DISTRIBUTION OF SIX ALIEN PLANT SPECIES IN UPLAND HABITATS ON THE ISLAND OF HAWAI'I

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ABSTRACT

The 1976-1981 distribution, elevation, and median annual rainfall of six alien plant species in upland habitats on the island of Hawai'i are described based on data collected at 7,864 sampling points (stations) along 117 transects within a 1,930-mi^2 (5,000-km^2) study area. Focal species were Malabar melastome (*Melastoma candidum*), banana poka (*Passiflora mollissima*), fountain grass (*Pennisetum setaceum*), strawberry guava (*Psidium cattleianum*), yellow Himalayan raspberry (*Rubus ellipticus*), and German ivy (*Senecio mikanioides*). Three species, strawberry guava, fountain grass, and banana poka, were widely distributed throughout the study area, while the remaining three species were found on less than 2% of the stations sampled. Relatively xeric habitats (median annual rainfall 49 in. or <1,250 mm) and low-elevation areas (1,640-4,265 ft or 500-1,300 m) were found to be consistently invaded by three or more of the species. Forty-six (72%) of the 64 vegetation types sampled contained at least one of the six alien plant species. Portions of the two largest vegetation units, 'ōhi'a *(Metrosideros polymorpha)* rain forest, and 'ōhi'a-koa *(Acacia koa)* rain forest, were colonized by five of the six species analyzed. Elevation and median annual rainfall ranges were used to predict the potential geographical distribution of each species in the study area, assuming no restriction in plant invasion over time. Four of the six species (banana poka, German ivy, strawberry guava, and yellow Himalayan raspberry) showed great potential for expansion of their ranges if they continue to invade areas with environmental conditions similar to those where they were found during this survey.

INTRODUCTION

Nearly 5,000 taxa of flowering plants have been purposely or accidentally introduced to Hawai'i during the past 200 years (St. John 1973). Fortunately, of this large number of alien species, fewer than 15% are established outside cultivation, and less than 2% are currently considered serious threats to native ecosystems (Smith 1985; Wester, this volume). However, the relatively small number of recognized noxious plants is expected to increase with time, both as new species are brought into the islands and as species that are already established expand in distribution and abundance.

The degree of threat posed by alien plants depends not only on site-related impacts where they have become established, but also on their potential for dispersal into new areas. For this reason, it is important to recognize the types of habitats the species are potentially able to colonize, and the possible extent of the distribution of the species if they are not effectively controlled.

In this paper we describe the current distributions and some of the habitat characteristics of six alien plants that are potential threats to the natural integrity of native ecosystems on the island of Hawai'i. This information is then used to develop a generalized model describing the potential ranges of these species in upland habitats, based on their current distribution in relation to two habitat variables: median annual rainfall and elevation. The prime objective of this analysis is to present a regional overview of the current and potential distribution of the six species. Of particular interest is the identification of general geographic and habitat zones that could be invaded if the species are allowed to continue to spread unabated.

The species discussed herein include one grass (fountain grass, *Pennisetum setaceum*), two vines (banana poka and German ivy, *Passiflora mollissima, Senecio mikanioides*), two shrubs (Malabar melastome and yellow Himalayan raspberry, *Melastoma candidum*, *Rubus ellipticus*), and a small tree (strawberry guava, *Psidium cattleianum*) (Table 1). Besides being recognized as threatening to the native ecosystems they presently occupy, these species were chosen as representatives of different life forms and different times of invasion into habitats they potentially affect.

Historical Background of the Six Focal Species

Malabar melastome is a moderate-sized shrub native to Southeast Asia. It was introduced as an ornamental to the island of Kaua'i from Florida in 1916 (Haselwood and Motter 1983). This species is currently considered a problem weed on the islands of Kaua'i and Hawai'i where it grows into dense thickets up to 6.5 ft (2 m) tall, displacing native vegetation. Dispersal is primarily by birds and other animals that feed on the plant's berry-like fruits. All species in the genus *Melastoma* are listed as noxious by the Hawaii Department of Agriculture (1978).

Banana poka is native to the Andes region of Peru, Bolivia, and Venezuela (Escobar 1980). It was brought to Hawai'i for its edible fruit in the early 1900s and was first collected in the wild near Pu'uwa'awa'a Ranch in North Kona in 1921 (LaRosa 1984). This species is now established on the islands of Maui, Hawai'i, and Kaua'i, with extremely heavy infestations on the latter two islands (Warshauer *et al.* 1983).

Table 1. Pertinent information on six alien plant species discussed in text. Data on origin, establishment date, and dispersal from Haselwood and Motter (1983); nomenclature follows Wagner *et al.* (1990).

Scientific Name [Common Name]	Family	Life[1] Form	Origin	First Collected	Dispersal (agent)	Considered[2] Noxious By
Melastoma candidum [Malabar melastome]	Melastomataceae	Ch	SE Asia	1916	Seed; (bird; mamm.)	A
Passiflora mollissima [Banana poka]	Passifloraceae	Vi	Tropical America	ca. 1900	Seed; (bird, mamm.)	C
Pennisetum setaceum [Fountaingrass]	Poaceae	HC	North Africa	1914	Seed; (wind; anim., vehic.)	A,C
Psidium cattleianum [Strawberry guava]	Myrtaceae	Ph	Brazil	1825	Seed; (bird, mamm.)	C
Rubus ellipticus [Yellow Himalayan raspberry]	Rosaceae	Ch	Himalayas	1961	Seed; (bird, mamm.)	B,C
Senecio mikanioides [German ivy]	Asteraceae	Vi	South Africa	1909	Seed; veg. (wind, anim.)	C

[1]Ch = Chamaephyte; HC = Hemicryptophyte; Ph = Phanerophyte; Vi = Vine.

[2]A = Hawaii Department of Agriculture (1978).
B = Proposed for inclusion on Hawai'i Dept. of Agriculture Noxious Weed List (M. Isherwood, pers. comm.).
C = National Park Service (1986).

Banana poka is a perennial vine that can climb up to 80 ft (25 m) into the tree canopy or densely cover the forest understory vegetation. The seeds are contained in a fleshy fruit that is eaten by many species of animals. Primary dispersal agents are believed to be several species of birds, rodents, feral pigs (*Sus scrofa*), and humans (Warshauer *et al.* 1983). Although banana poka is listed as noxious only by the National Park Service (1986), a cooperative research program is currently being conducted by the state of Hawai'i (Department of Land and Natural Resources), U.S. Forest Service, and the National Park Service to identify biological control agents for use against this species in Hawai'i (Markin, this volume).

Fountain grass is a perennial bunchgrass native to North Africa. It has been introduced to many areas around the world as an ornamental and was first collected by G. Munro on the island of Lāna'i in 1914. The species has since become established on most of the major Hawaiian Islands (Haselwood and Motter 1983). Although it is a dominant grass throughout most of the dry ranchland in the North Kona and South Kohala districts on the island of Hawai'i, it is not considered a particularly good pasture species (Whitney *et al.* 1939). The seeds of fountain grass are easily dispersed short distances by wind, but long-distance dispersal is probably the result of propagules being carried into new areas on vehicles or livestock from an infested area. Once established, this species can significantly increase the potential for fire and rapidly colonize an area that has been burned (Smith 1985). Fountain grass is recognized as a noxious weed by both the Hawaii Department of Agriculture (1978) and the National Park Service (1986).

A native of Brazil, strawberry guava was brought to Hawai'i as a fruit tree around 1825 (St. John 1973). This species is currently found on the six largest Hawaiian Islands. It is a small tree that can form extremely dense thickets up to 30 ft (10 m) tall. The seeds are widely dispersed by many species of birds and other animals, such as feral pigs, that feed on the fleshy fruit. Fruits of strawberry guava and other *Psidium* species are regularly picked by local residents to be either eaten directly or made into juice, jelly, or jam. Despite its local importance as a fruit tree, strawberry guava is recognized as a serious threat to native forest ecosystems below 4,900 ft (1,500 m) elevation (Smith 1985). The National Park Service (1986) considers it a species that needs to be controlled or eliminated within Park boundaries.

Yellow Himalayan raspberry was first collected in the town of Volcano on the island of Hawai'i in 1961, where it had been introduced for its edible fruit (Degener and Degener 1968). Native to tropical and subtropical regions of the Himalaya Mountains, this extremely thorny raspberry forms nearly impenetrable thickets where it has become established. Degener and Degener (1968) recognized the potential threat this species could pose to native ecosystems and recommended that it be controlled immediately to stop its spread. As with other *Rubus* species, the seeds of yellow Himalayan raspberry are readily dispersed by birds. Currently, the species is considered a noxious species by the National Park Service (1986) and has also been proposed for inclusion on the State of Hawai'i's noxious weed list (M. Isherwood, pers. comm.).

The history of introduction and current distribution of German ivy in Hawai'i is not well documented. Haselwood and Motter (1983) reported that this vine is native to South Africa and probably was introduced as an ornamental to the Kona side of the island of Hawai'i around 1909. German ivy apparently has become naturalized only on that island, with most populations concentrated in the North Kona and Mauna Kea-Mauna Loa saddle areas. This species is dispersed by either wind-blown seeds, or vegetatively as cuttings (Haselwood and Motter 1983). The National Park Service (1986) recognized German ivy as a species that may adversely impact native ecosystems in Hawaii Volcanoes National Park if it were to become established there.

METHODS

Field Sampling

Field work for this study was conducted between 1976 and 1981 during the U.S. Fish and Wildlife Service Hawai'i Forest Bird Survey (Scott *et al.* 1981). The Survey research areas covered approximately 47% (1,960 mi^2 or 4,952 km^2) of the island of Hawai'i, focusing primarily on forest bird habitats above 1,640 ft (500 m) elevation (Fig. 1). Field work was conducted along 117 transects, located 2 mi (3.2 km) apart and perpendicular to elevation contours, with a total combined length of 668 mi (1,078 km). Sampling points (stations) were established at 328 ft, 440 ft, or 492 ft (100, 134, or 150 m) intervals along the transects, depending on the study area (Scott *et al.* 1981, 1986). A total of 7,864 stations was sampled for the island of Hawai'i. Although in this paper we report primarily on data gathered on the distribution of six alien plant species, detailed information was also collected for several other introduced plants and animals, the distribution and abundance of native and nonnative forest birds, vegetation structure and composition, substrate characteristics, and phenology of selected plant species (Scott *et al.* 1981).

Data Analysis

Location coordinates used in plotting species presence for the stations sampled were generated by digitizing the start and end points for each transect into a computer mapping program, which then interpolated the relative locations of the stations based on transect length and station interval. For the analysis of habitat characteristics, elevation was taken from 1:24,000-scale U.S. Geological Survey quadrangle maps, vegetation types were identified using 1:24,000-scale maps prepared for the Hawai'i Forest Bird Survey study areas (Scott *et al.* 1981; Jacobi 1990), and median annual rainfall was determined from maps prepared by the Hawaii Division of Water and Land Development (Hawaii Department of Land and Natural Resources 1980). A summary of the distribution and frequency of all stations sampled on the island in relation to elevation and median annual rainfall classes is presented in Figure 2.

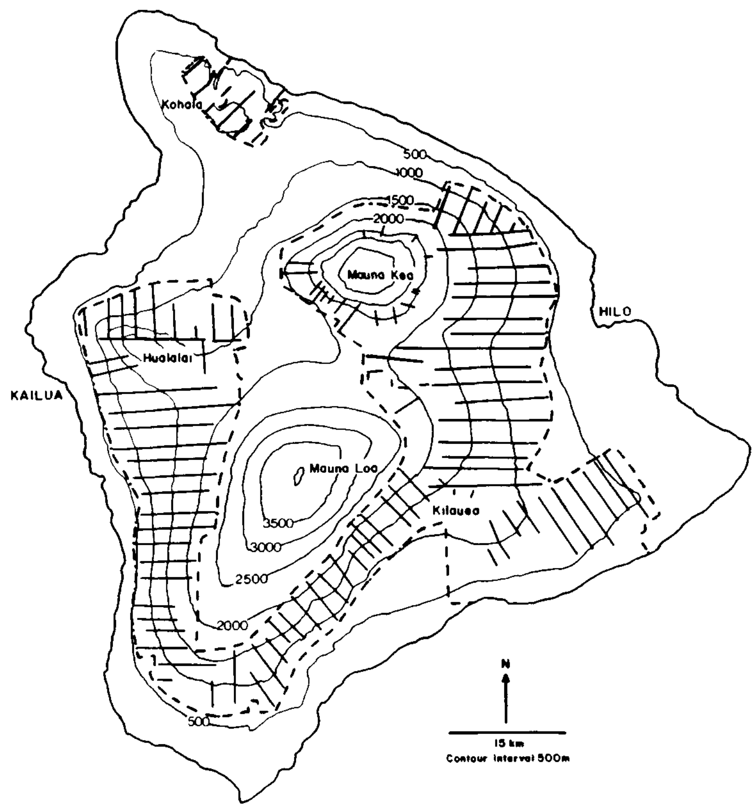

Figure 1. Location of study areas (dash-dot line) and transects (straight solid lines) established on the island of Hawai'i during the Hawai'i Forest Bird Survey.

MEDIAN ANNUAL RAINFALL (mm)

		0	1250	2500	3500	5000	7000	>7000	ELEV TOTALS No Sta	%Tot
	>3300 m								0	0 0
E	3300 m									
		11							11	0 1
L	2900 m									
		166							166	2 1
E	2500 m									
		306	10						316	4 0
V	2100 m									
		794	368	9					1171	14 8
A	1700 m									
		1067	724	387	88				2266	28 8
T	1300 m									
		334	796	264	678	101			2173	27 6
I	900 m									
		194	408	217	362	334		58	1573	20 0
O	500 m									
		16	19	53	73	27			188	2 3
N	100 m									
	0 m								0	0 0
	PPT No Sta	2888	2325	930	1201	462		58	7864	
	%Tot	36 7	29 5	11 8	15 2	5 8		0 7		

Figure 2. Summary of all stations sampled during the Hawai'i Forest Bird Survey plotted by elevation and median annual rainfall. Heavy line indicates elevation-rainfall cells sampled during the Survey.

Predicting Potential Range of the Plant Species

Elevation and median annual rainfall ranges for the six alien species were used to develop a general model to predict the potential geographic range of each species in the Hawai'i Forest Bird Survey study area, assuming no other restrictions of plant invasion over time. The two-way tabulation of stations sampled by rainfall and elevation classes (Fig. 2) was used as the basis for the model. It was assumed that each species has the potential to become established in the proximity of all stations falling within elevation and rainfall class cells that the species were found to occupy during the Survey. For example, a species may have been found at stations located in dry habitats at high elevation. The model would predict the species could eventually be found only on those additional stations showing the same combined low rainfall and high elevation characteristics, but not at low-elevation dry or high-elevation wet sites.

Although the elevation-rainfall model used in this paper is rather simplistic, it allows for a general prediction of the potential ranges of the six species on the island of Hawai'i based on data gathered systematically in the field. Further refinement of this model may be possible with the inclusion of additional information on other habitat variables (*e.g.*, substrate type, soil moisture availability, seasonality of precipitation) for each documented occurrence. Unfortunately, data on additional habitat variables are not available for the study area. Despite the small number of model variables, we believe the potential range maps presented in this paper provide a general overview of the areas that may be colonized by these species if they are allowed to continue to spread.

Finally, it should be emphasized that the model used to predict potential distribution is based only on information relating to stations containing the species during the Hawai'i Forest Bird Survey. The model does not take into account the fact that these recorded occurrences may not reflect the full range of environmental conditions the species may ultimately tolerate with continued invasion. This may certainly be the case with species in an early stage of invasion that could become established in areas outside the range of environmental conditions in which they were found during the Survey. This recognized limitation of the model may result in a conservative prediction of potential distribution for such species. A more accurate prediction may be possible as more information is collected on additional occurrences of these invading species.

RESULTS

Distribution and Environmental Ranges of the Six Species Studied

Three basic patterns are apparent in the distribution maps for the six species studied (Figs. 3-14). Two species (Malabar melastome and yellow Himalayan raspberry) were concentrated on the eastern portion of the Island (Figs. 3 and 11), two species (fountain grass and German ivy) were generally found on the western side of the Island (Figs. 7 and 13), and the

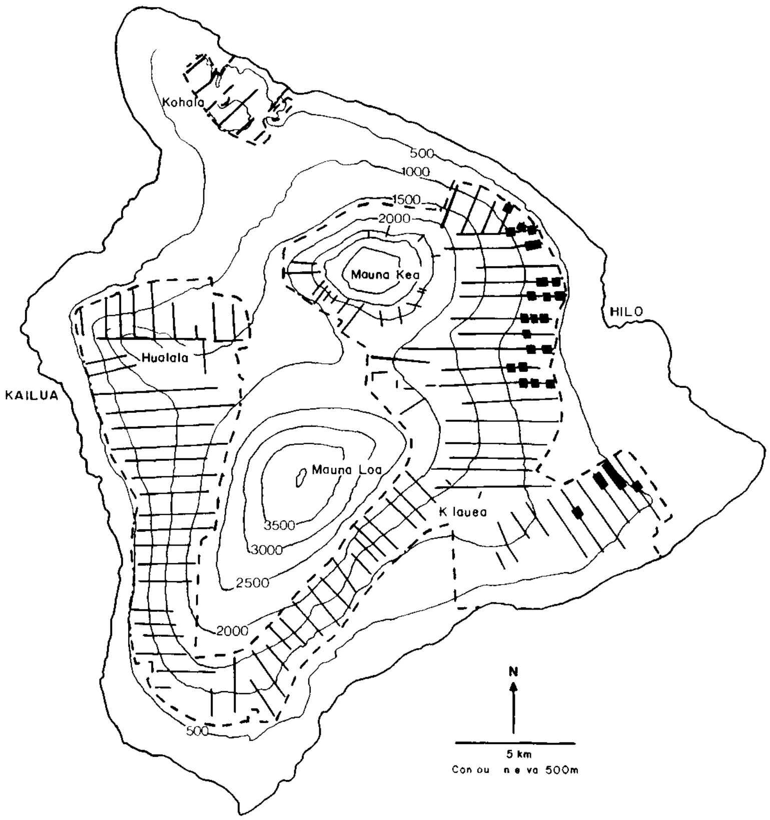

Figure 3. Occurrence of Malabar melastome during the Hawai'i Forest Bird Survey on the island of Hawai'i.

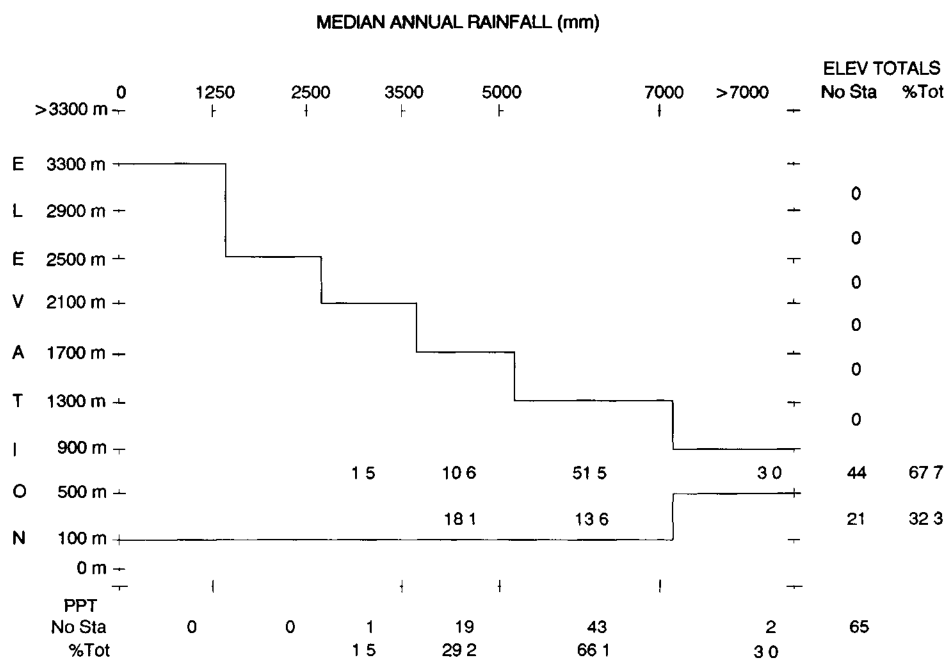

Figure 4. Plot of percent of total stations containing Malabar melastome in elevation and rainfall classes for the Hawai'i Forest Bird Survey study areas on the island of Hawai'i.

Figure 5. Occurrence of banana poka during the Hawai'i Forest Bird Survey on the island of Hawai'i.

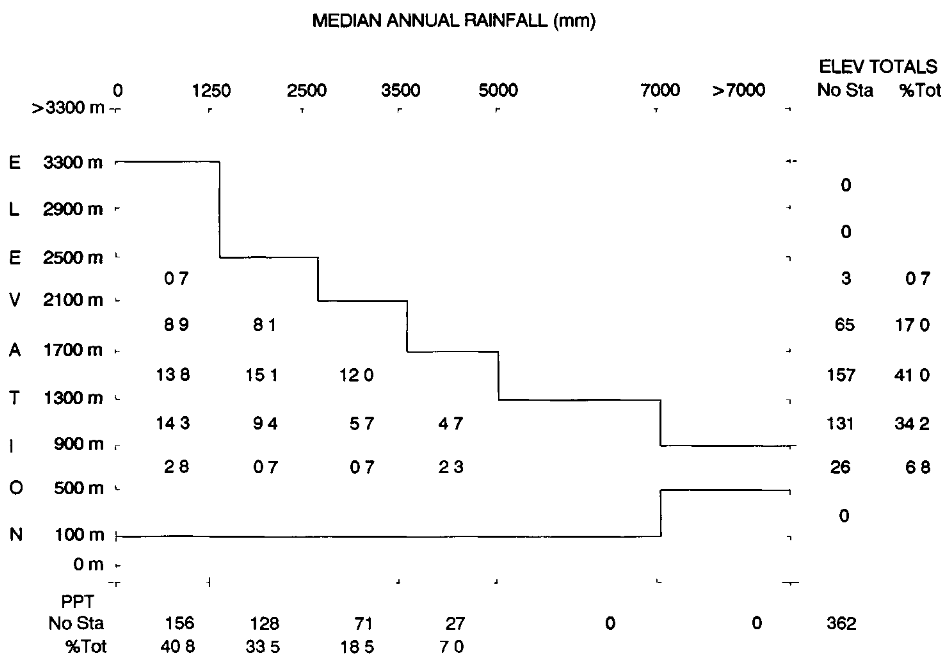

Figure 6. Plot of percent of total stations containing banana poka in elevation and rainfall classes for the Hawai'i Forest Bird Survey study areas on the island of Hawai'i.

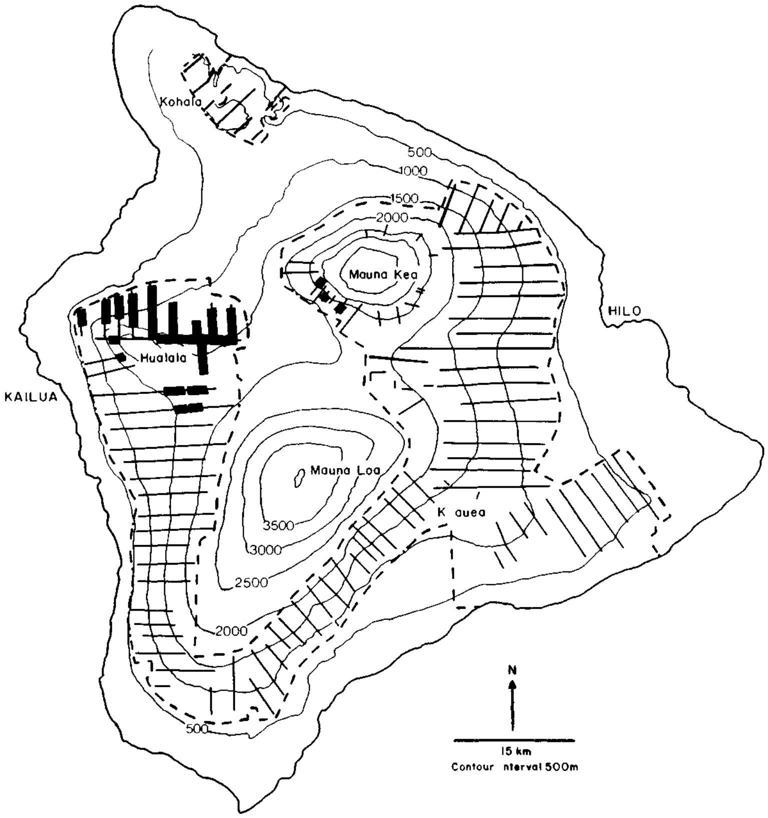

Figure 7. Occurrence of fountain grass during the Hawai'i Forest Bird Survey on the island of Hawai'i.

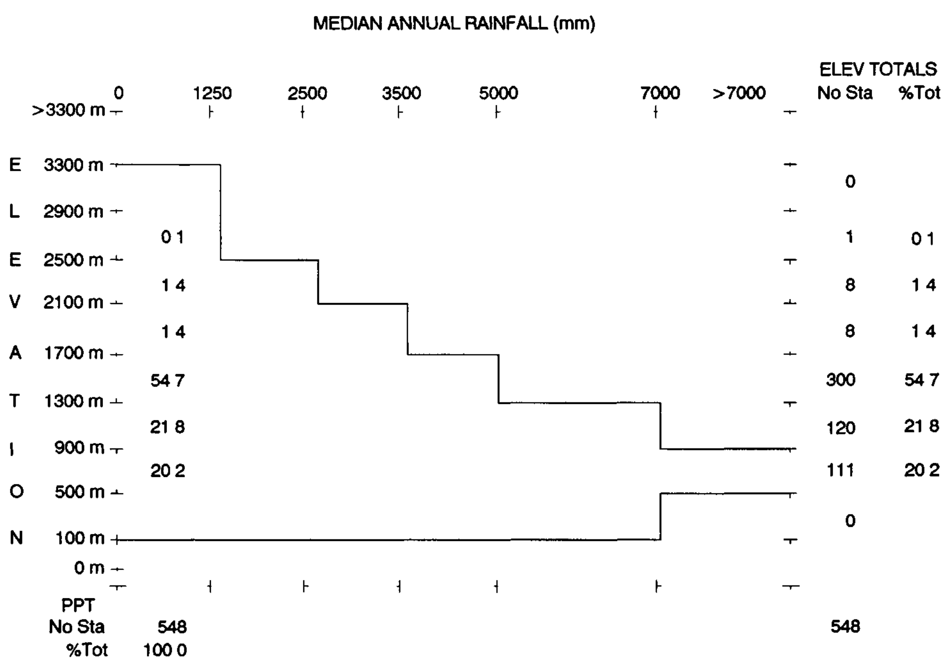

Figure 8. Plot of percent of total stations containing fountain grass in elevation and rainfall classes for the Hawai'i Forest Bird Survey study areas on the island of Hawai'i.

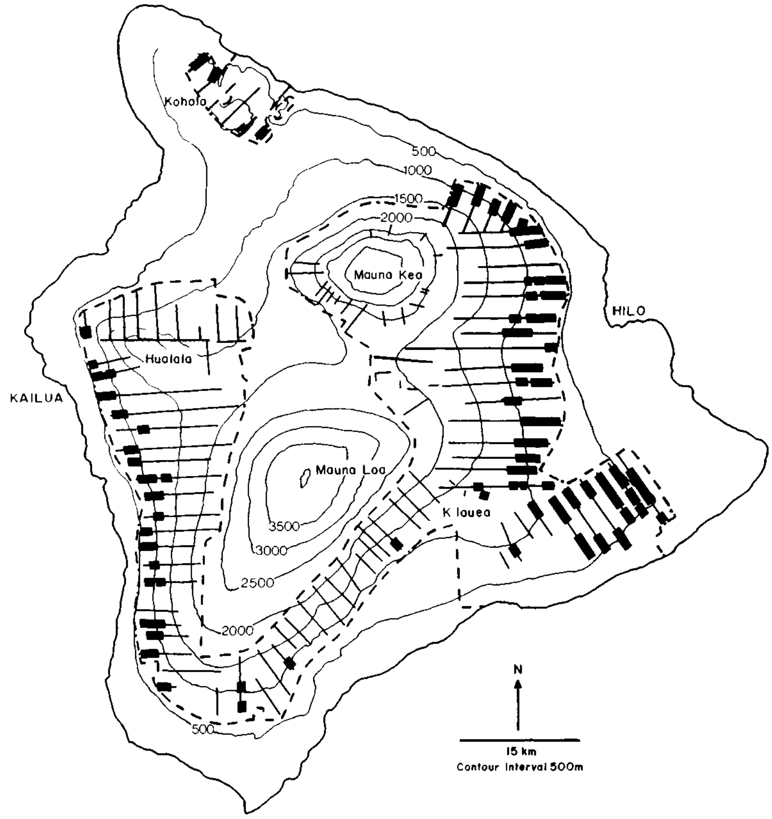

Figure 9. Occurrence of strawberry guava during the Hawai'i Forest Bird Survey on the island of Hawai'i.

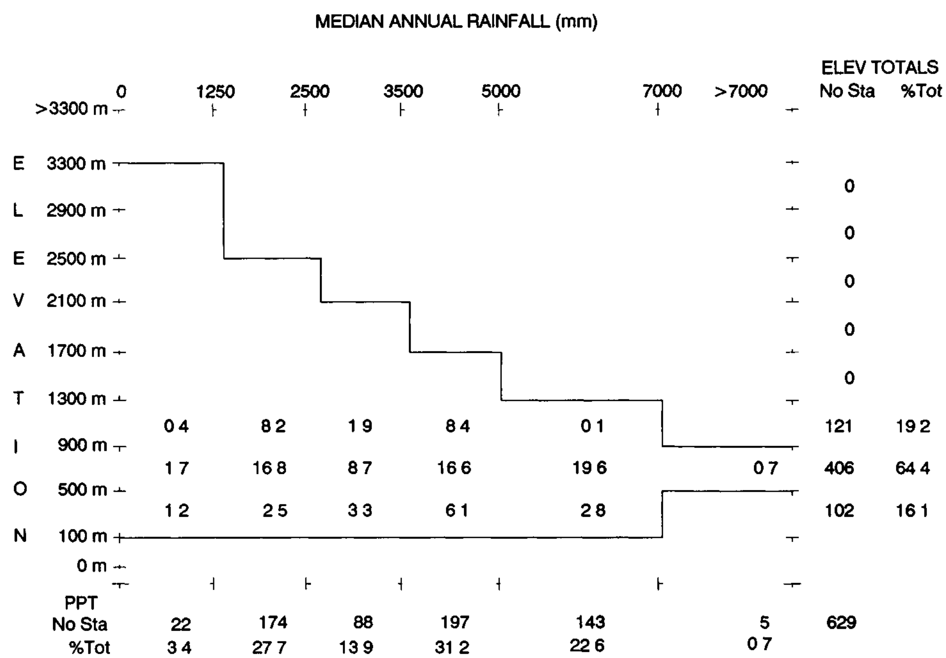

Figure 10. Plot of percent of total stations containing strawberry guava in elevation and rainfall classes for the Hawai'i Forest Bird Survey study areas on the island of Hawai'i.

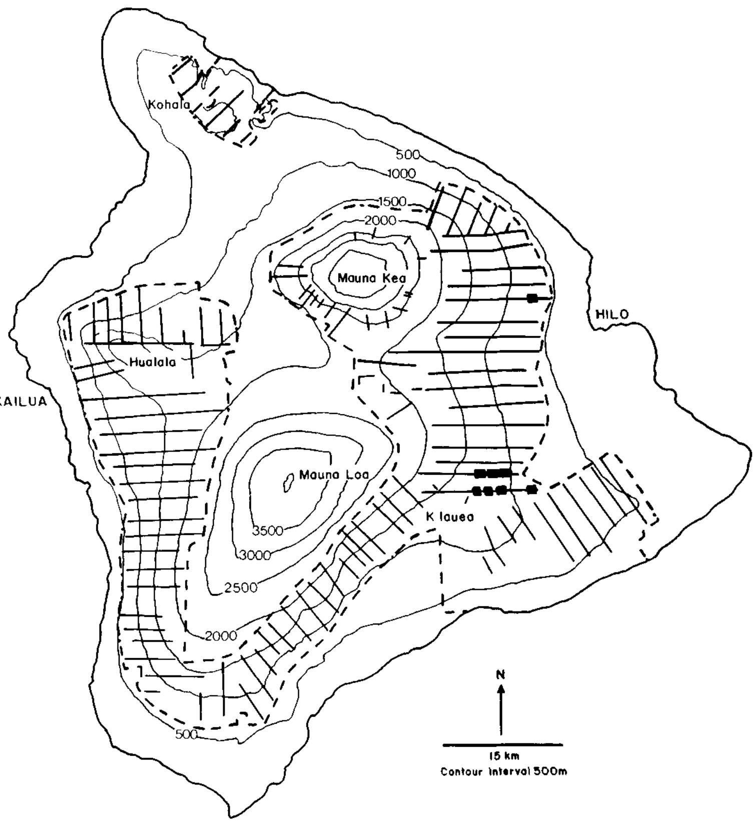

Figure 11. Occurrence of yellow Himalayan raspberry during the Hawai'i Forest Bird Survey on the island of Hawai'i.

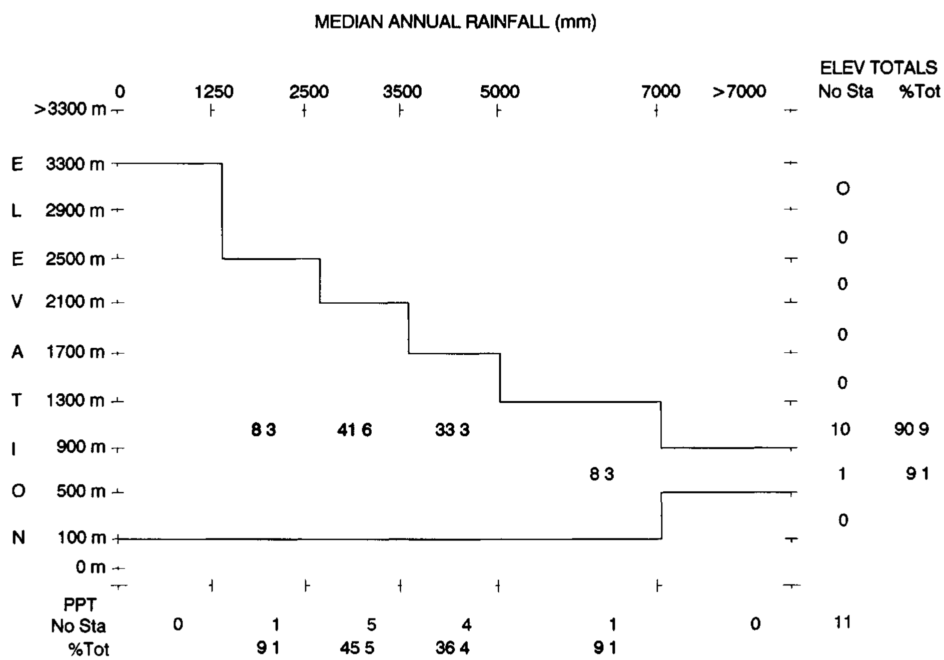

Figure 12. Plot of percent of total stations containing yellow Himalayan raspberry in elevation and rainfall classes for the Hawai'i Forest Bird Survey study areas on the island of Hawai'i.

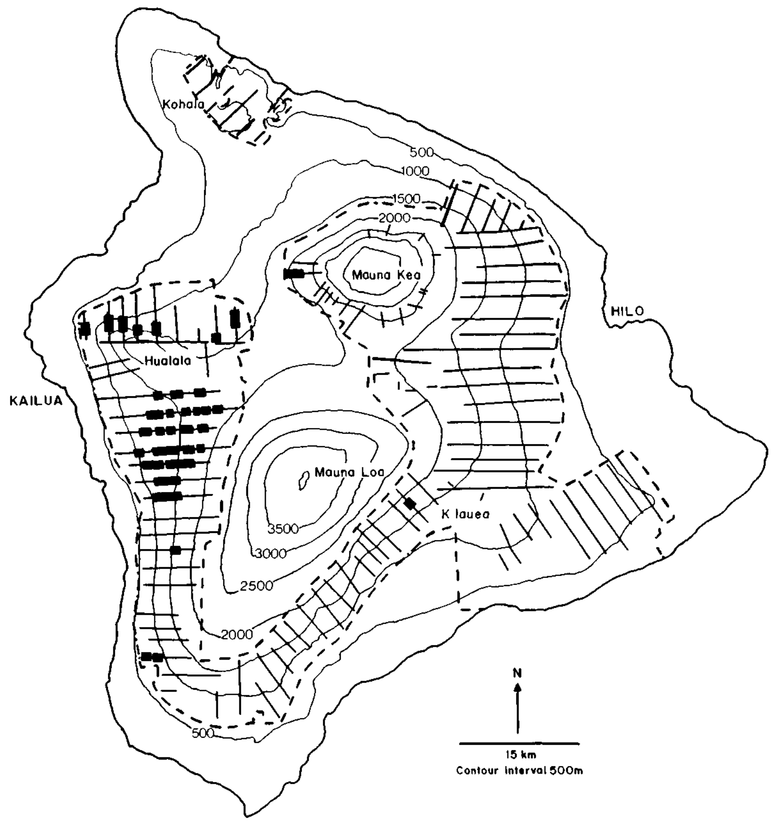

Figure 13. Occurrence of German ivy during the Hawai'i Forest Bird Survey on the island of Hawai'i.

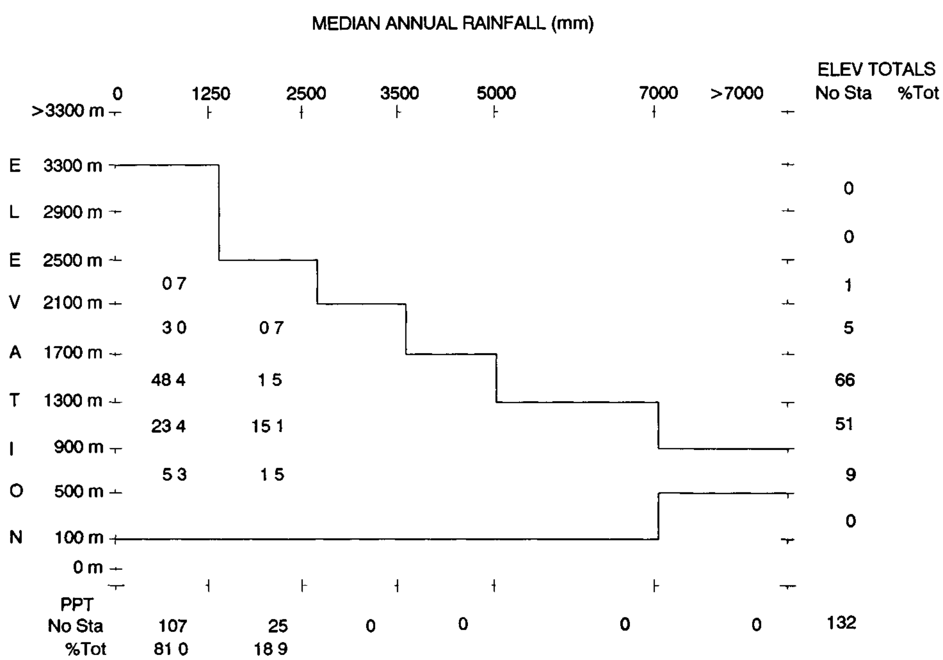

Figure 14. Plot of percent of total stations containing German ivy in elevation and rainfall classes for the Hawai'i Forest Bird Survey study areas on the island of Hawai'i.

remaining two species (banana poka and strawberry guava) were found in nearly all areas sampled (Figs. 5 and 9). Further separation in the distributions of these species is evident when elevation range, rainfall range, and vegetation types occupied are examined (Table 2; Appendix).

Malabar melastome was recorded at 65 stations, representing 0.8% of the total number sampled (Table 2). This species was found in two different areas below 2,950 ft (900 m) elevation on the eastern slopes of Mauna Kea, Mauna Loa, and Kīlauea volcanoes (Fig. 3). The majority of occurrences was in areas where the median annual rainfall is between 140 and 275 in. (3,500-7,000 mm), although it was also recorded at three stations just outside this range (Fig. 4). Malabar melastome was only found in wet habitats, ranging from open sedge-rush-native shrub communities, native koa (*Acacia koa*) and koa-ʻōhiʻa (*Metrosideros polymorpha*) forest, to highly disturbed communities dominated by many introduced plant species (Appendix). *Melastoma* was more common in wet ʻōhiʻa and ʻōhiʻa-koa forests than in the other six vegetation types occupied.

Banana poka was recorded at 382 stations, equivalent to 4.9% of the stations surveyed (Table 2). It was most abundant and widespread on the western side of the Island, concentrated on the slopes of Hualālai and Mauna Loa volcanoes (Fig. 5). Additionally, another relatively large population was found on the eastern flank of Mauna Kea, and a smaller one in the ʻŌlaʻa forest area northeast of Kīlauea Volcano. Two very small outlying populations were identified, one on the northern portion of the island in the Kohala region, and the other on the southwestern flank of Mauna Loa near Manukā State Park. Each of these outlying populations was characterized by a few immature plants recorded at a single station.

Banana poka was found between 1,640 and 8,200 ft (500-2,500 m) elevation, but most of the sightings were between 2,950 and 6,890 ft (900-2,100 m). Annual rainfall values for stations occupied by this species ranged from < 50 in. (<1,250 mm) to 200 in. (5,000 mm) (Fig. 6). The wide variation shown by banana poka with regard to both rainfall and elevation ranges is further reflected in the relatively large number of vegetation types (28) in which it was found (Appendix). Occupied vegetation units included dry native shrub communities, dry native forest, mesic forest and shrub units, to tall koa-ʻōhiʻa rain forest. Approximately 38% (147 stations) of the occurrences of banana poka were in the disturbed mesic koa-ʻōhiʻa forest type with native and alien shrub and grass understory. Other vegetation units with high incidence of this species were the less disturbed wet ʻōhiʻa forest and koa-ʻōhiʻa forest with tree fern (*Cibotium* spp.) and native shrub understory.

Fountain grass was found on the northern, eastern, and western slopes of Hualālai, and on the southwestern side of Mauna Kea (Fig. 7). The sampling grid did not cover other known populations on the southern flank of Kīlauea Volcano, in and adjacent to Hawaii Volcanoes National Park (Tunison, this volume). A total of 548 stations (7.0%) sampled was occupied by the species (Table 2). Fountain grass was found to have a relatively wide elevation range (1,640 to 9,515 ft or 500-2,900 m) but was limited to areas with median annual rainfall of less than 50 in. (1,250 mm) (Fig. 8). Only

Table 2. The six alien species, with a summary of elevation range, median annual rainfall range, and habitat types occupied for sightings made during the Hawai'i Forest Bird Survey (HFBS), station occurrence during the Survey for the island of Hawai'i, and predicted station occurrence in the Survey study area.

Species [Common Name]	Elevation Range (m)	Rainfall Range (mm)	Habitat Types Occupied	Station Occ. in HFBS (%)	Predicted Stations (%)
Melastoma candidum [Malabar melastome]	100 - 900	2,500 - >7,000	Hydric scrub and forest	65 (0.8)	1,071 (13.6)
Passiflora mollissima [banana poka]	500 - 2,500	<1,250 - 5,000	Xeric to mesic scrub and forest; hydric forest	382 (4.9)	6,899 (87.7)
Pennisetum setaceum [fountain grass]	500 - 2,900	<1,250	Xeric to mesic grassland, scrub, and open forest	548 (7.0)	2,861 (36.4)
Psidium cattleianum [strawberry guava]	100 - 1,300	<1,250 - >7,000	Mesic to hydric scrub and forest; xeric scrub and forest	629 (8.0)	3,934 (50.0)
Rubus ellipticus [yellow Himalayan raspberry]	500 - 1,300	1,250 - 7,000	Mesic to hydric forest	11 (0.1)	2,072 (26.3)
Senecio mikanioides [German ivy]	500 - 2,500	1,250 - 2,500	Xeric to mesic scrub and forest; hydric forest	132 (1.7)	4,991 (63.5)

dry and mesic habitats were colonized by this species (21 different vegetation types in all). The list includes grassland, shrub, and tree dominated communities (Appendix). Most of the records of fountain grass were from dry ʻōhiʻa forest (149 stations) and the alien grassland-shrub community with scattered native trees (114 stations).

Strawberry guava had the most widespread distribution of the six species discussed in this paper. A total of 629 stations (8.0% of all stations sampled) was occupied by this species (Table 2). Plants were found in the lower portions of all study areas on Hawaiʻi, with greatest concentrations on the eastern side of the Island (Fig. 9). Strawberry guava was found only below 4,265 ft (1,300 m) elevation but occupied stations in all rainfall classes (50-275 in. or <1,250->7,000 mm) sampled (Fig. 10). It was established in 23 different vegetation types ranging from dry grass and shrub communities to tall native rain forest (Appendix). The two vegetation units occupied most often were the wet ʻōhiʻa and tree fern forest (203 stations) and the wet koa-ʻōhiʻa and tree fern forest (159 stations).

Yellow Himalayan raspberry had the most limited distribution of the species analyzed. It was found at only 11 (0.1%) of the 7,864 stations sampled (Table 2), with the largest population concentrated in wet and mesic forest habitats immediately north of Kīlauea (Fig. 11). One additional sighting was made in the forest on the eastern slope of Mauna Kea, west of the city of Hilo. All but one of the stations with yellow Himalayan raspberry were in the 2,950 to 4,265 ft (900-1,300 m) elevation range, with rainfall distribution between 50 and 275 in. (1,250-7,000 mm) per year (Fig. 12). Plants were found in five different plant communities, including both mesic and hydric forest types (Appendix).

German ivy was found predominately on the western flanks of Mauna Kea and Mauna Loa, and on the northern and western slopes of Hualālai Volcano (Fig. 13). A single plant was also recorded on the eastern flank of Mauna Loa. This species occupied 132 (1.7%) of the Survey stations (Table 2). It was found only at stations with less than 100 in. (2,500 mm) of annual rainfall but encompassed an elevation range between 1,640 and 8,200 ft (500-2,500 m) (Fig. 14). German ivy was established in 19 different vegetation units ranging from dry shrub communities to rain forest (Appendix).

Predicted Potential Distribution

The predicted range model, based on median annual rainfall and elevation ranges, indicated a great potential for expansion of the geographical distribution of at least four of the six focal species if they continue to spread into areas with environmental conditions similar to habitats in which they were found during the Hawaiʻi Forest Bird Survey (Table 2). Banana poka showed the greatest potential range, with a predicted occupancy of 87.7% of the stations sampled (Table 2). The only major portions of the study area that this species does not appear to be able to invade are below 1,640 ft (500 m) elevation and where the median annual rainfall is greater than 200 in. (5,000 mm), both on the eastern side of the island. Additionally, banana poka has not become established above 8,200 ft (2,500 m) elevation, specifically in the upper portions of the Mauna Kea transects (Fig. 15).

A second species showing a large potential distribution is German ivy (Fig. 16). The model predicted that this species is capable of becoming established on 63.5% of the Hawai'i Forest Bird Survey stations (Table 2). The potential distribution map for German ivy suggests that all the sampled areas on the western and southwestern sides of the Island may be invaded, but only the upper portions of the eastern side are vulnerable. Based on the current environmental tolerance ranges of the species, high annual rainfall on the windward, eastern section of the Island could preclude the spread of German ivy into that area.

Strawberry guava is predicted to be able to occupy 50% of the stations sampled, limited primarily by elevation (Table 2; Fig. 17). Little difference between the distribution of this species on the map showing actual sightings during the Hawai'i Forest Bird Survey (Fig. 9) and the potential distribution map (Fig. 17) is evident. The relative evenness of its current distribution around the island of Hawai'i probably reflects the length of time it has been established there. If left uncontrolled, the major distributional change expected over time would be a filling-in of the area within the present geographical range of this species.

Fountain grass shows a relatively small potential distribution, primarily due to its observed restriction to dry habitats. Based on the predictive model, fountain grass has the potential to invade 36.4% of the Hawai'i Forest Bird Survey stations (Table 2), generally confined to the upper portions of the western side of the Island (Fig. 18). As mentioned earlier, however, the Survey did not sample a currently expanding population of this species on the southwestern flank of Kīlauea Volcano within Hawaii Volcanoes National Park and the adjacent Ka'ū and Puna districts.

Although the predictive model used data from only 11 stations for yellow Himalayan raspberry, this species appears to have a great potential for spread into most wet habitats at moderate to low elevations (26.3% of the stations sampled) on all portions of the island of Hawai'i (Table 2; Fig. 19). Other recent observations indicate yellow Himalayan raspberry has already invaded more dry habitats than those in which it was found during the Hawai'i Forest Bird Survey (J. Jacobi, unpub. data), suggesting the geographical distribution predicted from the Survey data set may be conservative.

The species that appears to be most limited in its potential spread is Malabar melastome (Fig. 20). The model suggests it could become established on just 13.6% of the total stations sampled (Table 2). The predicted range does not differ greatly from where the species was recorded during the Hawai'i Forest Bird Survey (Fig. 3), suggesting the current distributional area may just continue to fill in over time. Additional populations of the species appear to have the potential to become established on the lower southeastern flank on Mauna Loa and in the Kohala region.

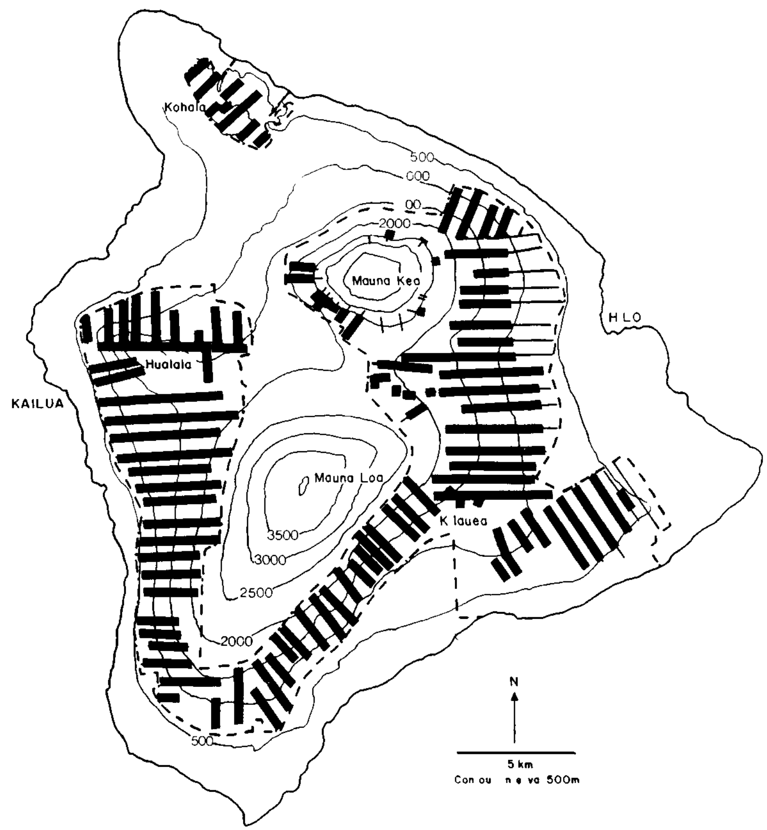

Figure 15. Predicted distribution of banana poka along the Hawai'i Forest Bird Survey transects on the island of Hawai'i, based on median annual rainfall and elevation of sites where the species was found in 1976-1981.

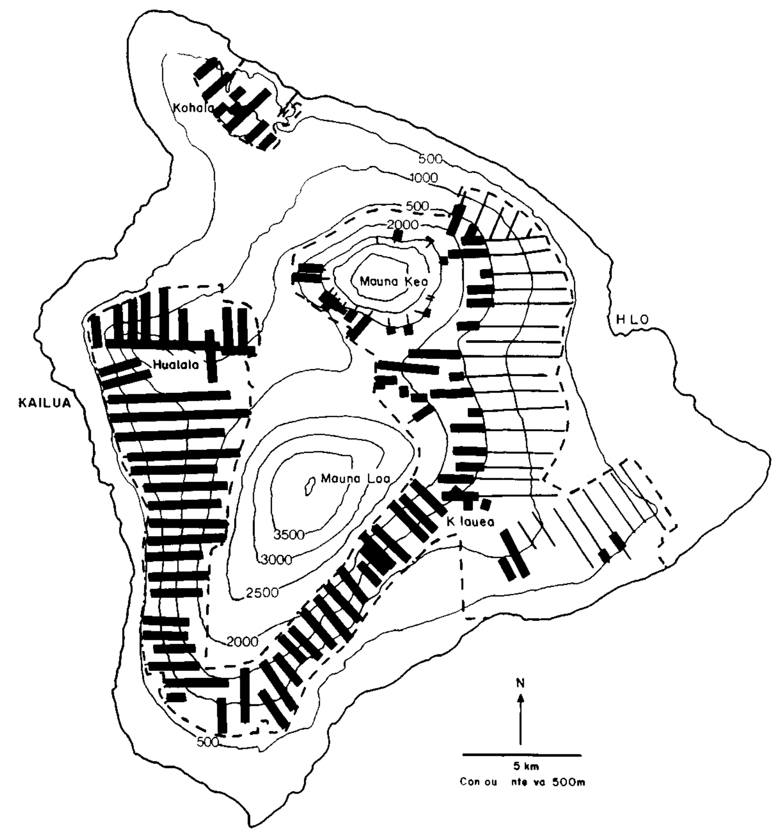

Figure 16. Predicted distribution of German ivy along the Hawai'i Forest Bird Survey transects on the island of Hawai'i, based on median annual rainfall and elevation of sites where the species was found in 1976-1981.

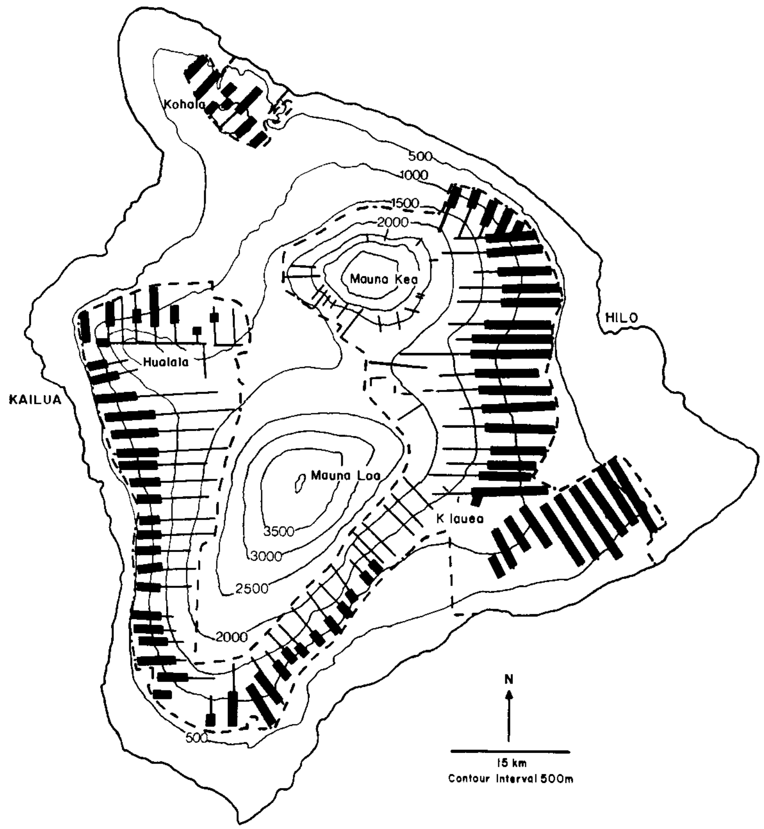

Figure 17. Predicted distribution of strawberry guava along the Hawai'i Forest Bird Survey transects on the island of Hawai'i, based on median annual rainfall and elevation of sites where the species was found in 1976-1981.

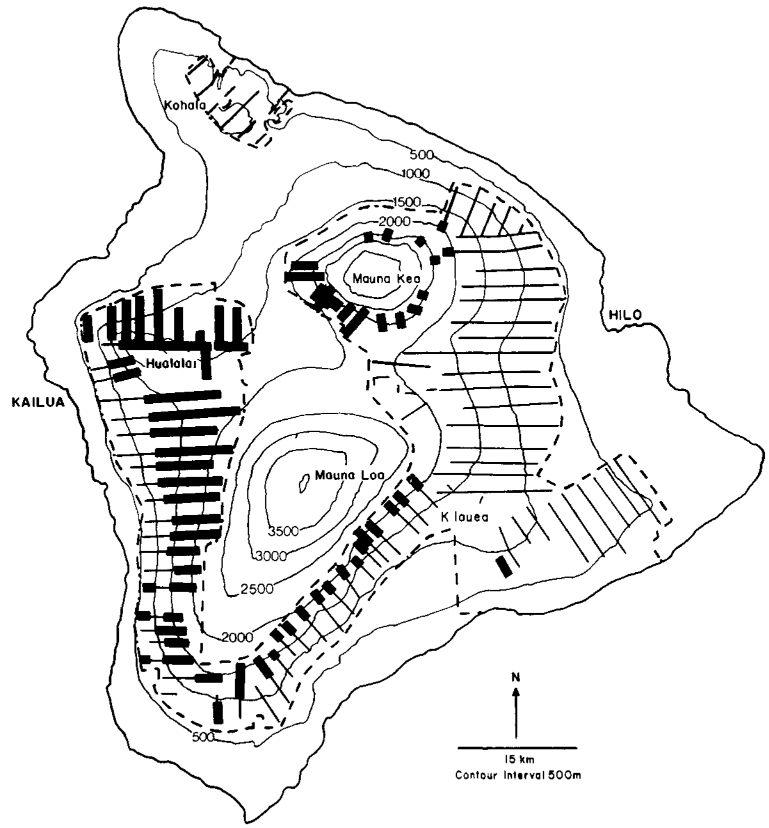

Figure 18. Predicted distribution of fountain grass along the Hawai'i Forest Bird Survey transects on the island of Hawai'i, based on median annual rainfall and elevation of sites where the species was found in 1976-1981.

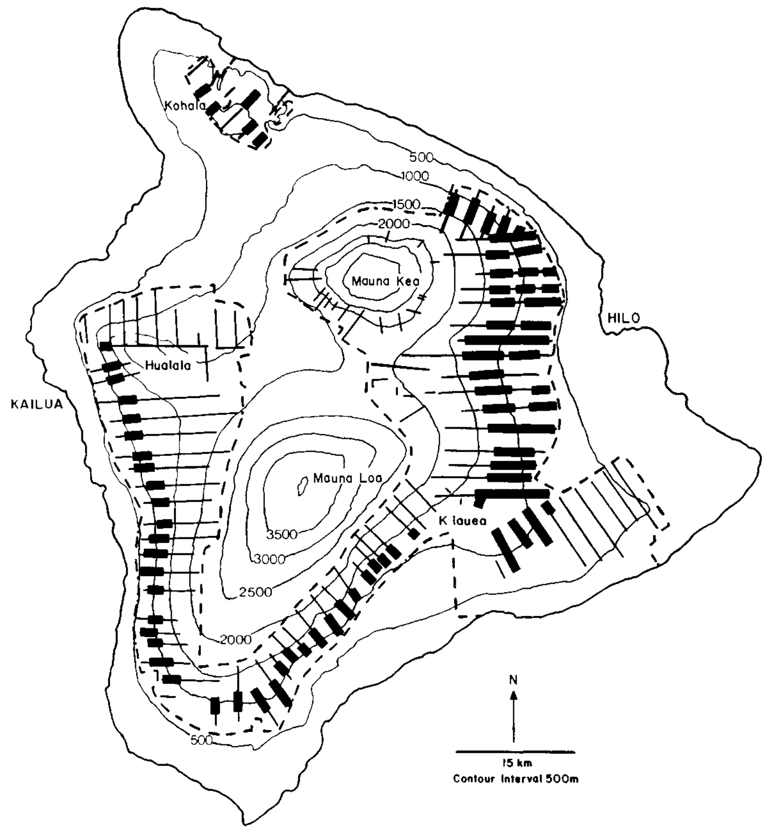

Figure 19. Predicted distribution of yellow Himalayan raspberry along the Hawai'i Forest Bird Survey transects on the island of Hawai'i, based on median annual rainfall and elevation of sites where the species was found in 1976-1981.

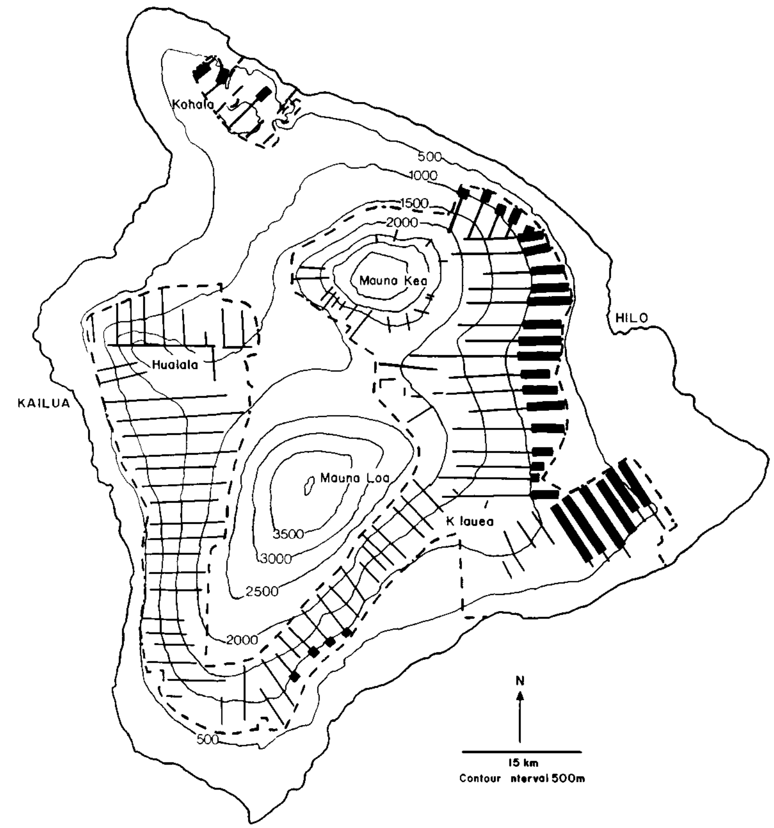

Figure 20. Predicted distribution of Malabar melastome along the Hawai'i Forest Bird Survey transects on the island of Hawai'i, based on median annual rainfall and elevation of sites where the species was found in 1976-1981.

DISCUSSION

Each of the six species examined shows a unique distributional pattern in terms of geographical areas, vegetation types, and habitat conditions (*i.e.*, median annual rainfall and elevation classes) occupied within the Hawai'i Forest Bird Survey study areas. The size of the area occupied (*i.e.*, number of stations) generally corresponds with the length of time a species has been established in the islands (Table 3). A noticeable exception is seen in the distribution of fountain grass, which was introduced at least by 1914 and was subsequently found on 548 stations during the Survey. The fact that this grass is easily dispersed by vehicles and the wind, and the considerable natural and unnatural disturbance in the habitats it occupies, may explain the large area it has invaded over such a relatively short period of time.

Table 3. Dates of introduction and number of stations occupied by the six alien species during the Hawai'i Forest Bird Survey, 1976-1981.

Species	Common Name	Date Introduced	No. stations Occupied
Psidium cattleianum	Strawberry guava	1825	629
Passiflora mollissima	Banana poka	1900	382
Senecio mikanioides	German ivy	1909	132
Melastoma candidum	Malabar melastome	1916	65
Pennisetum setaceum	Fountain grass	1914	548
Rubus ellipticus	Yellow Himalayan raspberry	1961	11

Combined Distributional Patterns

When the geographical ranges for all six species were plotted together (Fig. 21), the eastern and western sections of the Hawai'i Forest Bird Survey study areas were found to contain the broadest distribution of the six species. The ranges of two species (Malabar melastome and strawberry guava) overlapped on most of the lower eastern slopes of Mauna Kea, Mauna Loa, and Kīlauea volcanoes. In this area the alien species were generally confined to elevations below 3,280 ft (1,000 m). On the western side of the island, however, at least one of the six species was found throughout all areas sampled on Hualālai and up to 5,740 ft (1,750 m) on the eastern flank of Mauna Loa. The ranges of two of the species studied overlapped throughout a portion of this region, and three species were found to coexist in two smaller localities. The wide distribution of alien plants in this area was probably the result of a long history of disturbance to the native ecosystems by ranching and logging activities, and large populations of introduced ungulates.

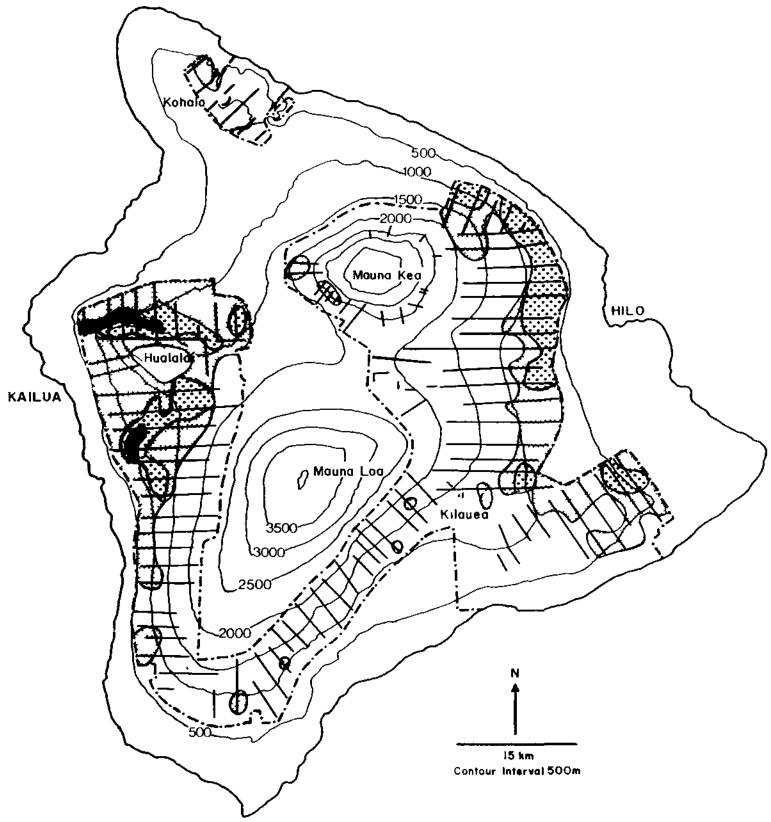

Figure 21. Overlap of the distributions of the six alien species within the Hawai'i Forest Bird Survey study areas on the island of Hawai'i, based on data collected during 1976-1981. Small dots = 1 species; large dots = 2 species overlap; black areas = 3 species overlap.

MEDIAN ANNUAL RAINFALL (mm)

ELEVATION	0–1250	1250–2500	2500–3500	3500–5000	5000–7000	7000–>7000
>3300 m						
2900–3300 m						
2500–2900 m	3					
2100–2500 m	2,3,6					
1700–2100 m	2,3,6	2,6				
1300–1700 m	2,3,6	2,6	2			
900–1300 m	2,3,4,6	2,4,5,6	2,4,5	2,4,5	4	
500–900 m	2,3,4,6	2,4,6	1,2,4	1,2,4	1,4,5	1,4
100–500 m	4	4	4	1,4	1,4	
0–100 m						

Figure 22. Summary of species recorded within each rainfall-elevation cell. 1 = Malabar melastome, 2 = banana poka, 3 = fountain grass, 4 = strawberry guava, 5 = yellow Himalayan raspberry, 6 = German ivy.

Most of the rainfall and elevation cells sampled were occupied by at least one of the alien plants (Fig. 22). Two habitat zones consistently invaded by three or more species were relatively dry sites (median annual rainfall <50 in. or <1,250 mm) between 1,640 and 8,200 ft (500-2,500 m) elevation), and low-elevation areas (1,640-4,265 ft or 500-1,300 m) with annual rainfall between <50 and 275 in. (<1,200-7,000 mm) (Fig. 22). The small number of alien species found established below 1,640 ft (500 m) in this study was probably a function of both the small sample size in this elevation band (188 stations) and the restricted number of species examined. Other studies have shown that low-elevation habitats in Hawai'i generally contain the greatest concentration of established alien plant species (Smith 1985).

Of the 64 plant communities sampled on the island of Hawai'i during the Hawai'i Forest Bird Survey, 46 were found to contain one or more of the six alien plant species (Appendix). The vegetation types invaded ranged from closed forest to treeless communities in dry, mesic, and wet habitats. Portions of the two largest communities, 'ōhi'a rain forest and koa-'ōhi'a rain forest, had been colonized by five of the six species analyzed.

Management Considerations

Developing an effective management program to restrict the spread and impacts of introduced species in native ecosystems requires an integrated approach. Mapping the current and potential range of the invading species should be an initial step in such a program. Information on distributional areas, species abundance, habitat requirements, and vegetation units currently occupied should be gathered as systematically as possible. However, care must be taken not to use so much time or other resources in this step that the invading population is allowed to expand significantly before actual control measures are initiated.

The analysis of current and potential ranges of the species discussed in this paper does not address population size or density. There is no doubt that different habitats will ultimately support different abundance levels of a particular species. Although the greatest direct effects on an ecosystem result from high abundance of the invading species, areas with low abundance in non-optimal habitats may serve as dispersal corridors for spread of the species into adjacent, more optimal areas. Management programs to reduce the overall effects of alien species must also focus control efforts on the smaller, and often discontinuous, populations in either an early stage of invasion or in sub-optimal habitats, to minimize their potential role in expansion of the distribution of a species. Warshauer *et al.* (1983) discussed the significance of such low-abundance areas in the continuing spread of banana poka on the island of Hawai'i. Mack (this volume) further stresses the importance of directing control efforts to small outlying populations of an invading species that have the greatest potential for rapid expansion in both range and abundance.

Finally, and most importantly, major emphasis should be placed on maintaining the natural structural and compositional integrity of the native ecosystems as a preventive measure to reduce the possibility of establishment of new alien plants in these communities. The relationship between animal damage and alien plant invasion has been frequently documented in the literature (*e.g.*, Harper 1965; Warshauer *et al.* 1983; Stone 1985). Hawaiian ecosystems with minimal animal or human disturbance appear to be most resistant to colonization by noxious introduced plants (Mueller-Dombois *et al.* 1981).

Outlook for Control

Most of the species discussed in this paper appear to be beyond the feasibility of mechanical or chemical control in areas where they have already become well established. This is especially true with fountain grass and German ivy on the western side of the island of Hawai'i, and with banana poka, Malabar melastome, and strawberry guava elsewhere. Yellow Himalayan raspberry is still in an early stage of invasion into wet and mesic habitats on the island. However, the rapid increase seen in its distribution in the Kīlauea region (J. Jacobi, unpub. data; T. Tunison, pers. comm.), even since the Hawai'i Forest Bird Survey, suggests mechanical control may already not be possible except in small areas managed intensively (Tunison and Stone, this volume).

The best potential for broad-scale control of species, such as those that are already well established, lies with the development of a successful biological control program. However, active steps can be taken to reduce the establishment of these species into new geographical areas. The potential range maps presented here may be useful in developing a surveillance program to watch for new infestations of these species. If small, localized infestations are detected early, conventional mechanical or chemical control techniques may be effective in eliminating a new population before it becomes well established. Specifically, the isolated patches of banana poka in the Kohala and Manukā regions, and German ivy on the southeastern flank of Mauna Loa, should be surveyed in greater detail and conventional control methods applied before they spread any further. Similarly, any new populations of yellow Himalayan raspberry outside its current range should be eliminated as quickly as possible.

The potential for range expansion of banana poka, German ivy, fountain grass, strawberry guava, and yellow Himalayan raspberry on the island of Hawai'i should be reason for great concern. Malabar melastome, on the other hand, appears to have the least potential for a significant increase in its distribution on the island of Hawai'i. Although additional information on the habitat requirements of these species may allow further refinement of their predicted ranges, we believe that the general picture of the possible expansion of the areas affected is not exaggerated.

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APPENDIX. List of vegetation types in which each of the focal species was found for stations sampled on the island of Hawai‘i during the Hawai‘i Forest Bird Survey.

VEGETATION TYPE	TOTAL NUMBER OF STATIONS	NUMBER OF STATIONS OCCUPIED (% OF STATIONS FOR VEG. TYPE) M.c.[1]	P.m.	P.s.	P.c.	R.e.	S.m.
XERIC HABITAT							
Dry alien grassland with scattered koa[2], māmane[3] and other native trees.	79						3 (4)
Dry alien grassland with scattered koa, ‘ōhi‘a[4] and other native trees.	45		8 (18)	3 (7)	5 (11)		
Dry alien grassland with scattered koa and other native trees.	13		1 (8)				
Dry alien grassland with scattered māmane trees.	22			4 (18)			
Dry alien grassland with scattered native and alien trees.	14		1 (7)	12 (86)			
Dry alien grassland with some native shrubs, scattered ‘ōhi‘a and other native trees.	164		7 (4)	114 (70)	3 (2)		1 (1)
Dry alien grassland with native and alien shrubs and scattered native trees.	64		6 (9)	62 (97)			10 (16)
Dry mixed grass-native shrub community with scattered māmane trees.	77		12 (16)	2 (3)			

VEGETATION TYPE	TOTAL NUMBER OF STATIONS	NUMBER OF STATIONS OCCUPIED (% OF STATIONS FOR VEG. TYPE) M.c.[1]	P.m.	P.s.	P.c.	R.e.	S.m.
Dry mixed grass-native shrub community with scattered māmane and naio[5] trees.	22			(5)	1		
Dry native shrub with mixed grass community.	17		4 (24)				
Dry native shrub community with scattered ʻōhiʻa and other native trees.	323		4 (1)	26 (8)			1 (<1)
Dry alien tree community with a native shrub and mixed grass understory.	1		1 (100)				
Dry koa community with mixed native trees and a native shrub-alien grass and shrub understory.	16		1 (6)				
Dry koa-māmane community with an alien grass and scattered native shrub understory.	164						12 (8)
Dry koa-ʻōhiʻa community with a native shrub-alien grass understory.	3		3 (100)	2 (67)			3 (100)
Dry māmane-mixed native trees community with an alien grass-native shrub understory.	115		8 (7)	9 (8)			2 (2)

APPENDIX, continued.

APPENDIX, continued.

VEGETATION TYPE	TOTAL NUMBER OF STATIONS	NUMBER OF STATIONS OCCUPIED (% OF STATIONS FOR VEG. TYPE) M.c.[1]	P.m.	P.s.	P.c.	R.e.	S.m.
Dry māmane-naio scrub forest with a mixed grass and native shrub understory.	122			5 (4)			1 (1)
Dry mixed native tree community with an alien grass and native and alien shrub understory.	31			31 (100)			
Dry naio scrub forest with scattered māmane and an alien grass and native shrub understory.	22			2 (9)			2 (9)
Dry naio scrub forest with other native trees and native shrub-alien grass understory.	26		1 (4)	25 (96)			3 (11)
Dry ʻōhiʻa forest with mixed native trees and a native shrub and mixed grass understory.	726		10 (14)	149 (21)			16 (2)
Dry ʻōhiʻa forest with mixed native trees and a native shrub-alien grass-shrub understory.	161		9 (6)	76 (47)	1 (1)		1 (1)
MESIC HABITAT							
Mesic alien grassland with scattered koa, ʻōhiʻa and other native trees.	120		4 (3)		1 (1)		3 (3)

VEGETATION TYPE	TOTAL NUMBER OF STATIONS	NUMBER OF STATIONS OCCUPIED (% OF STATIONS FOR VEG. TYPE) M.c.[1]	P.m.	P.s.	P.c.	R.e.	S.m.
Mesic alien grass and native shrub community with scattered ʻōhiʻa and other native trees.	70		1 (1)	14 (20)	4 (6)		
Mesic alien shrub community with scattered ʻōhiʻa and alien trees.	3		2 (67)	1 (33)			
Mesic alien tree community with some native trees and native and alien grass-shrub understory.	84		12 (14)	3 (4)	18 (21)		
Mesic koa-māmane forest with other native trees and an alien grass, native shrub understory.	12		6 (50)				
Mesic koa-ʻōhiʻa forest with other native trees and a native-alien shrub and grass understory.	685		147 (22)	4 (1)	9 (1)		13 (2)
Mesic koa-ʻōhiʻa forest with other native trees and a native fern and shrub understory.	134		16 (12)		1 (1)		9 (7)
Mesic māmane-naio-alien tree community with an alien grass understory.	1		1 (100)				

APPENDIX, continued.

VEGETATION TYPE	TOTAL NUMBER OF STATIONS	NUMBER OF STATIONS OCCUPIED (% OF STATIONS FOR VEG. TYPE) M.c.[1]	P.m.	P.s.	P.c.	R.e.	S.m.
Mesic native tree community with scattered alien trees and alien grass-shrub understory.	3		3 (100)				
Mesic 'ōhi'a forest with other native trees and native shrub-alien grass and shrub understory.	259		13 (5)	65 (25)	3 (1)	27 (10)	
Mesic 'ōhi'a forest with other native trees and a native shrub, matted-fern understory.	244			3 (1)	12 (5)		1 (<1)
HYDRIC HABITAT							
Wet matted-fern, mixed sedge-rush-native shrub community with scattered koa and 'ōhi'a trees.	14	2 (14)			2 (14)		
Wet matted-fern and/or native shrub community with scattered 'ōhi'a and other native trees.	143				6 (4)		
Wet native-alien shrub community with scattered 'ōhi'a and other native trees.	4				4 (100)		
Wet tree fern and native shrub community with scattered 'ōhi'a and other native trees.	186		9 (5)		15 (8)	4 (2)	

VEGETATION TYPE	TOTAL NUMBER OF STATIONS	NUMBER OF STATIONS OCCUPIED (% OF STATIONS FOR VEG. TYPE) M.c.[1]	P.m.	P.s.	P.c.	R.e.	S.m.	
Wet alien tree plantation with some native trees and an alien shrub understory.	37	2 (5)			12 (32)			
Wet alien tree, ʻōhiʻa forest with a matted-fern and native shrub understory.	75				21 (28)			
Wet koa-ʻōhiʻa forest with other native trees and an alien and native shrub understory.	35	19 (54)			29 (83)			
Wet koa-ʻōhiʻa forest with other native trees and a native shrub, matted-fern and tree fern understory.	106	5 (5)			24 (23)			
Wet koa-ʻōhiʻa forest with other native trees and a tree fern, native shrub understory.		21 720	50 (3)	(7)	159	1 (22)	23 (<1)	(3)
Wet pioneer ʻōhiʻa forest with a matted-fern and native shrub understory.	70				7 (10)			
Wet ʻōhiʻa forest with native shrubs/matted-fern and some tree ferns in the understory.		1 177	(1)		21	(12)		
Wet ʻōhiʻa forest with other native trees and a native shrub-alien grass and shrub understory.	61				7 (12)	1 (2)		

APPENDIX, continued.

APPENDIX, continued.

VEGETATION TYPE	TOTAL NUMBER OF STATIONS	NUMBER OF STATIONS OCCUPIED (% OF STATIONS FOR VEG. TYPE) M.c.[1]	P.m.	P.s.	P.c.	R.e.	S.m.
Wet ʻōhiʻa forest with other native trees and a tree fern and native shrub understory.	1871	15 (1)	42 (2)		203 (11)	2 (<1)	1 (<1)
NUMBER OF STATIONS OCCUPIED:		65	382	548	629	11	132
VEGETATION TYPES OCCUPIED:		7	28	21	23	5	19

[1] M.c. = *Melastoma candidum*; P.m. = *Passiflora mollissima*; P.s. = *Pennisetum setaceum*; P.c. = *Psidium cattleianum*; R.e. = *Rubus ellipticus*; S.m. = *Senecio mikanioides*

[2] *Acacia koa*

[3] *Sophora chrysophylla*

[4] *Metrosideros polymorpha*

[5] *Myoporum sandwicense*

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