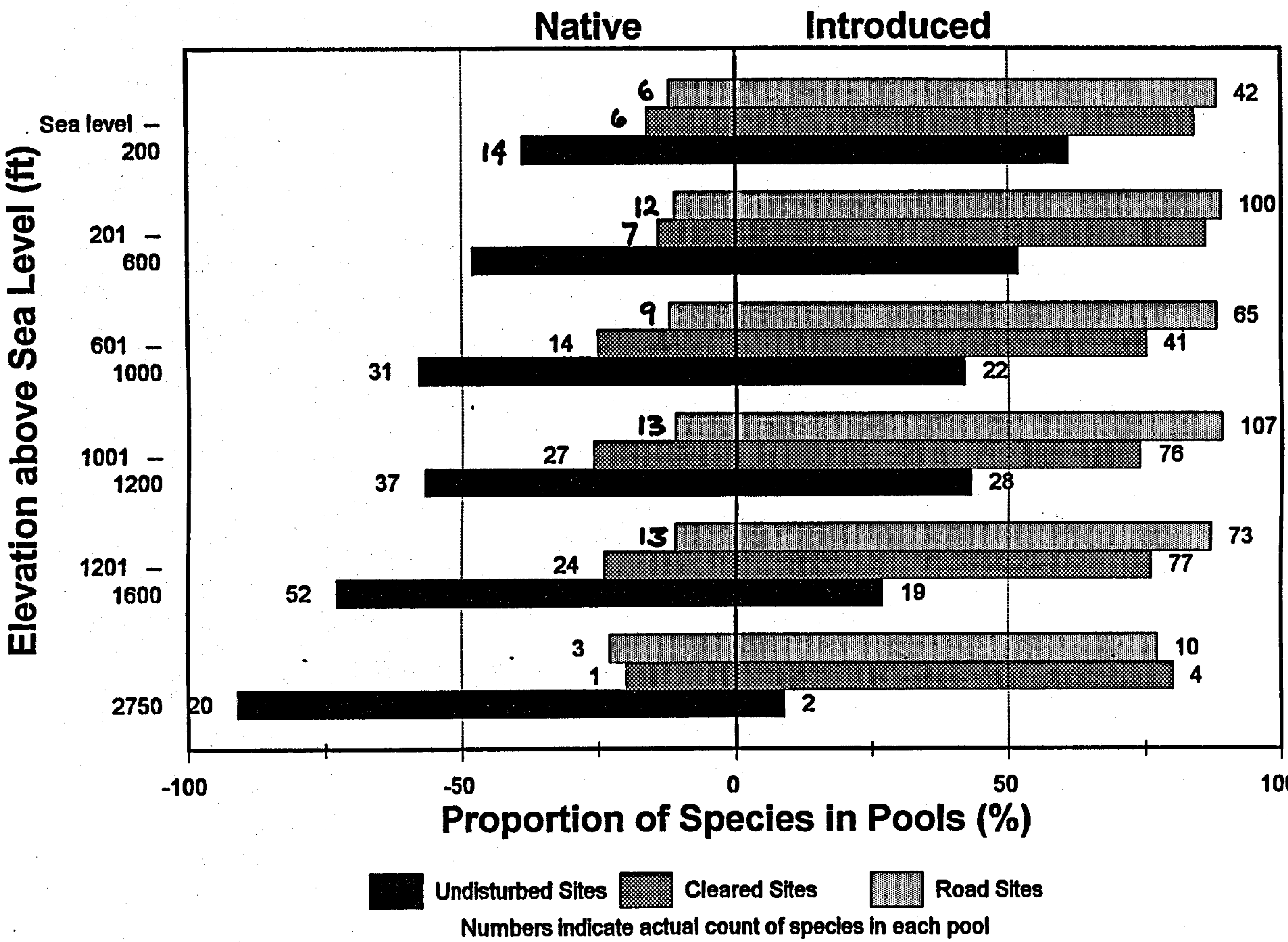

Figure 11. Comparison of species pools in disturbed road sites and cleared sites with species pools in undisturbed sites, by elevation class.

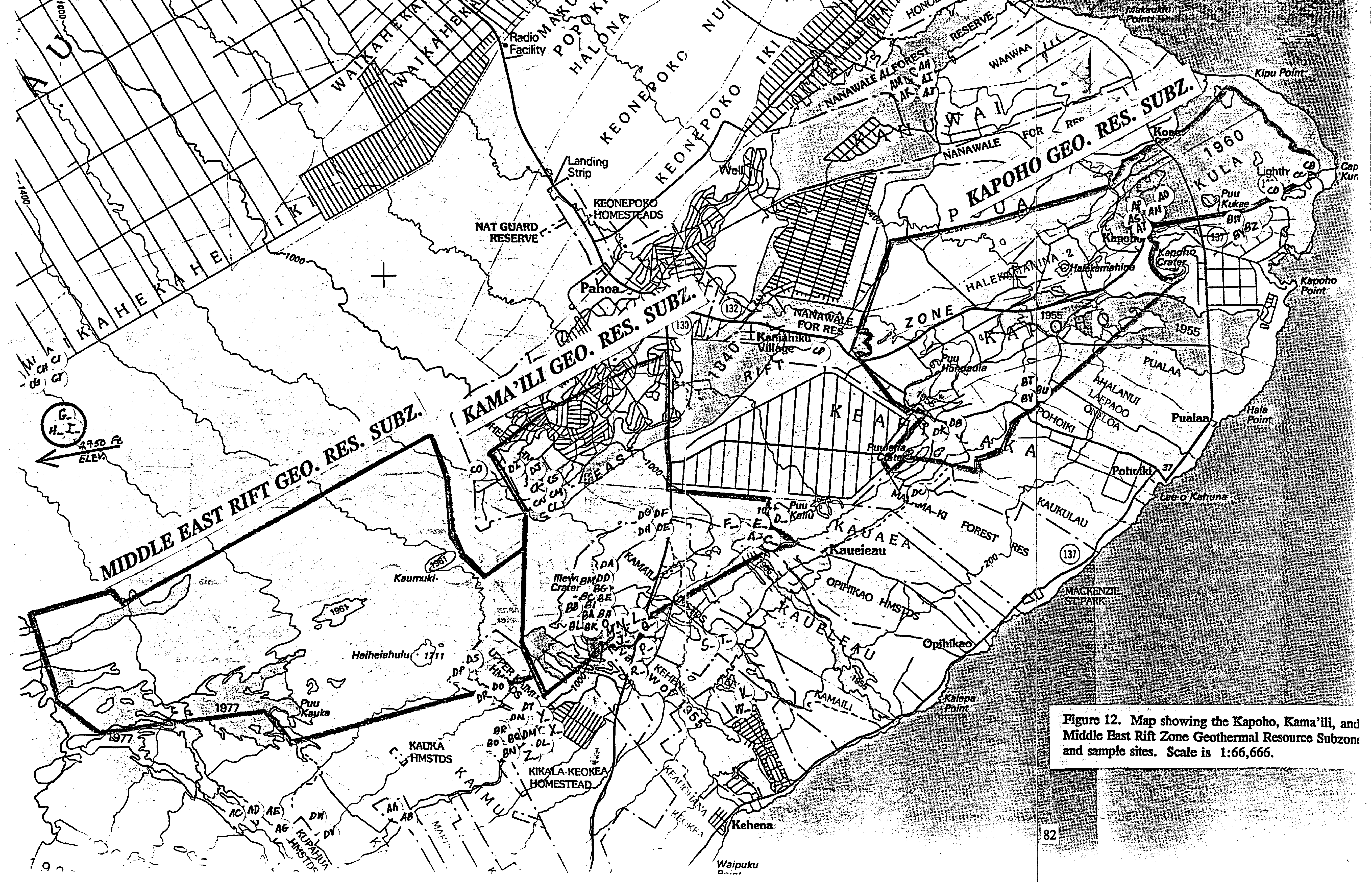

Figure 12. Map showing the Kapoho, Kama'ili, and Middle East Rift Zone Geothermal Resource Subzone and sample sites. Scale is 1:66,666.