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MULLEIN SURVEY AND REMOVAL EFFORTS ON MAUNA LOA IN HAWAI'I VOLCANOES NATIONAL PARK

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ABSTRACT

Common mullein (*Verbascum thapsus* L.) is a biennial herb naturalized in mostly temperate areas on the Island of Hawai'i. Mullein was first observed growing on Mauna Loa in Hawai'i Volcanoes National Park in the 1970's. Localized efforts to eradicate mullein along roadsides in the Park began in 1989. This report documents monitoring and control efforts of mullein in the Park between 1994-1999. Mullein occupies 1,003 hectares of open lava flows located between 1,500 and 2,100 m elevation in the Park. Range expansion is expected to continue at both lower and higher elevations. Densities and recruitment are highest (>1,400 ind/ha) on weathered 'a'ä flows that edge vegetated kïpukas. Lowest densities (<1 ind/ha) and recruitment occur on open 'a'ä with little or no soil development. Recruitment of new individuals is highly variably between years and is likely influenced by fluctuations in seasonal rainfall. Manual uprooting mullein effectively reduces populations by the third or fourth year of annual removal treatments. Successful control requires consistent and thorough follow-up treatment. Workloads vary between 5-10 ha/worker days in moderate to low density infested areas. An estimated 200 worker days will be required annually to remove mullein from existing populations, other than the most densely infested areas in the Park. Based on these findings, management should emphasize containment and range reduction of the current distribution. Cooperative agreements with private and state landowners should be made to control mullein in areas adjacent to the Park in order to reduce re-invasion from outside areas into the Park. Use of herbicides and biological'control agents as alternatives to uprooting mullein should be investigated. Long term studies of the impact of mullein on native plant communities will help managers prioritize mullein control efforts in the Park.

INTRODUCTION

Common mullein (*Verbascum* ***thapsus*** L.) is a biennial herb naturalized in primarily temperate areas on the Island of Hawai'i (Juvik and Juvik 1992). Native to Eurasia, it was introduced to Hawai'i in the early 1900's. Large populations are currently established on the slopes and saddle area between Hualalai, Mauna Loa and Mauna Kea Volcanoes between 1,600 m and 3,300 m elevation. Small incipient populations occur along roadsides at lower elevations on the dry leeward side of the island in Ocean View Estates in South Kona and near Kona Airport (Juvik pers. obs., Ansari pers. obs.). Mullein had been sold as a garden plant on Maui. This practice was discontinued when it was discovered and stopped **by** concerned Maui citizens (Medeiros pers. comm.). Occasional plants have been extirpated on Haleakala (Nagata pers. comm.).

Successful establishment is partly due to prolific seed production (approx. 150,000 seeds per individual), and extended seed longevity (Manning 1965). Herbarium-stored seeds retain viability up to 90 years or more (Kivilaan and Bandurski 1933). Seed fall occurs largely within 7 m of the parent plant (Gross and Werner 1978). Long-distance dispersal is dependent on foraging birds, mammals, humans and vehicles. Mullein does not establish where herbaceous groundcover is dense. However, on young lava flows where soils are poorly developed or recently disturbed soils where native plant abundance is sparse, mullein densities can reach up to 200 individuals/ 100 m^2. Mullein achieves serious pest status at this high density (Smith 1985, Juvik and Juvik 1992).

In Hawai'i Volcanoes National Park (HAVO), mullein is found primarily on 'a'ä flows between 1,520 m and 2,140 m elevation on Mauna Loa. Individuals were first sighted growing along roadsides on 'a'ä flows at 1,830 m elevation in the 1970's (Pratt ***pers. obs.).*** Seed dispersal into the Park was attributed to vehicular and human transport, and wind or bird dispersal from nearby populations occurring upland and adjacent to the Park. Park hunters have reported that wild turkeys will waddle up the stalks, knocking them over, and proceed to forage on the reproductive parts (Mattos ***pers.*** *obs.*). Based on its distribution along elevation and rainfall gradients on Mauna Kea on the Big Island, mullein has the potential to expand its range substantially in HAVO (Figure 1).

Localized efforts to eradicate mullein along roadsides in the Park began in 1989. These efforts were sporadic-and confined to the Keamoku Lava Flows surrounding Ki'puka Kulalio, where most mullein populations were thought to exist (Figure 2). Plants were manually uprooted, and recalcitrant individuals were treated with a 2% solution of Round-Up. Approximately 5-10 worker days were spent removing 1500-2000 individuals annually between 1989 and 1993. In 1992 and 1993, ground surveys conducted along pre-established transects showed that the extent of mullein was much greater than was previously thought.

Beginning in 1994, monitoring and control of mullein was intensified to achieve the following objectives:

1. Determine the current distribution of mullein in the Park
2. Prevent the spread of mullein to new areas
3. Assess the effectiveness of control treatments on population levels

4. Quantify the work load needed to contain and eradicate mullein from the Park
5. Initiate protocols to monitor growth and impact of mullein on native plant communities

The information was used to determine the feasibility of containing and removing mullein throughout the Park. Successful eradication of alien species by resources managers have been largely confined to localized species in the Park. Fountain grass (*Pennisetum setaceum* (Forssk.) Chiov.) is the only widespread alien plant to be managed throughout HAVO (Tunison 1994). This report documents the population distribution, treatment effectiveness and workloads required to control mullein. Several strategies for control are formulated based on these findings.

METHODS

Distribution in the Park

Surveys were conducted to map the distribution of mullein in the Park beginning in spring 1996. Intensive ground and aerial surveys were limited to lava fields and the communities immediately adjacent to them between 1,220 m and 2,440 m elevation on Mauna Loa. Survey areas were divided into 77 map units (Figure 3). The upper and lower boundaries of each map unit were defined by 11 transects that were established in 1985 to survey feral goat activity. These transects were placed at 200-500 m intervals and began at the Park's southwest boundary fence line and were run at a 34 degree true north bearing to the northeast boundary fenceline. The east and west boundaries of each map unit were defined by physical features including changes in substrates, edges of plant communities, and park boundaries. Sometimes boundaries were arbitrary to make map units more manageable. Information on mullein in other areas of the Park was obtained through personal communications by Park employees who conduct localized survey and eradication of other weed species along roadsides and in more remote areas of the Park.

In spring **1996,** one biological technician and two volunteer biologists surveyed on foot 72 of 77 map units that spanned 1,286 hectares of potential mullein range in HAVO. These ground surveys were conducted by walking each map unit, searching, and counting the number of mullein individuals. Plants were uprooted in most units that contained mullein. Where populations were extremely dense (>1000 individuals/ha) individuals were left untouched. In 1999, two additional map units were ground surveyed (units 19aa and 20aa). Aerial surveys, conducted by personnel using low flying helicopter, were conducted over remaining map units 13h, 14f, 15f, and an additional 1,700 hectares of open lava fields located upslope of the map units and extended to **2,440** m elevation.

The final distribution map of mullein was made by first drawing the map units on to 1:24,000 orthophotoquad map. The number of individuals found in each unit was recorded on the map and color codes were assigned to each density class. Density categories were 0, ≤1, 1.1-10, 10.1-100, 100.1-1000, and >1000 individuals per hectare. Individuals found outside the map units were mapped as discrete populations.

Population growth and phenology

Between 1997-1999, growth and recruitment of mullein were measured in four 50 x 50 m plots located in two sites (Figure 3). Site 1 (elevation ca. 1,700 m) was located along the eastern edge of Kipuka Maunaiu on an 'a'ä flow where mullein populations were typically dense (>1,000 ind/ha). Site 2 (elevation ca. 1,680 m) was located on an open 'a' a field where mullein populations were sparse (<10 individuals/ha). In each site, two 50 x 50 m^2 plots were established. Rosette diameter at widest point, stalk height (if present), and length of inflorescence were recorded for each individual. Stalk lengths were summed if more than one stalk was present on an individual. In one of each paired plots, individuals were tagged and their survivorship and growth monitored annually. In the second of each paired plots, all individuals were uprooted. Follow-up censuses were taken in both plots annually. New arrivals were tagged and their stalk length, rosette diameter, and phenology recorded. A chi-square test was conducted to analyze differences in recruitment, mortatity and reproduction between sites and treatments.

Seed production in the 50 x 50 m^2 plots was estimated by collecting 12 fruiting stalks, determining the average number of capsules occupying a randomly chosen *5* cm segment of the stalk, and finding the average number of seeds per capsule. To determine seed dispersal into the plots a 15 x 15 cm^2 board coated with Tanglefoot sticky glue was placed in the center of five randomly selected 10 x 10 m^2 subplots, and the number of mullein seeds stuck to each trap were counted. Traps were replaced at 3-month intervals beginning in October 1998.

In 1997, frequency and cover of all plant species, and density of all woody species in each 50 x 50 m^2 plot were recorded to provide a baseline description of the native plant communities invaded by mullein and the effect removal or non-removal will have on subsequent plant composition. Presence/absence of all species in the entire plot was recorded. Cover was measured along four, 50-m transects that were established at 10 m intervals beginning 10 m from the plot origin (southwest corner). Cover was determined using the point line-intercept method (USDI National Park Service 1992). A ¼ inch diameter, 2-m-long pole was placed at 50 cm intervals along each transect and all species intercepting the pole were recorded. Density of native woody species was counted in 25, 10x10 m^2 subplots. Individuals were grouped into the following height classes: <10 cm, 10.1-50 cm, 50.1-100 cm, 1.01m-1.5 m, 1.51m-2.0 m, 2.01-3 m, 3.01-4 m, 4.01-5m etc. Diameter at breast height (DBH) was recorded for all individuals $\geq$ 1.5 m height.

Control effectiveness

Mullein was treated by uprooting plants. Individuals and seeds were left where they were pulled. Treatment effectiveness was determined by tallying the individuals removed from three experimental plots (50 x 25 m^2, 50 x 100 m^2, 25 x 20 m^2) located in Site 3, (Figure 3), and tracking the number, size and phenology of plants found at successive treatments. Immature plants found during follow-up treatments were presumed to be germinants derived from the existing seed bank. Plants with reproductive stalks were considered to be overlooked plants. Plots were established and initial removal conducted in 1994. Follow-up treatments were conducted in 1995 and 1996.

Additional data on treatment effectiveness were obtained from evaluating initial removal efforts, and follow-up treatments conducted in large map units. Mullein was uprooted from units during surveys conducted in 1996. Re-treatment was conducted at yearly intervals in units 16b and 18b between 1997-1999. Re-treatment of units 13a-17a and 13b were conducted in 1997, but discontinued in 1998. Re-treatment in units 6a-12a, and 9b-12b were conducted in 1998 and 1999.

Workload requirements

The time required to systematically search and uproot mullein once in **all** infested areas was determined by recording the number of days spent in treating infested units and conducting aerial surveys. Workloads are based on the number of worker-days required to survey and treat mullein, and the number of years that treatment is required.

RESULTS

Distribution of mullein in the Park

Mullein infests 1,002 hectares in the Park (Figure **4).** Moderate densities of 10-100 individuals/ha are commonly found on 'a'ä flows edging kïpukas located between 1,500 and 2,100 m elevation. The native vegetation is sparse (<10 % cover) in these areas, and composed of predominantly low-stature native shrubs, 'a'ali'i (*Dodonaea viscosa* Jacq.), pukiawe (*Styphelia tameiameiae* **(Cham.** & Schlectend.) F. v. Muell.) and kukae-nene (*Coprosma ernodeoides* **A.** Gray), and small ferns adapted to xeric conditions. The herbaceous weed hairy cat's ear (***Hypochoeris radicata* L.)** is one of few exotic species besides mullein that is able to persist in this harsh environment. Mullein densities are lowest farther away from the edges of kïpukas, on open 'a'ä fields, or **at** higher (2,300 m), and lower (1,400 m) elevations. Densities are as low as <1 individuals/ha in remote areas. Infestations are most dense in areas that straddle vegetated ki'pukas and extremely weathered 'a'ä **flows** with pockets of **soil.** The vegetation in these edge communities are more abundant (35-65 % cover), and composed of remnant stands of mämane (***Sophora chrysophylla*** (Salisb.) Seem.) and 'a'ali'i surrounded by sparse grasslands of native *Deschampsia nubigena* Hillebr., introduced velvet grass (***Holcus lanatus*** L.), and natal red top (*Melinis repens* (Willd. Hubb.). These core infestations are estimated at >1,400 individuals/ha and extend over ~~70 hectares.~~

Range expansion occurred down slope of the main infestations on open 'a'ä flows during the survey period. In 1999, small populations were found in units **8a** and 9a. No mullein was found in these units in 1996-1998, and all individuals found in 1999 were immature, which suggests that these were incipient invasions. Seeds were probably brought into the units by wind or birds.

No mullein was reported in areas below the Mauna Loa area of the Park during the survey period (Zimmer pers. obs.).

Population growth and phenology

Population growth and phenology of mullein were documented in areas of high and low density. In 1997, the average density of mullein in two 50 m^2 plots located in the high density area was 1,412 ± 48 individuals/ha (Table 1). Approximately 11.7 ± 2.9 % of the individuals produced seeds. Multiple stalk production and fasciation occurred in only a few individuals (< 0.5 %). Six of seven individuals that produced multiple stalks showed signs of mechanical damage. The average rosette diameter of mature individuals was 23.7 ± 1.4 cm. The average fruiting stalk length was 25.5 ± 1.0 cm, and the average number of seeds per cm of stalk length was 3,993 ± 125 seeds/cm (n = 7). Estimated average seed production per individual was 102,000 ± 4000, and average seed production per hectare was 30.4 ± 8.6 million seeds.

Censuses conducted in Plot 1 in 1998 and 1999 showed that of the 365 individuals found in the plot in 1997, 81 (22 %) fruited before dying, 232 (64 %) died before reaching reproductive maturity, and 52 (14 %) survived the two years without producing flowers or fruit (Figure 4a). Most of the mortalities of immature individuals occurred within the first monitoring period between 1997 and 1998 (89 %).

Recruitment of new individuals in Plot I varied dramatically from year to year (Table 2). Between 1997 and 1998, only five new individuals were found in Plot I. The disproportionately small number of new recruits compared to the number of mortalities (281) reduced the total number of live individuals four-fold from 365 to 89. In contrast, 168 new individuals were found between 1998 and 1999, and the total number of individuals increased to 224 in Plot 1.

Recruitment of new individuals was proportionally greater in the high-density Plot II where mullein was removed at each census (p = 0.00, chi-square test). The number of new recruits in 1998 was 25, and in 1999 248. Soil disturbance caused by uprooting of individuals may have induced greater germination in the removal treatment. Similar year-to-year fluctuations in recruitment occurred in Plot II and Plot I.

Average mullein density in the low-density site was 62 ± 10 individuals/ha; 44.8 ± 16.3% of the individuals were reproductive. The average rosette diameter of mature individuals was the same as in the high-density plots, however average length of fruiting stalk was 20 % shorter (20.5 ± 1.4 cm). A multiple stalk was observed on one individual and no-fasciation was observed within the low density plots. Average seed production per individual was estimated at 82,000 & 5800, and average seed production per hectare at 2.4 ± 1.2 million seeds.

The proportion of individuals that reached reproductive maturity was greater in the low-density site Plot III than in the high-density site Plot I (p = 0.00, chi-square test). Censuses conducted in Plot III in 1998 and 1999 showed that of the 18 individuals found in the plot in 1997, 13 (72 %) fruited before dying, 4 (22 %) died before reaching reproductive maturity, and 1 (6 %) survived the two years without producing flowers or fruit (Figure 4b). No recruitment of new individuals was observed in Plots III and IV during the 1998 census (Table 2). Recruitment of new individuals was low in 1999. Nine new individuals were observed in Plot III. Five new individuals were observed in Plot IV where individuals were uprooted. The effect of uprooting individuals on subsequent recruitment was not apparent in the low-density site.

No mullein seeds were found in seed traps placed either in the low- or high-density plots between fall 1998 and winter 1999.

Three mouflon sheep (*Ovis musimon*) were observed in the unit during spring 1998, despite the area being designated a Special Ecological Area and fenced to exclude feral ungulates. Two animals were subsequently removed by fall 1998. The location of the third individual was not determined. There was evidence of browsing impacts on up to two/thirds of the flowering or fruiting individuals in both the low- and high-density infested areas during the 1997, 1998 and 1999 censuses. In most cases, stalks were partially stripped, or the tips were damaged or removed.

Treatment effectiveness

Populations were reduced to between 20 and 57 % of original numbers after one treatment of uprooting mullein in three experimental plots established in 1094. Most individuals found in follow-up treatments were recently established. No measurements of the soil seed bank or seed dispersal into the plots were taken which made it difficult to determine whether recruitment was from the pre-existing seed bank or seed dispersal into the area. Two fruiting individuals found in Plot 2 in 1995 were probably individuals missed during the initial treatment, although the possibility of individuals acting as annuals was not ruled out. A second removal treatment reduced populations to between 8 and 16 % of pre-treatment numbers.

Plant populations were halved after initial treatment in map units 10-13a, but were not substantially reduced until the third or fourth year of follow-up treatments in units 16b and 18b (Table 4). A single lapse in treatment resulted in large increases in the population, including a five-fold increase in units 1Oa-l3a. Treatment was effective in reducing or eliminating incipient populations that contained no reproductive individuals. Despite yearly survey and re-treatment, new populations established in units 8a and 9a.

Workload requirements

Ninety-four worker days were spent surveying and uprooting 19,092 mullein plants from 73 map units covering 1,280 hectares in 1996 (Table 5). Extremely dense populations and limited personnel prohibited treatment in five units (13d, 13e, 14cd, 14d, 15cd). Re-treatment of selected units was conducted in 1997 using one technician and volunteer groups. Twenty-seven worker days were spent removing **2,438** plants from eight units covering 157 hectares. Treatment efforts were expanded in 1998 to include 22 units that encompassed 309 hectares. Two technicians and a YCC volunteer group spent 41 worker days removing 3,537 plants. In 1999, 62 worker days were spent removing 7,165 plants from 24 units covering **548** hectares. An additional three worker days was spent on aerial surveys of units 16g, 19d, and the area above the units to 2,440 m elevation. Individuals with stalks or rosette diameters $\geq$ 20 cm are detectable. The number of worker days required to retreat a unit was highly variable and depended on the number of plants present, the remoteness, difficulty of terrain, **size of the** unit and the experience of the workers.

DISCUSSION

Mullein expansion in the Park

Mullein has not reached its "potential" range within the Park. From surveys, follow-up treatments and population studies it is evident that mullein is invading new areas and increasing its densities in areas it has already invaded. Mullein currently infests 1,003 hectares of open lava flows in the Park. It threatens to invade an additional 7,000 hectares of this habitat type based on its elevational distribution on Mauna Kea and Hualalai.

Rapid range expansion is expected at lower and higher elevations. The current infestation is mapped between 1,463 and 2,133 m elevation, with new populations occurring at the lower elevational boundary during the course of the surveys, Mullein seedlings have been observed growing on gravel driveways in residential areas in Volcano at 1,066 m elevation (Authors pers. obs.). Prior to the study, one individual was observed growing along a roadside below 305 m elevation in the Park (Zimmer pers. obs.). Infestations on Mauna Kea and Hualalai extend up to 3,291 m elevation (Juvik and Juvik 1992). Substrates on Mauna Loa are much younger and less weathered than on Mauna Kea and Hualalai, and lack of soil development may limit to some degree the establishment of mullein in the Park. However, lack of suitable substrates may only retard the rate of establishment rather than the extent of mullein as lava flows continue to erode over time. Based on mulleins occurrence in other areas on the Big Island, mullein will continue to expand its range at both higher and lower elevations in the Park.

Mullein densities are continuing to increase in all areas where individuals have established. Populations increased up to five-fold in some units despite sporadic attempts to remove individuals over a two-year period. Even where mullein densities are highest along the edges of vegetated kïpukas in the Park, densities have the potential to further increase based on surveys conducted on Mauna Kea, where densities are as high as 20,000 individuals/ha (Juvik and Juvik 1990).

Large yearly fluctuations in recruitment of new individuals in experimental plots were possibly brought about by a prolonged drought that occurred in 1998 that was subsequently followed by the return of normal tradewind rainfall patterns in 1999. Low recruitment caused by drought conditions in one year was offset by high recruitment the following year. This was made possible by the persistence of a seed bank that ensured continued recruitment despite the manual removal of an entire generation from half of the plots. There was no evidence of recruitment from seeds dispersed into the plot from individuals located outside the study area.

Recruitment of new individuals in plots located on open 'a'ä was substantially lower than those located on flow edges where mullein densities were generally much higher. Lack of soil development on the relatively unweathered 'a'ä limits the availability of suitable sites for seed germination and seedling establishment. However seedlings that did establish had a much greater chance of reaching reproductive maturity than those in the high density site ($p = 0.00$, chi-square test). Half of the individuals censused in the low-density plots were reproductively mature in 1997, and almost three-quarter of the individuals went on to produce fruiting stalks before dying. In the high-density plots, only one-fourth of the individuals produced fruits by the second year of the study. Half of the individuals died before reaching reproductive maturity, and the remainder (15%) survived beyond the two years expected of biennials without having reached reproductive maturity. This latter response may have been induced by the **1998** drought that created conditions unfavorable for successful seedling establishment. Studies of other biennial and annual species have shown that individuals will prolong time to flowering to favor seed set when conditions are optimal for successful seedling establishment (Reinahtz **1984).**

Mulleins ability to invade native plant communities on well-developed soils that lie within the elevation and rainfall zones of the current infestation was not directly addressed in this study. However, no recruitment was observed inside the vegetated k'ipukas that crews hiked on their way to survey mullein map units. The thicker vegetation in these areas is considered to be a competitive barrier to mullein's establishment (Juvik and Juvik 1992). However, many communities are at various stages of recovery from ungulate activity and fire, and more recently disturbed sparsely vegetated areas may provide opportunities for mullein to invade as evidenced by the increased recruitment in experimental plots where mullein was uprooted.

The long-term impacts of mullein expansion and population growth on native plant communities have not been determined. Mullein has largely established where native plant abundance is sparse and competition for resources is limited. Mullein densities are much lower than on Mauna Kea and may continue to remain low on open 'a'ä flows. While numbers continue to increase rapidly along edge communities, more time will be required before the effects of increased mullein densities on open mämane/'a'ali'i communities will be evident. The long-term effects may be to increase the rate of soil development and succession on 'a'ä flows. Increased soil development provides greater opportunities for alien weeds to establish that are otherwise limited by the lack of suitable substrate. Increased weed densities would lead to increased competition for resources and displacement of native plant communities including rare and endangered species. One threatened (*Silene hawaiiensis* Sherff) and two endangered plant species (***Plantago hawaiiensis*** (A. Gray) Pilger, and ***Asplenium fragile*** Presl) are present in native communities on Mauna Loa.

Mullein removal efforts in the Park

Mullein can be successfully controlled by manually uprooting individuals where densities are low to moderate (< 1,000 individuals/ha). Where populations have only recently established and contain few reproductive individuals, numbers are substantially reduced by the first or second year of initial and follow-up treatments. In areas where densities are higher and an abundant seed bank exists, populations were not substantially reduced until the third or fourth year of annual removal treatments.

Successful control is highly dependent on consistent follow-up treatment and search efficiency. A one year lapse in follow-up treatment leads to dramatic increases up to six-fold of the initial population. A thorough search of the control area is required to successfully reduce populations but is often hard to achieve due to the difficulty of the terrain, large size, and remoteness of some areas. Low-lying rosettes are easy to miss in the rocky terrain and members of control teams must work closer together and at a slower pace to avoid missing individuals.

Rapid and substantial response to control in small experimental plots did not always translate to comparable successes in large managed units. Unlike the experimental plots where populations were substantially reduced by the first year, moderate density populations in the managed units were not substantially reduced until the third or fourth year of follow-up treatments. The large variation in control efficiency between units may be partly due to an insufficient number of crew for the size of the control area, and greater abundance of seeds in the soil seed bank.

Between 1996 and 1999, the number of worker days spent on searching and removing mullein were not sufficient to reduce mullein's range in the Park. The maximum number of worker days spent annually on mullein was **94** in 1996. This was not sufficient to make a comprehensive survey of the range of mullein in the Park. Aerial surveys conducted in 1999 identified several satellite populations undetected in the initial survey. Incipient populations continued to become established, possibly due to seed dispersal by wind, birds, or unintentional human transport, and required yearly follow-up visits to prevent establishment of mature individuals and a seed bank. Follow-up treatment of mullein has been conducted in one-third of its range in the Park, and in only one-fourth of the units has follow-up control continued for two or more years. Successful containment and reduction in mullein range and densities will require substantial increases in the number of worker days annually devoted to mullein control.

Strategies to control mullein in the Park

Mullein has not reached its "potential range" in the Park. However its current distribution prohibits eradication from the Park as an immediate goal for managers. Approximately 200 worker days will be required annually to remove mullein from existing populations, other than the most densely infested areas. An additional undetermined number of worker days will be needed to treat core populations where densities are highest. Manual eradication will demand intensive and consistent yearly effort by Park managers. In these dense areas, herbicide treatment may be a more time-effective method of control than manual uprooting. A 2 % solution of Round-Up applied as a foliar spray effectively kills individuals (Zimmer pers. obs.). Managers should anticipate continued recruitment from the existing seed bank for an indeterminate number of years following initial treatment of a population. Seed persistence in the soil seed bank was not determined, but germination of herbarium stored specimens indicates seed longevity up to 90 years (Kivilaan & Bandurski 1933).

Range reduction is an alternative to eradication. Low to moderate density areas compose 90% of mulleins range in the Park. Reduction can be implemented incrementally and at a rate compatible to the resources that are available to managers. Range reduction should begin at the perimeter of mulleins range in the Park. Thirty-four management units covering 700 hectares compose the perimeter. An estimated 150 worker days will be annually required to search and remove mullein from this area. Three worker days (3 personnel for *8* hours) will be annually required to conduct aerial surveys to identify new populations outside mulleins current range. Follow-up treatment will be needed at yearly intervals. As mullein densities are reduced at the perimeter, more efforts can be focused on controlling interior populations.

Increased use of aerial surveys will be required to reduce workloads as mullein densities are substantially reduced. The large area over which mullein exists, its remoteness and difficult terrain makes ground search and control of mullein in low density areas extremely inefficient. A more effective use of resources is to conduct aerial surveys of the perimeter of the infestation and beyond to identify recalcitrant and new populations. Based on these findings, the field crews would be directed to remove specific populations rather than sweep the entire area for potential infestations.

Containment of mulleins current range in the Park will initially require the least amount of effort by Park managers. Annual aerial surveys (3 worker days + helicopter) will need to be conducted to identify new populations, and ground crews ***(80*** worker days) will be required to control expansion at the edges. Workloads will increase over time as greater densities and seed proliferation inside the unmanaged areas and outside the Park boundaries will increase pressure for mullein expansion beyond its current range.

Control of mullein will need to **be** continued indefinitely regardless of whether eradication, range reduction, or containment is the goal. Despite anticipated population declines following consistent removal efforts, an abundant seed bank, and seed dispersal from nearby unmanaged areas will ensure the continued re-establishment of mullein in the Park. No surveys **of** mullein were conducted outside the Park, but mullein occurs on either side of the Mauna Loa Strip in the Park. These populations, if not controlled, will provide a continued seed source for future seedling establishment in the Park. More research is needed to test herbicides that effectively suppress expression of the seed bank, and evaluate potential bio-control agents that reduce the spread of mullein.

An alternative action for managers is to abandon control of mullein in the Park. The impact of mullein on native plant communities has not been determined, and may not merit control when compared to the clearly disruptive impacts of alien species in other areas of the Park. Recruitment is slow on open **'a'ä** flows, and densities may remain low due to the limited availability of adequate sites for seed germination and seedling establishment. More long-term studies are needed to evaluate the impacts of high densities of mullein on ki'puka edge communities. On the other hand, native ecosystems on **'a'ä** flows have been regarded by managers as the most "pristine" systems in the Park, and the most impervious to invasion by exotic species. Pre-emptive control of mullein now will prevent any potential disruption of ecosystem function caused by increased mullein establishment in the future.

RECOMMENDATIONS

1. Mullein containment should be implemented now to prevent further range expansion and reduce the potential impacts that high densities of mullein may have on native plant communities and ecosystem function. Mullein is at a relatively early stage of invasion in the Park. It currently occupies one-eighth of **its** "potential" range, and population densities are one-tenth as high as those found at similar elevations on Mauna Kea. The cost of eradication is prohibitive given the large range, its difficult terrain, and abundant and persistent seed bank. Range reduction can be implemented following removal of new and satellite populations, and at a scale consistent with the resources made available to Park managers.

2. Intensive follow-up control *is* needed following initial treatment to contain or reduce the distribution of mullein. Manual control efforts must be conducted at least yearly to prevent additions to the seed bank and the establishment of new individuals. However, populations should be substantially reduced by the fourth year of consistent and thorough treatment of an area.

3. Aerial surveys are needed to augment ground survey and control of mullein and reduce workloads where populations are low and far-flung. The expansive range of mullein, its remoteness and difficult terrain make detection and control of remote populations difficult for ground crews. The difficult terrain will also cause workloads to remain high in many management units despite substantial reductions in mullein densities.

4. Cooperative agreements with private and state landowners should be made to control mullein in areas adjacent to the Park, Populations are exploding in the Keauhou Ranch area that borders the Park (Authors pers. **obs.).** Removal of mullein in buffer zones would reduce re-invasion and establishment of new mullein populations by seed dispersal from outside areas into the Park.

5. Protocols should be developed and implemented to reduce the spread of mullein into other areas of the Park where mullein has not yet established. Mullein has been occasionally sighted along roadsides at lower elevations (300 m elevation). Boots and vehicles used by mullein control crews should be sanitized before being used in other areas of the Park.

6. Research is needed to develop alternative methods to manual control of mullein. The Park does not have the resources to control mullein indefinitely. Foliar application of Round-Up kills individuals but does not eliminate recruitment of the seed bank. Velpar and other herbicides that effectively inhibit seed germination and establishment of seedlings need to be tested. The dense pubescence of mullein leaves and stalks may limit the effectiveness of some herbicides, and chemical leaching through the rocky substrates may reduce the effectiveness of herbicides that suppress seed germination. Biological control agents may offer the only long-term solution to mullein control in the Park and Hawai'i. Research is needed to identify potential insect pests and pathogens and test their suitability as biological control agents.

7. Finally, long term studies of the impact of mullein on native plant communities and ecosystem function should be implemented. The effects of high mullein densities on soil development, competition for resources, and facilitation of weed establishment has not been determined. Impact studies should be conducted on Mauna Kea where densities are already high, and in the Park to gather baseline information on the native communities that mullein invades and measure changes over time. Seed persistence in the soil needs to be determined. Projected work loads are currently based on seed longevity studies of herbarium stored specimens (Kivilaan & Bandurski 1933). Seed viability may be substantially reduced under field conditions. The potential range of mullein in Hawai'i has not been clearly established. Current estimates are based on 1992 distribution maps on Mauna Kea (1,600 m to 3,300 m elevation). Since then individuals have been observed at lower elevations along roadsides on the leeward side of the island (Ansari pers. obs., Juvik

pers. **obs.,** Zimmer pers. obs.). Substrate differences between Mauna Kea and Mauna Loa may make extrapolations of potential range expansion inaccurate for the Park. The younger and less weathered substrates on Mauna Loa may limit the availability of suitable sites for seedling establishment. Understanding the potentially disruptive effects of mullein on native plant communities will help managers prioritize mullein control efforts in the Park.

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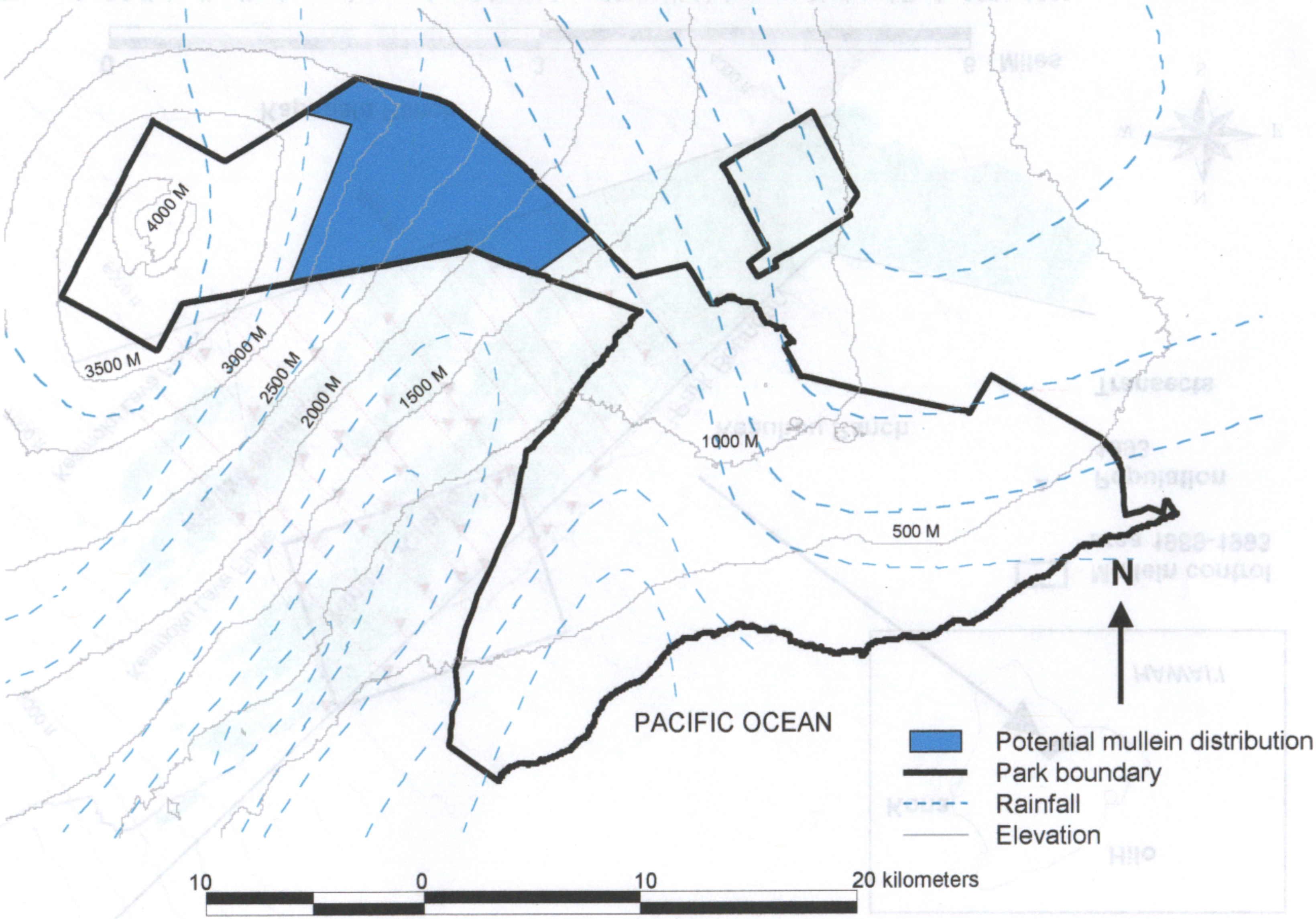


Figure 1. Potential distribution of mullein in Hawai'i Volcanoes National Park. Estimate based on elevation and rainfall distribution on Mauna Kea (Juvik & Juvik, 1992).

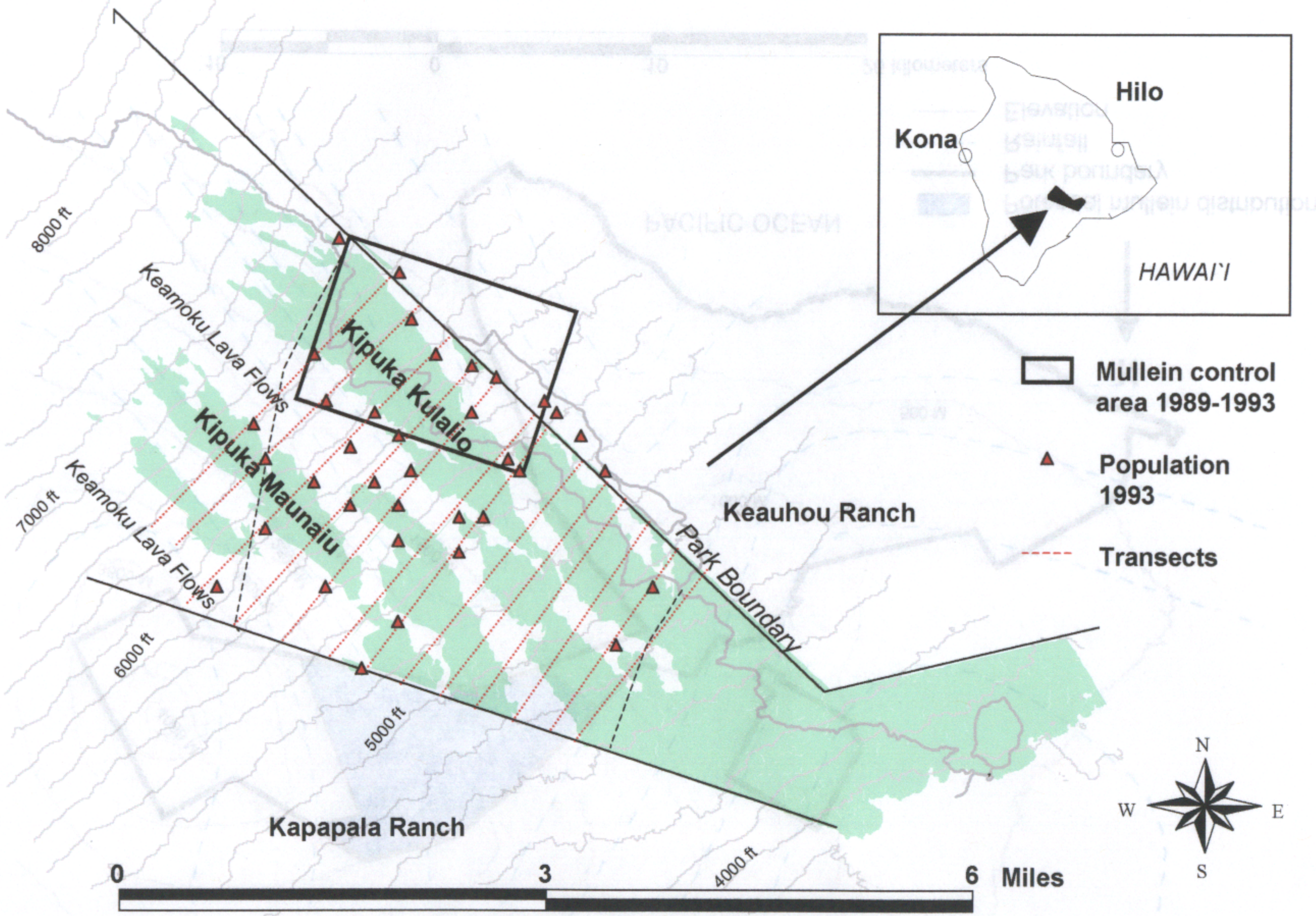


Figure 2. Mullein distribution and control on Mauna Loa, Hawai'i Volcanoes National Park, 1989-1993.

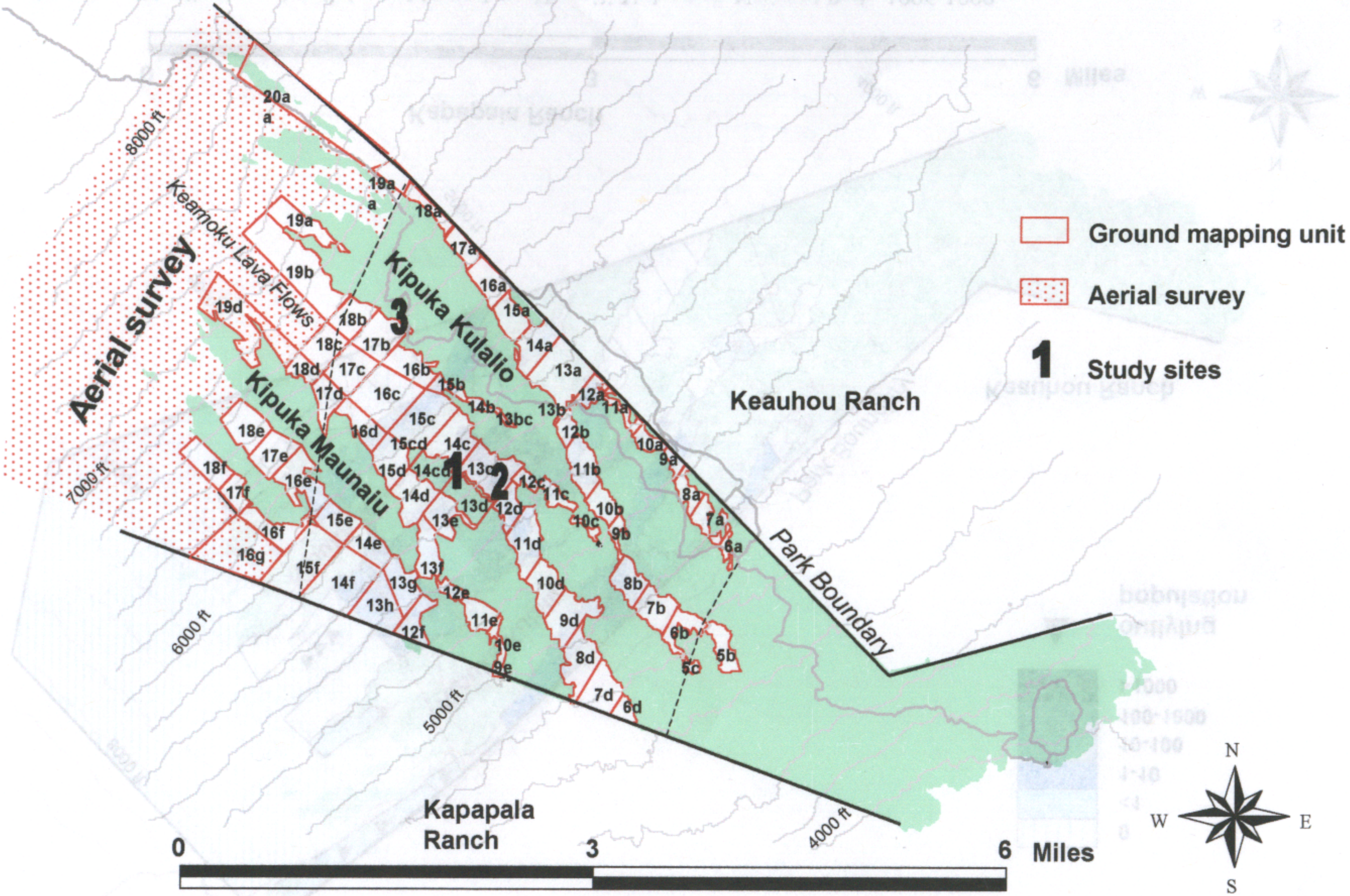


Figure 3. Location of study sites and mapping units on Mauna Loa, Hawai'i Volcanoes National Park.

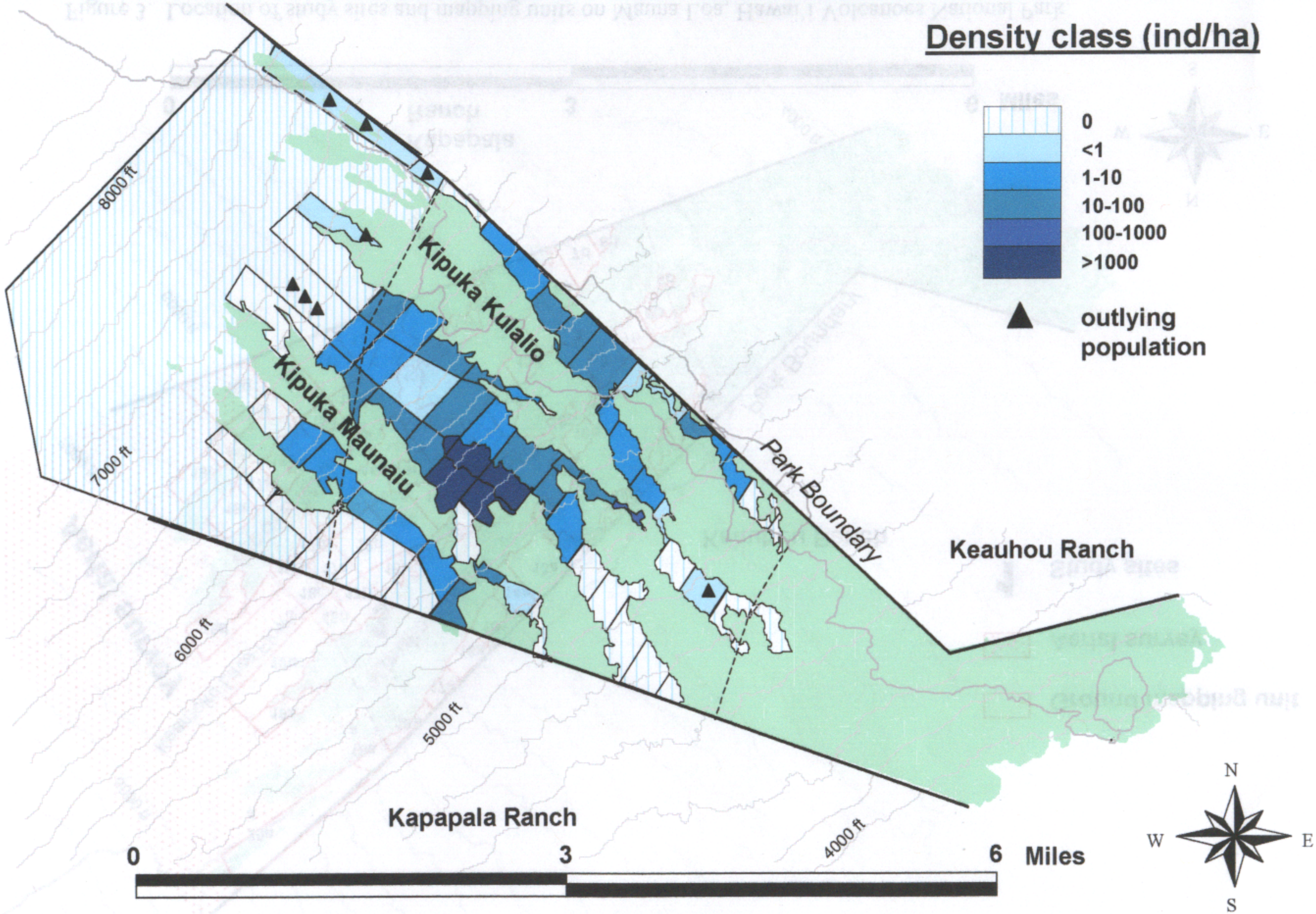
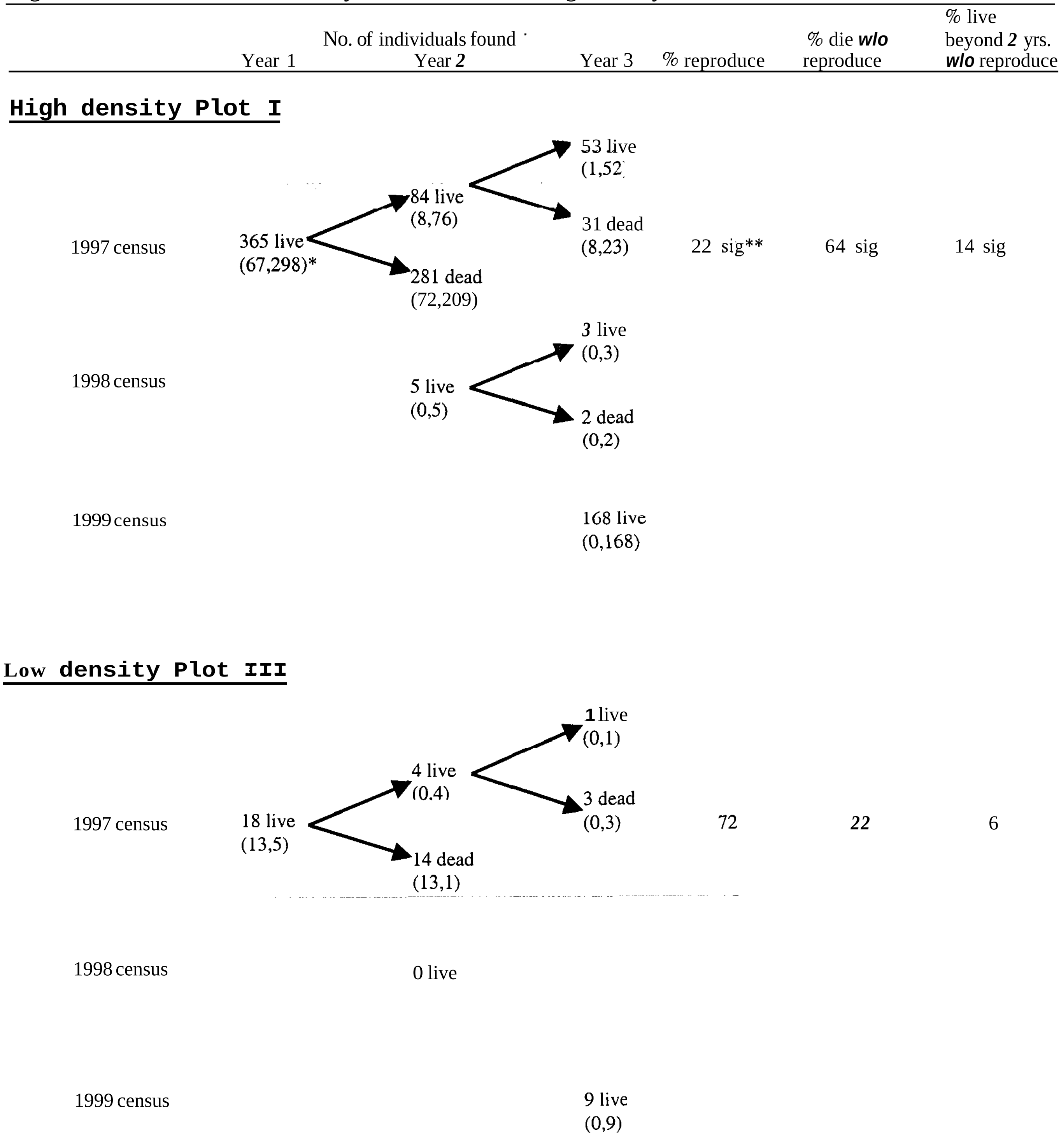


Figure 4. Distribution of mullein on Mauna Loa, Hawai'i Volcanoes National Park, 1996-1999.

Figure 4. Recruitment and mortality of mullein low and high density sites, 1997-1999.



*(mature, immature) individuals
**chi-square test comparing low density and high density plots.

Table 1. 1997 mullein population census in low and high density sites.

	Ind./ha	ind./ plot	no. fruiting individuals	rosette @ maturity	avg. stalk length	seed/ha (million)
High-density site						
Plot I	1460	365	32	25.3	24.5	21.6 *
Plot II	1364	341	70	22.6	26.5	38.8
Avg	1412	353	51	23.7	25.5	30.4
SE	48	12	19	1.2	1.4	8.6
Low-density site						
Plot III	72	18	11	21.7	21.9	4.0
Plot IV	52	14	4	24.0	19.0	1.6
Avg	62	16	8	22.8	20.5	2.4
SE	10	2	4	1.2	1.4	1.2

* based on 1 cm length = 3992.8 seeds ±125

Table 2. Mullein recruitment in control(uprooted) and non-control plots.

	High-density site		Low-density site	
	Plot I	Plot II (uprooted)	Plot III	Plot IV (uprooted)
Year 1	5	25*	0	0
Year 2	168	248*	9	5

*significant $p < 0.05$; chi-square test comparing relative recruitment between uprooted and control plots

Table 3. Number of mullein pulled in 3 experimental plots located in Site 3.

Plot	8/94	7/95	4/96
1	114(20)*	29	18
2	117(16)	66(2)	10
3	142(29)	42	20

*( ) = fruiting individuals

Table **4.** Number of mullein pulled in managed units.

Unit	1996	1997	1998	1999
7b	9		0	0
8a	0		0	20
9a	0		0	**81**
I I b	59(5)*		80(2)	34(0)
12b	39(3)		107(12)	50(0)
10-13a	114(20)		620(116)	305(6)
13a-17a	3,690(225)	1,422(nd)*		
16b	225(13)	227(53)	117(23)	
18b	461(32)	789(95)	157(96)	150(0)

*( ) = fruiting individuals, **(nd) = no data available

Table 5. Number of worker days spent surveying and removing mullein, 1997-1999.

Year	Number of Units	Area (ha)	Plants treated	Worker days
1996	73	1280	19,092	94
1997	8	157	2,348	27
1998	22	309	3,537	41
1999	24	548	7,165	62
1999A*	2A*	1,800	0	3

A* = aerial surveys conducted in units 16g, 19d and outside units to 8,000 ft elevation in the Park