INTRODUCTION

The lava-ignited Kupukupu fire began May 17th, 2002 and burned 3,367 acres (1363 hectares) of rain forest, mesic and dry native woodland communities. Approximately 455 acres (184 acres) of 'ōhi'a /swordfern (*Metrosideros polymorpha/Nephrolepis multiflora*) were affected. The potential of native vegetation recovery in 'ōhi'a/swordfern is expected to be limited by the presence of alien plants. Recovery of the vegetation from past fires (1972, 1981,1992) in this area had favored non-native herbaceous and woody species whereas native tree and shrub species recovery was low (Warshauer 1974, Tunison *et al.* 1995). Only 46% of 'ōhi'a survived by resprouting at the base of affected trunks and no significant seedling recruitment was observed 18 months after a 1992 fire. In contrast, invasive swordfern and broomsedge (*Andropogon virginicus*) re-established quickly. Invasive trees (*Morella faya, Psidium cattleianum*) and shrubs (*Lantana camara*) also have the potential to proliferate following the burn. These species were present in low numbers prior to the burn and are capable of forming dense stands following disturbance (Smith *et al*. 1985). Some native species (i.e. *Sophora chrysophylla, Santalum paniculatum*) that might recover quickly from fire were too scarce prior to the burn to significantly affect colonization. These species showed initial signs of recovery after a 1972 fire, but herbivory by goats limited their re-establishment (Warshauer 1974). Goats were removed beginning in the mid-1970s, but lack of available source material limited natural recovery of many native plants.

There is a high probability of future fires affecting this area. Fuel loads in swordfern-dominated communities are characterized with aboveground biomass >18 tons per acre (not counting trees) composed of mostly standing dead and live swordfern (Wright *et al.* 2002). New lava outbreaks remain a potential ignition source in the area. Since 1969, three of four wildland fires that occurred were lava-ignited in this area. The impact of future fires will likely remove much of the remaining fire-sensitive native 'ōhi'a, small trees and shrubs and prevent stand regeneration in the area. Park managers determined that re-establishment of native species was needed to restore the former plant diversity and vegetation structure. The focus for re-introduction was on establishing fire-tolerant native species that would be able to persist in the presence of swordfern and recurring fire. Between 1993 and 2001, seven research burns and additional laboratory experiments were conducted to test native species capacity to survive and colonize after fire (Loh, unpublished). The results from these experiments were used to identify fire-tolerant species for establishment in recently burned seasonally dry 'ōhi'a woodlands where fire-adapted alien grasses had rapidly invaded and shifted fire regimes (Loh *et al.* 2007). For the Kupukupu Burn, a similar approach was taken whereby fire-tolerant species were targeted for re-establishment in the burn area. A second smaller component of the project focused on experiments to re-establish mesic forest in two test plots. A total of 35 native species were targeted for re-establishment in the burned area. All species were either present in the pre-burn community or had been historically documented in the area. In both fire-tolerant and mesic forest plots, plants were established by a combination of planting and seeding into the burn area.

Rehabilitation efforts began in October 2002 and were completed in March 2005. Monitoring to evaluate the survivorship of plantings and recruitment from seeding continued to Fall 2006. This report summarizes the restoration efforts and monitoring results.

Methods

Study Area

The 455 acre (184 heactare) area targeted for restoration (Fig. 1) was located on the southwest end of the Kupukupu Burn (1,900-2,500 ft elevation). The former plant community was a sparse to moderate woodland of native 'ōhi'a with an understory dominated by alien swordfern (1,900-2,200 ft elevation, median annual rainfall between 59-79 in/yr) and identified as part of the seasonally dry lowland zone of the park. Alien grasses (e.g. *Andropogon virginicus*, *Melinis repens*, *Setaria gracilis*, and *Paspalum spp*.) were also present to varying degrees of abundance. Very few native trees and shrubs persisted other than 'ōhi'a and 'a'ali'i. The area had previously burned on several occasions (1972, 1981,

1992) so that many fire-sensitive native species had already been lost or significantly reduced, and only a few mesic forest remnants remained prior to the current fire episode. The 'ōhi'a that remained in the area showed signs of previous fire-damage including evidence of resprouts. Historic impacts by feral goat herds, which numbered in the thousands until they were removed in the 1970's, have contributed to the lack of native plant diversity in this area (Warshauer 1974).

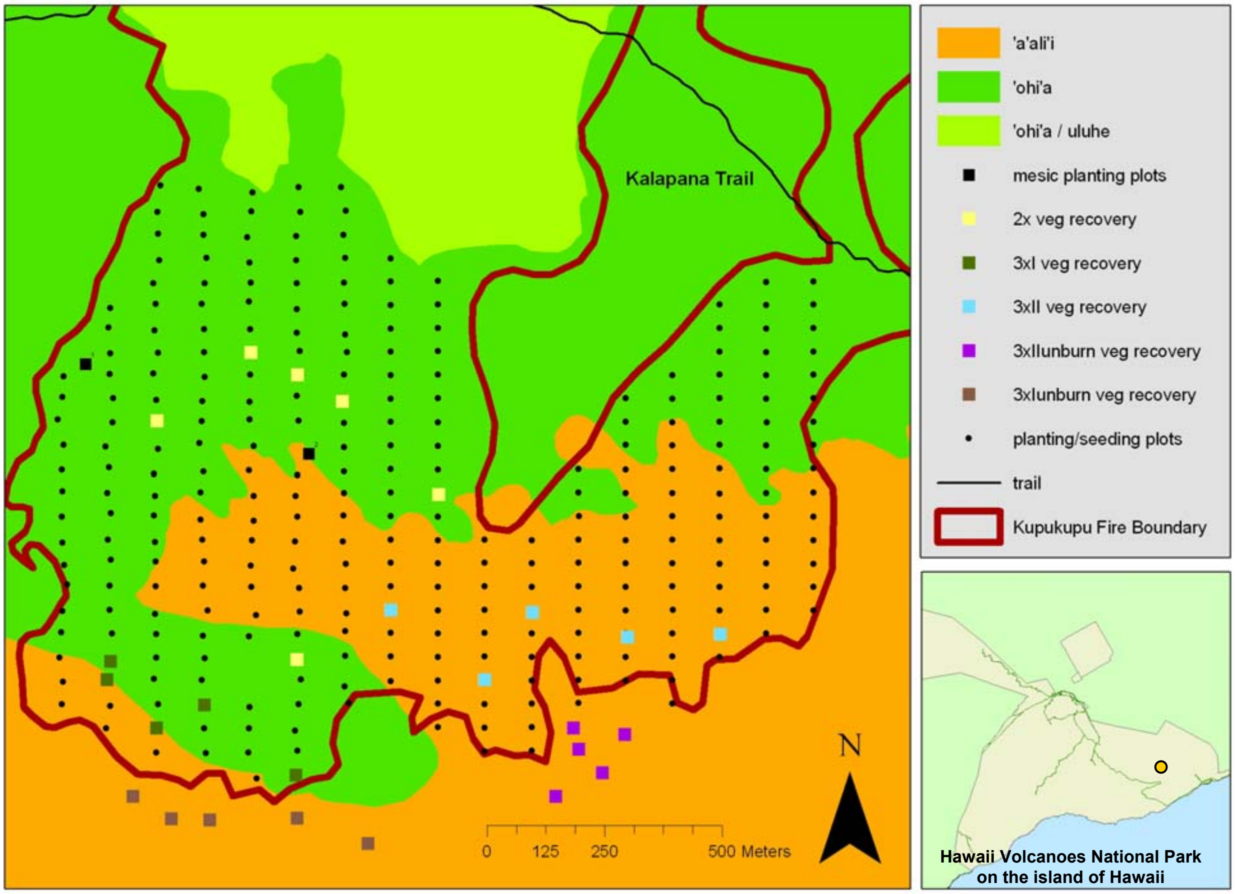

Figure 1. Distribution of planting/seeding and monitoring plots in the Kupukupu Burn.

Native Plant Restoration

Plant Material Collection, Propagation and Planting.

Thirty-five native plant species were targeted for re-establishment by planting and/or seeding in the burn area (Table 1 and 2). Plant material for propagation and seeding was collected from source locations closest to the burn area. Primary collecting sites were between Hilina Pali road, Mauna Ulu, East Rift rain forest and Naulu trail. Material was collected from as many individuals as possible in order to maximize genetic diversity. For common species, material was collected from >100 individuals. For less common species, material was collected from at least 25 individuals. Fewer than 10 individuals were used as source material for locally rare native species, ‘akoko (*Chamaesyce celastroides*), and hōawa (*Pittosporum confertiflorum*). We were not able to locate ripe seeds for kōlea (*Myrsine lessertiana)* and kōpiko (*Psychotria hawaiensis)*. This was primarily due to fire activity in the East Rift area eliminating nearby seed sources.

Table 1. Species planted in fire-tolerant (n=291) and mesic (n=2) plots in the Kupukupu burn area.

Common name	Genus	Species	Plot Type: Fire-tolerant	Plot Type: Mesic	Total planted
Herbaceous, vines, and ferns			# of plants	# of plants	
Maile	*Alyxia*	*olivaeformis*	0	16	16
Pua kala	*Argemone*	*glaucum*	240	0	240
Kākalaioa	*Caesalpinia*	*bonduc*	91	0	91
‘Uki’uki	*Dianella*	*sandwicense*	587	210	797
Kupukupu	*Nephrolepis*	*exaltata*	0	86	86
‘Awikiwiki	*Canavalia*	*hawaiiensis*	300	27	327
Shrubs					
Ko’oko’olau	*Bidens*	*hawaiiensis*	698	0	698
'Akoko	*Chamaesyce*	*celastroides*	13	0	13
Pilo	*Coprosma*	*menziesii*	166	512	678
Na'ena'e	*Dubautia*	*cilioata*	293	0	293
‘Ūlei	*Osteomeles*	*anthyllidifolia*	877	0	877
Māmaki	*Pipturus*	*albidus*	584	420	1004
Kolomona	*Senna*	*gaudichaudii*	536	0	536
'Ilima	*Sida*	*fallax*	581	0	581
Pūkeawe	*Styphelia*	*tameiameiae*	0	5	5
Auhuhu	*Tephrosia*	*purpurea*	243	0	243
'Ōhelo	*Vaccinium*	*reticulatum*	0	11	11
'Akia	*Wikstroemia*	*phillyreifolia*	578	0	578
‘Akia	*Wikstroemia*	*sandwicensis*	0	114	114
Trees					
Kukui	*Aleurites*	*moluccana*	0	9	9
Lama	*Diospyros*	*sandwicensis*	28	0	28
Wiliwili	*Erythrina*	*sandwicensis*	128	0	128
‘Ōhi’a	*Metrosideros*	*polymorpha*	0	110	110
Naio	*Myoporum*	*sandwicense*	585	105	690
Kōlea	*Myrsine*	*lanaiensis*	22	0	22
Kōlea lau li'i	*Myrsine*	*sandwicensis*	0	383	383
Olopua	*Nestegis*	*sandwicensis*	0	105	105
Alani	*Melicope*	*clusifolia*	0	48	48
Hōawa	*Pittosporum*	*confertiflorum*	0	10	10
Hōawa	*Pittosporum*	*terminalinoides*	0	32	32
Alahe’e	*Psydrax*	*odoratum*	329	210	539
Neneleau	*Rhus*	*sandwicensis*	1136	210	1346
‘Iliahi	*Santalum*	*paniculatum*	324	105	429
Māmane	*Sophora*	*chrysophylla*	1170	210	1380
'Ohe mauka	*Tetraplasandra*	*hawaiiensis*	199	0	199
Total			9708	2938	12646

Table 2. Species seeded in the Kupukupu Burn.

Common name	Genus	Species	Plot Type: all plots	Plot Type: Fire-tolerant	Plot Type: Mesic	Total seeds
			n = 291 seeded Oct. 2002 # of seeds	n = 30 seeded Summer 2003 # of seeds	n = 10 seeded Summer 2003 # of seeds	
Herbaceous, vines, and ferns						
Pua kala	*Argemone*	*glaucum*		3,000		3000
‘Uki’uki	*Dianella*	*sandwicense*		1,500		1500
Shrubs						
Ko’oko’olau	*Bidens*	*hawaiiensis*	22,350			22350
Pilo	*Coprosma*	*menziesii*		1,500	500	2000
Na'ena'e	*Dubautia*	*cilioata*		3,000		3000
‘Ūlei	*Osteomeles*	*anthyllidifolia*	145,500			145500
Māmaki	*Pipturus*	*albidus*		30,000	10,000	40000
Kolomona	*Senna*	*gaudichaudii*		1,500		1500
'Ilima	*Sida*	*fallax*		3,000		3000
Trees						
Naio	*Myoporum*	*sandwicense*		9,000	3,000	12000
Alahe’e	*Psydrax*	*odoratum*		1,800	1,000	2800
‘Iliahi	*Santalum*	*paniculatum*		900	300	1200
Māmane	*Sophora*	*chrysophylla*	145,500			145500
Total			313350	55200	14800	383350

After collection from the field, seeds were processed for storage at the HAVO nursery. Fruits dry at maturity (no fleshy pulp) were further dried in open drying racks and stored in refrigerators. A food processor (cuisinart 14-cup food processor model DFP-14BCN type 33) equipped with a plastic blade (dough blade) was used to remove fleshy fruit from seeds. After briefly processing the seed pulp was decanted to separate the seeds from the pulp. These seeds were then sterilized in a 5% bleach solution, dried and stored in the refrigerator for up to 6 months or until they could be used for propagation or seeding into the burn area.

Plant propagation was conducted in temporary park greenhouses at HAVO, which included a 100 x 24 ft hoop house, and two 20 x 20 ft quarantine areas. For species not previously used in park restoration projects, plant propagation techniques had to be developed or refined. These included ʻakoko (*Chamaesyce celastroides*), kukui (*Aleurites moluccana*), kākalaioa (*Caesalpinia bondoc*), pilo (*Coprosma menziesii*), kupukupu (*Nephrolepis exalta*), alani (*Melicope clusiifolia*), hōawa (*Pittosporum confertiflorum*), neneleau (*Rhus sandwicensis*), and ʻohe mauka (*Tetraplasandra hawaiensis*). Propagation techniques developed for the project are currently being summarized in a separate technical report. The majority of the species were approximately one year old when planted. Plant sanitation protocols to prevent the introduction of new pests with plantings into the burn area are described in Appendix A.

The planting and seeding of fire-tolerant native plants was concentrated in 291 plots (fire-tolerant plots) that were established along 17 transects (100 m apart) that spanned the 455 acre burn restoration area (Fig. 1). Circular plots (15 m radius) were established at 50 m intervals along each transect. In each plot, between 25 and 53 seedlings (average =33/plot) were planted. A total of 9,707 plants composed of 23 species were planted across 10 sessions conducted between July 2003 and February 2005 (Table 1). The 23 species included in these plots are a subset of native species that have been identified as fire-tolerant (survive or colonize following fire) though field and laboratory tests or following wildfire (Loh *et al.* unpublished).

In addition, two 50 m x 50 m plots (mesic plots) were established in former mesic forest remnants located within the 455 acre burn restoration area. The mesic plots included plantings of 12 fire-sensitive species in addition to 9 of the fire-tolerant species (Table 1). Although kukui is a Polynesian introduction, it was included in the restoration plan because it can create a moist microclimate (pers. observation) which may slow future fires into the mesic plots. It is not considered invasive at HAVO and was part of the pre-burn community. A total of 2,938 individuals were planted in two planting sessions conducted in February and March 2005. Four months prior to planting, plots were treated with herbicide (2% Round Up Pro in water) to reduce competition from alien weeds (swordfern and grasses) that had rapidly established in the plots following the fire.

Plant survivorship was measured in the two mesic plots and in a subset of 31 randomly selected fire-tolerant plots. All planted individuals were flagged at the time of planting and were relocated one-year post planting to determine their survival, reproductive status and vigor, on a scale of 1-5 (1 = vigorous growth, 2 = healthy, 3 = fair, 4 = poor, 5 = dead). Total percent survivorship was calculated by dividing the total number of live plants in all plots by the total number planted multiplied by 100. Percent survivorship was also calculated for each species separately.

Seed Broadcast

In October 2002, seeds of three species were sown into 291 fire-tolerant plots (Table 2). Each plot received approximately 500 acid-treated māmane (*Sophora chrysophylla*), 500 ʻūlei (*Osteomeles anthyllidifolia*), and 50 or 100 ko`oko`olau (*Bidens hawaiensis*). The latter quantities were assigned randomly to a plot. At this stage, 5 mo after the burn, kupukupu fern (*Nephrolepis multiflora*) had rapidly re-established and had to be removed by hand-pulling individuals from a 2.5 m radius area centered in the plot. The cleared area was soil "scratched" with a 3-pronged hand tool to loosen the soil prior to applying seeds. In summer 2003, ten plots, located in former mesic forest, received an additional seed mix of five species: ‘iliahi (*Santalum paniculatum*), māmaki (*Pipturus albidus*), naio (*Myoporum sandwicensis*), pilo (*Coprosma menziesii*), and alahe’e (*Psydrax odorata*). Thirty fire-tolerant plots received an additional seed mix of 10 species: iliahi (*Santalum paniculatum*), māmaki (*Pipturus albidus*), naio (*Myoporum sandwicensis*), pilo (*Coprosma menziesii*), alahe’e (*Psydrax odorata* ‘ilima (*Sida fallax*), kolomona (*Senna gaudichaudii*), na’ena’e (*Dubautia ciliolata*), pua kala (*Argemone glauca*), and ‘uki ‘uki (*Dianella sandwicense*). Seedling recruitment was monitored in the summer of 2003, 2004 and 2005 using the subset of 30 fire tolerant plots and 10 mesic plots (Fig. 2). All seedlings were tallied by size class: 0-10 cm, 10.1-50 cm, 50.1-100 cm, 100.1-150 cm, 150.1-200 cm. For each species in a plot, five individuals belonging to each size class were tagged to follow individual survivorship (Fig. 3). Reproductive maturity as evidenced by fruiting or flowering was noted for each tagged individual.

Figure 2. Seedling monitoring in typical swordfern density at one year.

Figure 3. ‘Iliahi and a’ali’i seedlings, June 2004

Natural Recovery Following Fire

Community Response

To evaluate vegetation recovery in the ‘ōhi’a swordfern area, thirty randomly located 20 x 30 m monitoring plots were established in the burn area. Plots were pre-stratified by past fire occurrence: 2x burn (1972, 2002), 3xI burn (1972, 1981, 2002), and 3xII burn (1972, 1992, 2002) and whether they were located in planting and seeding plots or not (managed vs. unmanaged). Plots were established and read in the Fall 2003, one year following the fire. Unmanaged plots (n = 15) were reread summer 2005 along with an additional 10 plots established in an adjacent area not burned by the Kupukupu fire that served as control plots: 3xI unburn (1972, 1981) and 3xII unburn (1972, 1992). Due to a 2003 wildfire that swept parts of the surrounding area, we were unable to find an area that could serve as an unburn control for the 2x unburn.

Within the vegetation recovery plots, species richness, cover, and native tree and shrub density were recorded using modified protocols from the DOI Western Region Fire Monitoring Handbook (1992). Modifications included a reduction in plot size (20 m x 30 m), and tree size classified by basal diameter rather than DBH. Vegetation cover (< 2 m height) was measured along a single 30 m transect, which bisected the plot, using the pole intercept method. A two meter pole (1/4th inch diameter) was placed at 30 cm intervals along a 30 m tape measure (total number of intervals = 100). At each interval, each plant species touching the pole was recorded once. If no vegetation was encountered, substrate type (soil, rock, litter, bryophyte) was recorded. Shrub density was measured in three 2 m x 10 m subplots placed on the left side of the cover transect. Each individual was classified by type: seedling, resprout, or mature. Tree density was measured throughout the entire plot. Individual trees were classified by type (seedling, basal resprout, or epicormic resprout), height (live stems) and basal diameter of individuals greater than two meters in height was measured (live stems $\geq$ 1 cm diameter).

Species richness was compared among burn types and management treatments using a nested ANOVA with management nested within burn type. There were no differences in percent vegetation cover, shrub and 'ōhi'a density data between managed and unmanaged treatments so these treatments were pooled for subsequent analysis of these parameters among burn types. Data from 2005 was analyzed using a one-way ANOVA. Non-parametric equivalents were used when the data did not meet the assumptions of the statistical model.

Recovery of Mature ʻŌhiʼa Following Fire.

In June 2002, one hundred and two ʻōhiʼa trees were tagged along a single transect (C) to determine the percentage of mature ʻōhiʼa that were able to survive following fire. Tree height, basal diameter, char height, and scorch height were recorded for each individual. In addition, burn severity was estimated using protocols described in the DOI Western Region Fire Monitoring Handbook (1992). Four year survivorship of individuals was recorded in summer 2006.

Results

Between October 2002 to March 2005, over 1,500 worker days were spent on collecting plant material, propagating, planting, seeding and monitoring for the restoration project. Volunteers contributed about ¼ of the labor. A total of 12,646 seedlings were planted and 400,000 seeds were broadcast in the burn.

Native Plant Restoration

Planting

Overall survivorship of planted individuals was higher than expected given the harsh site conditions including periodic heavy vog, shallow soils, and competition from quickly recovered swordfern. One year following planting, 58% of individuals had survived and fourteen of the herbaceous and shrub species had reached reproductive maturity (Table 3). Survivorship by species ranged from a high of 92% for ʻakoko (*Chamaesyce celastroides)* to a low of 35% for ahuhu (*Tephrosia purpurea*) with a 45-70% survival for the majority of species planted. The thick vog (sulfate aerosols, sulfuric acid (H_2SO_4), and other oxidized sulfur species) had caused the disintegration of many of the metal flags used to mark planting, so that relocation of the plants was often difficult where swordfern grew most abundantly. Missing plants were assumed dead. Consequently, the actual survivorship of plantings could be higher especially for low stature herbaceous and shrub species. Of the 832 individuals found alive, 67% of the plantings were healthy with a vigor rating of one or two (Fig. 4). Twenty-four percent were found to have a vigor rating of three with only 10% with a vigor rating of four.

Figure 4. Growth of some species such as ‘iliahi (*Santalum paniculatum,* shown here at 1.5 years), ko’oko’olau (*Bidens hawaiensis*), neneleau (*Rhus sandwicensis*) and naio (*Myoporum sandwicense*) was particularly high. After one year these species were taller than the dominate swordfern layer in many plots.

One-year survivorship of individuals in the mesic plots was 53%. Survivorship by species ranged from a low of 10% for ohelo (*Vaccinium reticulatum*) to nearly 90% for hōawa (*Pittosporum spp*.). Maile (*Alyxia oliviformis*) and kupukupu (*Nephrolepis exaltata*) were the only mesic species reproductive after one year. Most of the mesic tree species are expected to take five to ten years to reach reproductive maturity. Over three-quarters of the plants found alive were classified as healthy (vigor 1 or 2); with only 19% a vigor rating of 3 and 4% a vigor rating of 4.

Table 3. Average one-year survivorship of individuals planted in the Kupukupu burn area. Asterisk (*) indicates reproduction of planted individuals was observed in non-monitoring plots. The number of planted individuals monitored for survivorship is indicated by n.

Common name	Genus	Species	Fire-tolerant n =	% survival	Mesic n =	% survival	fruiting/flowering
Herbaceous, vines, and ferns							
Maile	*Alyxia*	*olivaeformis*			16	87.5	yes
Pua kala	*Argemone*	*glaucum*	66	25.7			yes*
Kākalaioa	*Caesalpinia*	*bonduc*	60	48.3			no
‘Uki’uki	*Dianella*	*sandwicense*	66	66.6			yes
Kupukupu	*Nephrolepis*	*exaltata*			86	9	yes
‘Awikiwiki	*Canavalia*	*hawaiiensis*	84	48.8			yes
Shrubs							
Ko’oko’olau	*Bidens*	*hawaiiensis*	76	69.7			yes
'Akoko	*Chamaesyce*	*celastroides*	13	92			yes
Pilo	*Coprosma*	*menziesii*	61	57.3			yes
Na'ena'e	*Dubautia*	*cilioata*	62	67.7			yes
‘Ūlei	*Osteomeles*	*anthyllidifolia*	93	40.8			no
Māmaki	*Pipturus*	*albidus*	63	31.7			yes
Kolomona	*Senna*	*gaudichaudii*	62	25.8			no
'Ilima	*Sida*	*fallax*	62	51.6			yes
Pūkeawe	*Styphelia*	*tameiameiae*			5	40	no
Auhuhu	*Tephrosia*	*purpurea*	66	43.9			yes
'Ōhelo	*Vaccinium*	*reticulatum*			11	9	yes
'Akia	*Wikstroemia*	*phillyreifolia*	62	85.5			yes
‘Akia	*Wikstroemia*	*sandwicensis*			114	71	no
Trees							
Kukui	*Aleurites*	*moluccana*			9	33.3	no
Lama	*Diospyros*	*sandwicensis*	25	60			no
Wiliwili	*Erythrina*	*sandwicensis*	53	60.3			no
‘Ōhi’a	*Metrosideros*	*polymorpha*			110	76.3	no
Naio	*Myoporum*	*sandwicense*	63	85.7			no
Kōlea	*Myrsine*	*lanaiensis*	22	50			no
Kōlea lau li'i	*Myrsine*	*sandwicensis*	63	85.7	383	58.2	no
Olopua	*Nestegis*	*sandwicensis*			105	26.6	no
Alani	*Melicope*	*clusifolia*			48	20.8	no
Hōawa	*Pittosporum*	*confertiflorum / terminalinoides*			42	88	no
Alahe’e	*Psydrax*	*odoratum*	67	77.6			no
Neneleau	*Rhus*	*sandwicensis*	121	71.9			no
‘Iliahi	*Santalum*	*paniculatum*	62	46.7			no
Māmane	*Sophora*	*chrysophylla*	124	49.1			no
'Ohe mauka	*Tetraplasandra*	*hawaiiensis*	61	49.1			no

Seed Broadcast

Fire-tolerant plots. The three species (māmane, ko'oko'olau and 'ūlei) directly seeded in 2002 began germinating within the first year of seed application (Fig. 5). At the first year census (2003), seedling density averaged 12 seedlings/plot with the majority of individuals less then 50 cm in height. Māmane had the highest establishment rate with 9 seedlings per plot. Ko'oko'olau and 'ūlei followed with 1 and 2 seedlings respectively. No seedlings of these species were found in the control (unseeded) plots.

By 2004, the mean number of seedlings per plot increased to 21, largely due to increased recruitment of ko'oko'olau seedlings (7 seedlings/plot) (Fig. 5, 2004). Of the 10 species added in 2003, four germinated in the first year. The highest establishment was found for alahe'e with 6 seedlings per plot (all under 10 cm tall). Lower establishment was found for 'iliahi, pilo, and kolomona. No seedlings were found for the other six species: māmaki, naio, 'ilima, na'ena'e, pua kala, and 'uki'uki.

By the third census (Fig. 5, 2005) the average number of seedlings per plot had decreased to 6 individuals, with most individuals between 10 to 50 cm tall. Ko'oko'olau (3 seedlings/plot) and māmane (2 seedlings/plot) were the most common species in the plots. There were no seedlings of alahe'e or kolomona.

Individual fates of ko'oko'olau, 'ūlei and māmane seedlings were followed for two cohorts of seedlings tagged in 2003 and in 2004. Forty percent of the seedlings tagged in 2003 survived one year (n = 192). Survivorship was 90% for ko'oko'olau, 39% for 'ūlei and 28% for māmane. Highest mortality occurred among the smallest size class (< 10 cm). Two year survivorship for seedlings tagged in 2003 was approximately twenty-five percent. Ko'oko'olau maintained the highest overall survivorship followed by 'ūlei and māmane. A second cohort tagged in 2004, which included ten additional species, had much lower one year survival (19%, n = 154). None of the alahe'e or kolomona seedlings survived and only one pilo and nine 'iliahi survived beyond the first year.

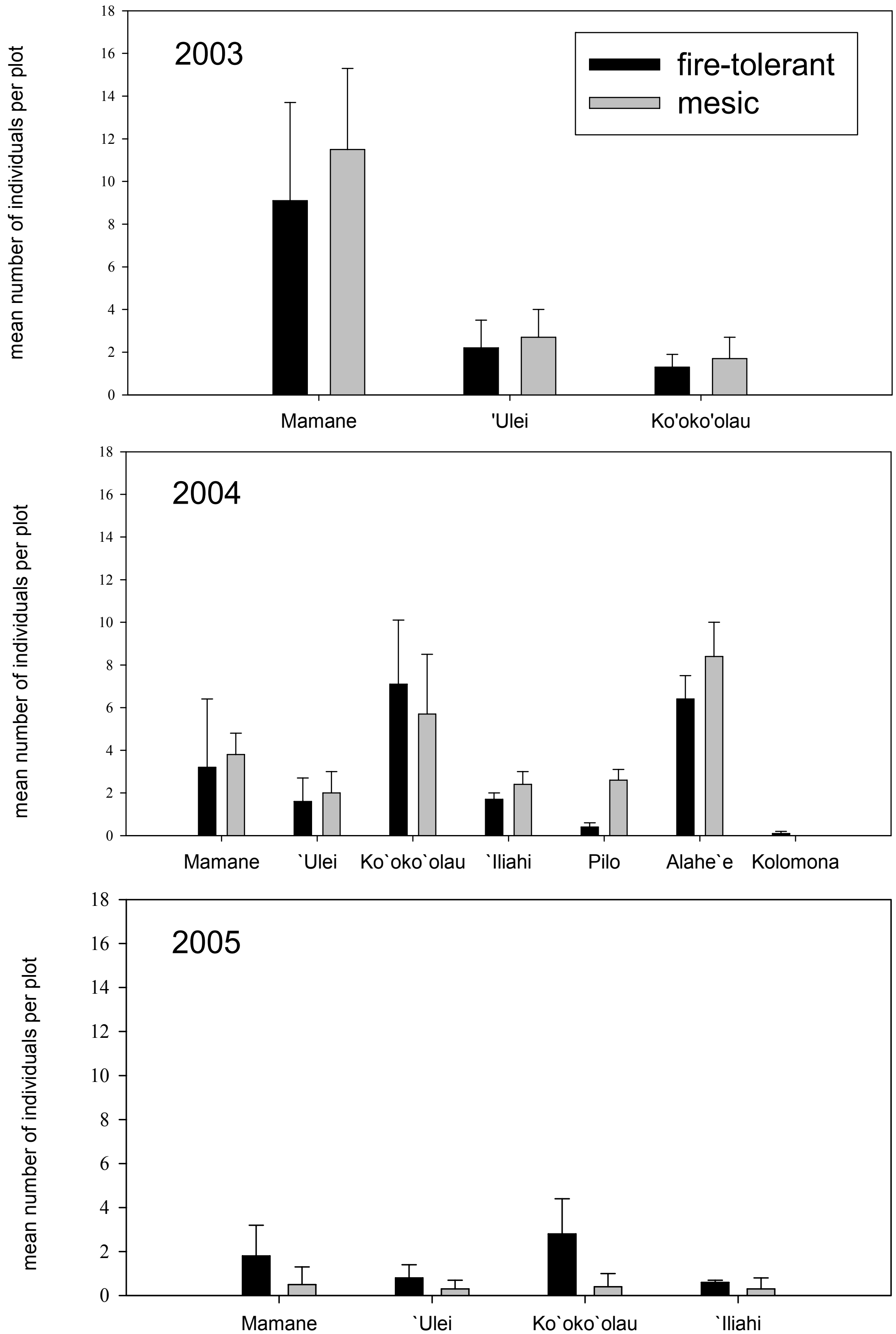

Figure 5. First, second and third year seedling establishment from artificial seeding into the Kupukupu Burn (means + SE).

Mesic plots. In 2003, average seedling establishment (16 seedlings/plot) in the mesic plots was similar to the fire tolerant plots (Fig. 5, 2003). Establishment was higher for māmane (12 seedlings/plot) than for ko'oko'olau (2 seedlings/plot) and 'ūlei (3 seedlings/plot). In 2004, the density of māmane and 'ūlei seedlings had decreased while ko'oko'olau seedlings increased to 6 seedlings/plot. A second application of seeds to the plots in 2003 led to increased overall seedling recruitment in 2004 (25 seedlings/plot), this included new recruitment for pilo (3 seedlings/plot), alahe'e (8 seedlings/plot), and 'iliahi (2 seedlings/plot). No seedlings were observed for naio or māmaki.

Individual survivorship patterns in the mesic plots were similar to the fire tolerant plots with an overall one-year survivorship rate of 49% for the first round of species seeded in 2003 (n = 116 tagged). Among species, first year survivorship was 67% for ko'oko'olau and 'ūlei and 39% for māmane. The greatest mortality was in the smallest size class (< 10 cm). After two years (2005), overall survivorship had dropped to 23%. Ko'oko'olau maintained the highest survival with 56%. One-quarter of the 'ūlei seedlings had survived whereas only 10% of the māmane seedlings were alive in 2005. First year survivorship of seedlings produced from the second round of seeding in 2004 was much lower (7%, n = 92). There were no surviving alahe'e seedlings and only one pilo and five 'iliahi in 2005.

Natural Recovery Following Fire

Vegetation Community Response

Species richness. A total of fifty-three native and alien species were identified in burn plots one year following the wildfire. There were no apparent differences in the mean number of species that established across the three types of burn area monitored (2x burn, 3xI burn, 3xII burn). There was a higher number of native species in the managed plots compared to the unmanaged plots across burn types as a result of planting and seeding efforts in the former (Fig. 6, $p \leq 0.0046$). Over the next two years, species richness remained stable for both alien and native species with no significant differences found among burned plots. Comparisons among the burn and unburn plots three years following the wildfire showed a significantly lower number of species present in the 3xII unburn plots than in the 3xI unburn plots and burn plots (Fig.4, $p \leq 0.001$)

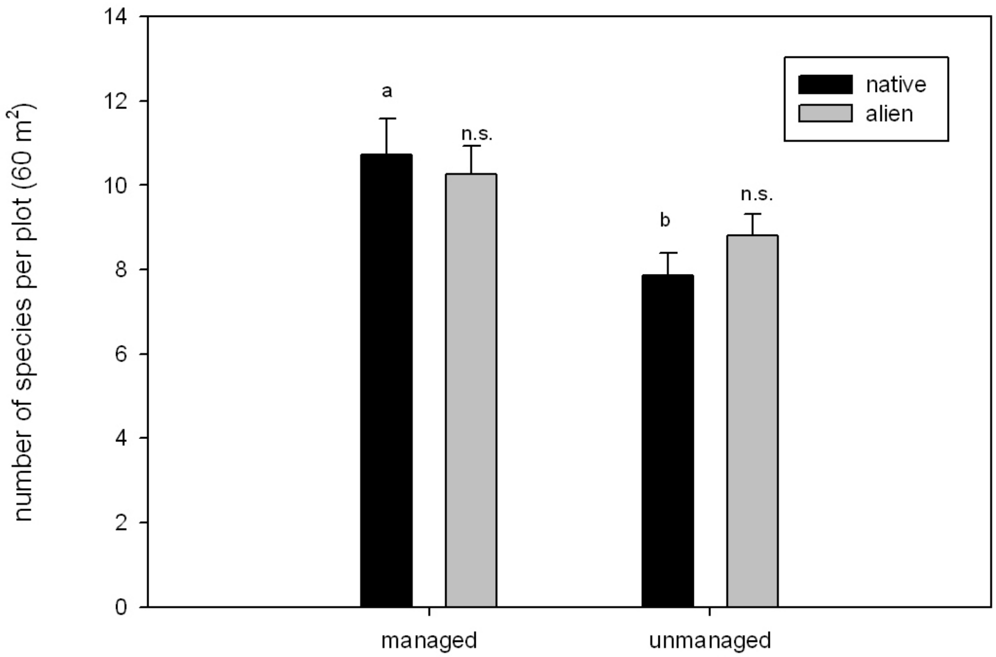

Figure 6. Species richness one year following the Kupukupu fire in managed and unmanaged plots (means + SE). Bars with different letters (a,b for native; n.s. for alien) indicate a significant difference at $p \leq 0.05$.

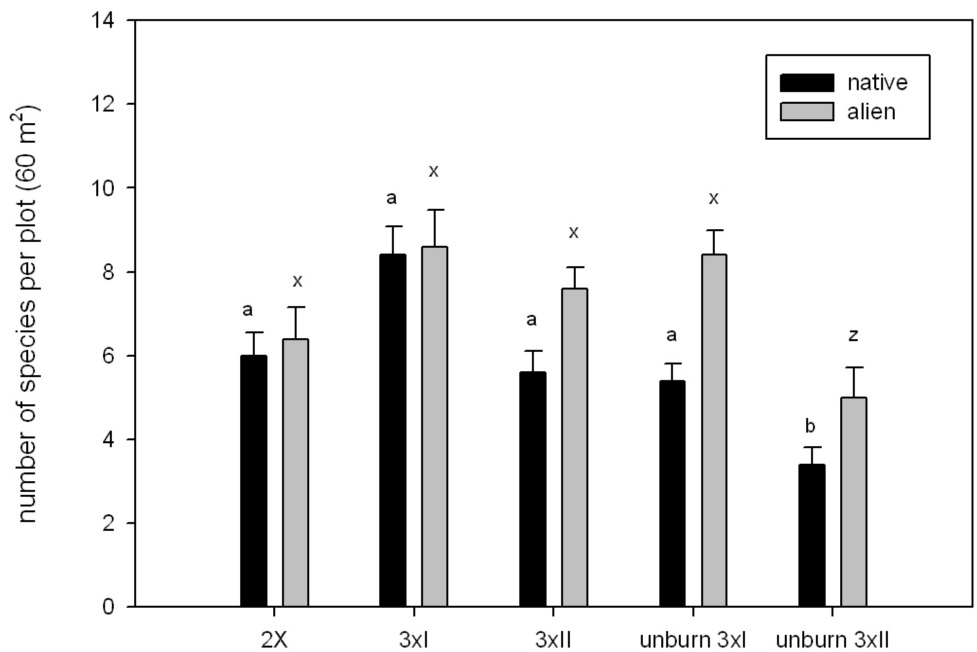

Figure 7. Species richness three years following fire across burn types (2005). Bars with different letters (a,b for native; x,z for alien) indicate a significant difference at $p \leq 0.05$.

Percent Cover. One year following the fire, alien swordfern (58-85%) dominated the vegetation cover in the burn (Fig. 8). Native species, primarily 'a'ali'i, 'ōhi'a and *Cyperus polystachyos* comprised 23-30% of the vegetation cover. Total native species cover did not differ among burn sites. However, 'a'ali'i, a fire-tolerant shrub, was more abundant in the 3x burn than in the 2x burn. Cover of alien species was significantly higher in the 2x burn plots ($p \leq 0.002$) due to greater cover of swordfern.

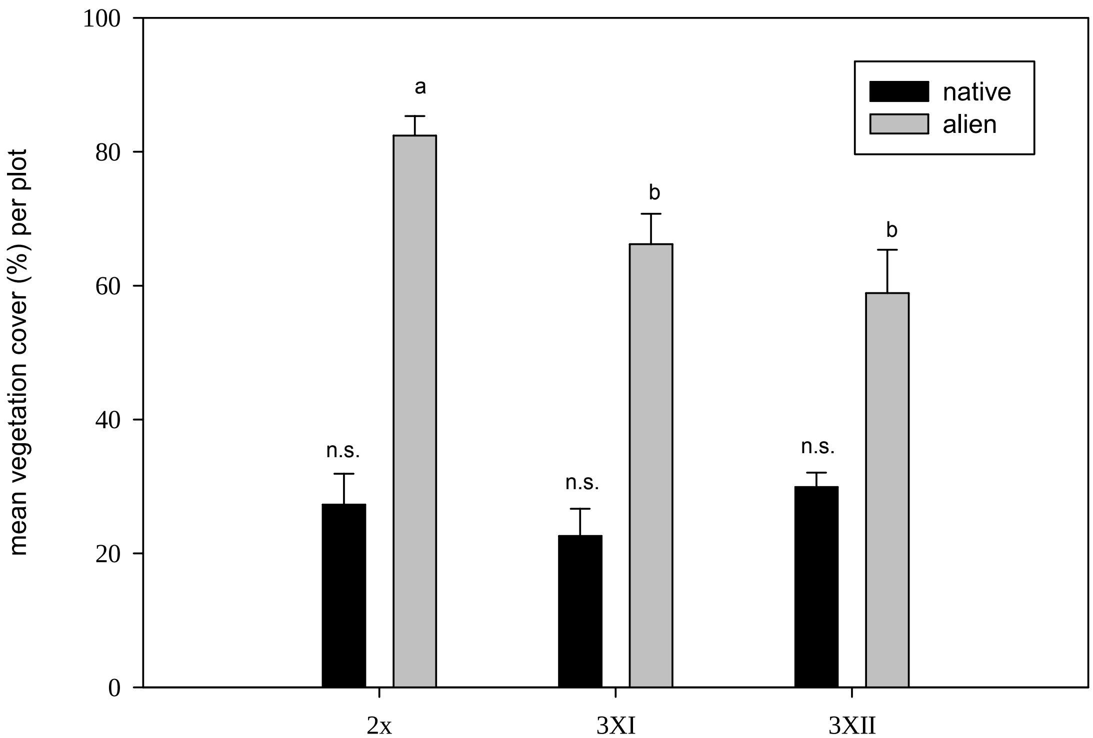

Figure 8. Vegetation cover (%) one year following fire (means + SE). There were no significant differences between managed and unmanaged plots (data pooled for illustration). Different letters indicate significant differences at $p < 0.05$.

By 2005, or three years following fire, the most significant difference between the vegetation cover inside and outside the burn was that burn plots had higher amounts of swordfern (60-80% burn plots, 20-40% unburn plots) than unburned plots while unburned plots had much more alien grass cover (<10% burn plots, 20-50%unburn plots) (Figure 9). There were no differences in total alien or native species cover among sites. In addition, there were no significant changes in cover between the first and third year in native or alien species cover.

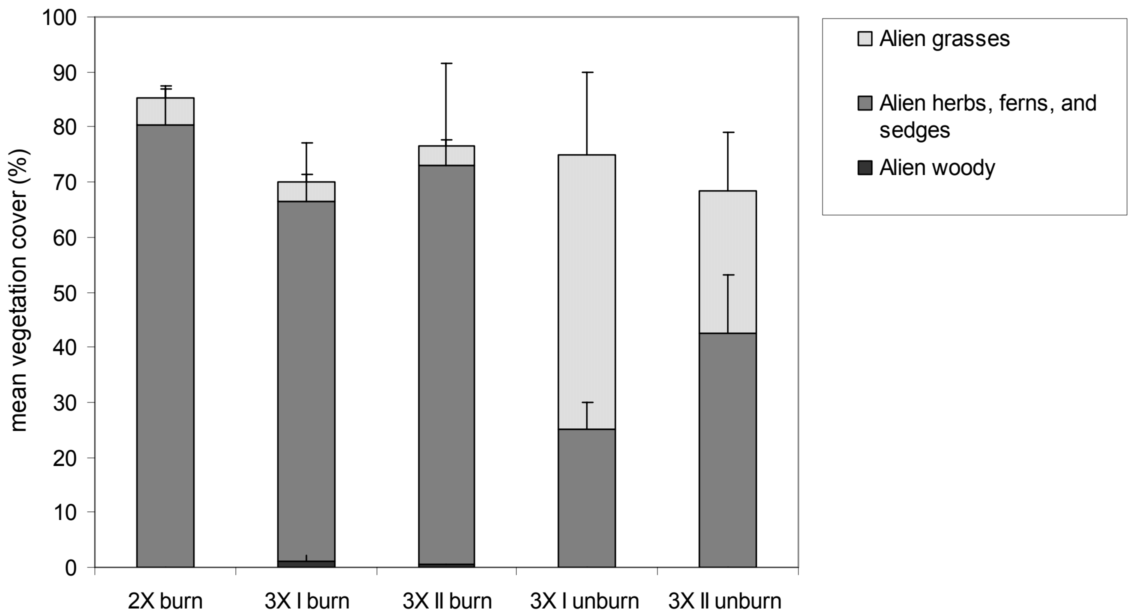

Figure 9. Alien vegetation cover three years following fire in 2005 (means + SE).

Shrub density. Native shrub density, largely represented by ‘a’ali’i, was highest in the 3xII burn and lowest in the 2x burn in 2003 (Fig. 10, $p \leq 0.001$). Individuals of alien shrub species *Pluchea symphytifolia, Lantana camara*, *Indigofera suffruticosa*, and *Psidium guajava* were found, however densities were so low that formal analysis was not conducted (< 3 ind/plot).

Three years following fire, a’ali’i continued to be the dominate shrub in burn plots. Densities were lower than in the first year ($p \leq 0.028$), due largely to losses among the smaller size classes (individuals < 50 cm). The initial burst of seedling recruitment the first year following the fire, subsided in subsequent years. There were no significant differences in shrub densities between each burn type and their respective unburn controls.

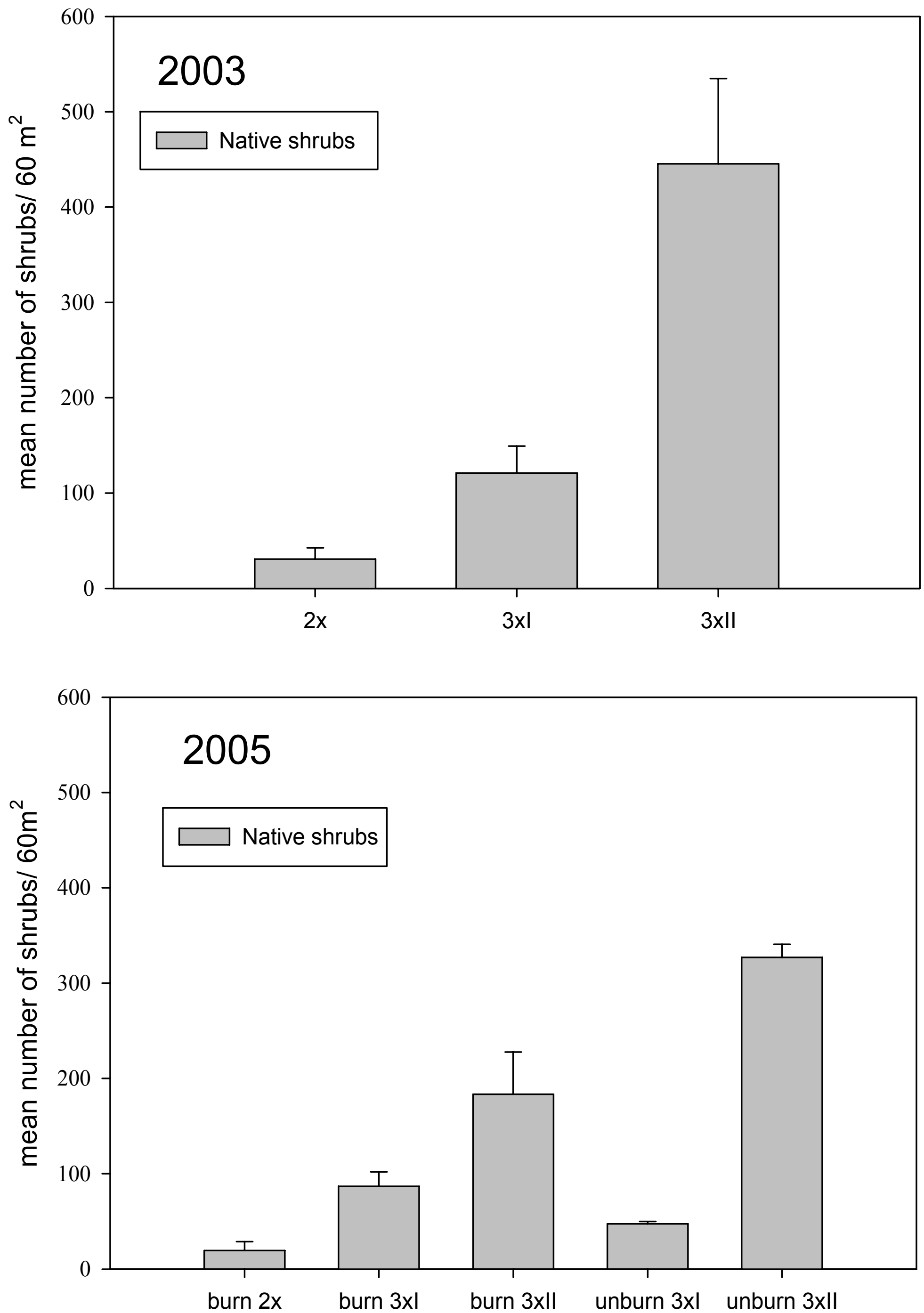

Figure 10. Mean density of native shrubs one year (2003) and three years (2005) following fire. Managed and unmanaged plots are pooled (n = 10) for 2003.

Tree Density. The most common tree in the burn area was ‘ōhi’a. A fire sensitive species, densities in the 3x burns (0-20 individuals/600m^2) were lower than in the 2x burn (15-50 ind./600m^2), but were not very different from their pre-burn numbers as reflected in the control plots (Fig. 11).

Establishment of ‘ōhi’a was primarily through re-sprout. Very little seedling establishment was evident (e.g. 13 individuals found among 45 plots). Many of the resprouts observed in 2003 had died by 2005 (e.g. 42 individuals/plot to 27 individuals/plot in the 2x burn plots).

Other trees found occasionally in plots were non-native strawberry guava (*P. cattleianum*), and faya (*Morella faya*), and native māmane (*S. chrysophylla*), pilo (*C. menzeii*), ‘iliahi (*S. paniculatum*), and wiliwili (*E. sandwicensis*). The majority of native trees were from planting or seeding into the burn. An exception was one pilo (resprout) and two māmane (1 resprout and surviving individual) (Table 4).

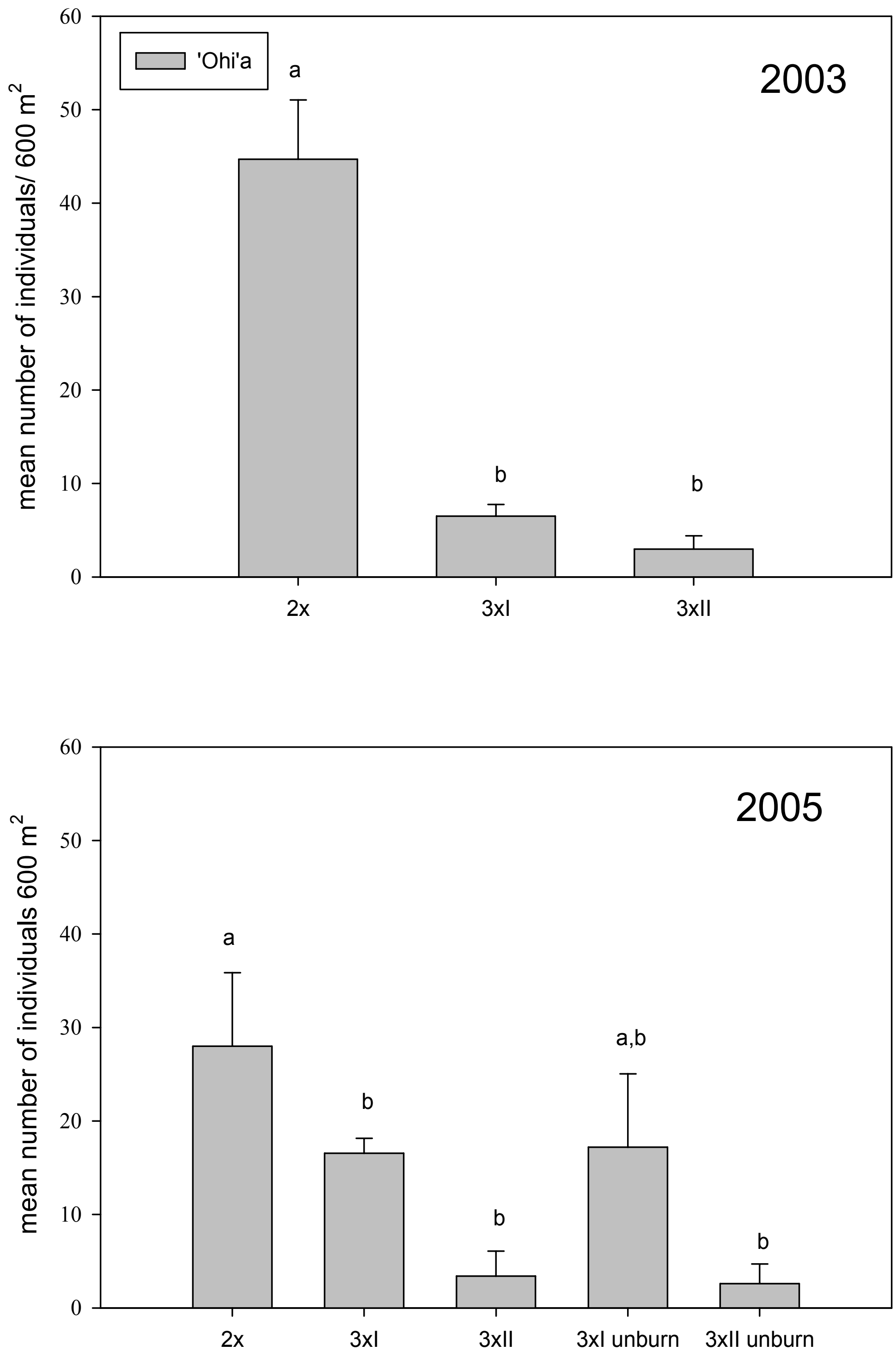

Figure 11. Mean density of 'ohi'a trees one (2003) and three years (2005) following fire. Managed and unmanaged plots are pooled for 2003 data. Different letters (a,b) indicate significant differences at $p < 0.05$.

Recovery of Mature ‘Ōhi’a Following Fire

Among the 102 'ōhi'a tagged individuals monitored in the burn, char height ranged from 1-9 m with an average of 3.9 m. The scorch height ranged from 3.5 m to 13.5 m with an average of 7.6 m. Burn severity of the substrate was 3.4 and 2.0 for the vegetation. The average tree height was 8.6 m with a range of 4-14 m. Thirty-one percent of the tagged 'ōhi'a survived four years following the burn. Regeneration was by live crown (34%), epicormic resprout (28%), or basal resprout (69%).

Discussion

Rehabilitation of the Kupukupu Burn was the first attempt by park managers to restore fire-affected ‘ōhi’a/swordfern communities and the second attempt at large scale burn restoration at Hawai’i Volcanoes National Park. Field and laboratory experiments conducted between 1993 and 2000 had identified fire-tolerant native plant species that could be used to restore burn-damaged areas where the likelihood of recurring future fires was high (Loh unpublished). Based on this information, managers restored 1,000 acres of seasonally dry 'ōhi'a woodland (4,000 ft elevation) affected by the 2000 Broomsedge Burn. The Kupukupu Burn Rehabilitation provided managers with the opportunity to do large scale restoration in a different environment and in a more remote area of the park. The project took three years to complete. Almost 1,500 worker days was spent on the various tasks (vegetation recovery monitoring, seed collection, propagation, planting seeding, data summarizing). Included in the efforts were volunteers, Youth Conservation Corp (YCC), cooperators and park seasonal and permanent staff. Funding provided by Burn Area Rehabilitation was $280,164, park staff and volunteers contributed additional support for the project.

Establishment of Native Plants by Planting and Seeding

Native plant establishment through planting and seeding appeared promising based on early monitoring results. Initial establishment of individuals by seed augmentation into the burn was evident for five of the twelve species (māmane, 'iliahi, ‘ūlei, ko’oko’olau, pilo). Subsequent one year survivorship of tagged seedlings was 28% for māmane, 39% for ‘ūlei, and 90% for ko’oko’olau. Since highest mortality is expected within the first year (McDaniel unpublished, Ainsworth unpublished), there is a strong likelihood that many first year survivors will continue to grow to reach reproductive maturity. Range of seedling survivorship was similar to those observed for māmane (40%) and ko'oko'olau (100%) in the Broomsedge Burn and was much higher for ‘ūlei than previously measured in seeding experiments conducted in dry 'ōhi'a woodlands (Loh *et al*. 2007, Ainsworth unpublished). Seedlings were not observed for six of the augmented species. With the exception of māmaki, these species have inherently low (< 5%) germination rates even under controlled greenhouse conditions (McDaniel unpublished data). Māmaki has higher germination rates in the nursery (~30%), but the seedlings are very sensitive to drought conditions and seed broadcast may be more successful in a wetter environment. Of the seedlings that germinated, but did not survive, various plant pathogens may be hindering establishment. In the nursery, wire-stemming fungus (*Rhizoctonia spp.*) has been observed on alahe’e seedlings and stem borers were observed on kolomona seedlings. In addition, initial establishment rates for these species were very low which may not have provided a sufficient sample size to accurately evaluate survivorship in these species.

Among planted individuals, survivorship ranged between 35% (*Tephorsia purpurea*) to 92% (*Chamaesyce celastroides*). In general, survivorship rates were lower in Kupukupu than were recorded in the Broomsedge Burn rehabilitation project (Loh *et al*. 2007) and higher than in the ongoing Kipuka Pepeiao Fire rehabilitation (McDaniel unpublished data). Together these three sites represent a moisture gradient that extends across the seasonally dry ‘ōhi’a woodlands in the park (Broomsedge = wettest, Kupukupu = intermediate, Pepeiao = driest). This data illustrates the influence of local climatic factors on individual species survivorship. *Myoporum sandwicensis* appears to be more resilient to climatic differences then the other species, maintaining a high survival rate (>70%) across all three sites. Other conditions unique to the Kupukupu area, such as vog and swordfern competition (rather than alien grasses) may have had a significant impact on survival.

By 2006, 14 of the 35 planted species had reached reproductive maturity; all were herbaceous or shrub species. Of the 15 planted tree species, 11 had survivorship rates greater than 40% after one year suggesting that many of these will continue to survive and reach maturity. During the last 30 years, this area has experienced four large wildfires and additional fires will likely occur in the future. Consequently, reproductive maturation of planted individuals and establishment of a soil seed bank before another wild fire is critical to ensure the long-term persistence of planted species. The assumption, based on observations in previous wildfire and research burns, is that future fires may top-kill individuals, but these fire-tolerant species will survive and proliferate through vegetative re-growth and seedling recruitment from the soil seed bank in response to fire.

Natural Recovery of Pre-Burn Community After Fire

The vegetation in the pre-burn community had been largely shaped by a series of previous fires that had occurred in 1972, 1981, and 1992 (NPS unpublished data). Very few native species, with the exception of 'ōhi'a and 'a'ali'i, remained in the area. Instead, large swards of fire-adapted non-native swordfern and broomsedge dominated the pre-burn landscape. Four years following the 2002 Kupukupu Burn, natural recovery of ‘ōhi’a (31%) was low and consistent with similar data collected from the 1992 burn where two year survivorship was ~40% (Tunison *et al.* 1995). Among the 2002 burn survivors, about a third of the individuals had crown survivorship, the rest regenerated from basal or epicormic resprouts. Very little seedling establishment was observed in the burn, and it is doubtful that seedlings will contribute much to the future recovery of ‘ōhi’a stands. This may lead to continued stand reduction with recurring fire in the future.

In contrast 'a'ali'i quickly reestablished by seedling regeneration in the burned area. The positive response of ‘a'ali'i to fire is consistent with previous studies conducted in the park (D’ Antonio *et al.* 2000, Tunison *et al.* 1995) that found recovery was largely by seedling recruitment. Similarly, the rapid re-establishment of alien swordfern is consistent with results from these previous studies.

Conclusions

The Kupukupu Burn Rehabilitation project is the second in a series of efforts to restore native plant communities affected by recent wildfire. Over the past 35 years, four wildfires have occurred in this area. The 3,367 acre Kupukupu Fire was the largest of these wildlfires. More wildfires can be anticipated in the future given the abundance of burnable fuels (e.g. swordfern, broomsedge) recurrence of extended dry periods, and a nearby ignition source provided by active lava flows. Previous studies (Tunison 1995, Ainsworth 2007) indicated that multiple fires reduced the abundance and diversity of native species in the area. The assumption that future fires will continue to erode the remaining native species, have led park managers to adopt an aggressive approach to restoring these areas using a subset of native species that were historically documented in the area and appear to be fire tolerant.

Recommendations

Based on the results of this project, the following management recommendations for restoration of other fire-affected dry ‘ōhi’a woodlands in HAVO include:

1. Continue to establish seed stockpiles and plant orchards to increase plant material available for large-scale restoration. In the 2000 Broomsedge Burn (1,008 ac) and 2002 Kupukupu (3,700 ac), low supplies of plant material and seeds limited the pace of plant production and, in some instances, the

number of individuals of a species established in the burn. In the Broomsedge burn, a lot of time (estimated 40% of volunteer worker days) was devoted to searching for and collecting plant material for plant propagation and seeding. The rapid response in the Kupukupu Burn was largely due to previously stockpiling of several species in anticipation of a wildfire event. For species with seeds that do not remain viable in storage over several years (Yoshinaga 2002), or whose seeds are extremely scarce, plant orchards should be established. Cultivation of stock material could be in outdoor nurseries or in natural areas, and would provide a steady supply of plant material for future propagation and restoration. Orchards would also protect the genetic integrity of species by preserving plant material collected from source material that may be otherwise inaccessible or vulnerable to negative stochastic events.

2. Continue to monitor the effectiveness of planting and seeding efforts, and the natural recovery in the burned area. For this fire, the strategy was to create small fire-tolerant native plant associations concentrated in plots scattered across the 455 ac restoration area. The assumption was that individuals would mature, reproduce, and eventually establish a soil seed bank for future proliferation following the next fire event. This jumpstart approach toward the development of an alternative fire-tolerant native plant community, based on both experimental burns and wildfire, was perceived as the most feasible strategy for rehabilitating large expanses of fire damaged-areas, and was first applied in the 2000 Broomsedge Burn area (Loh et al. 2007). In the Kupukupu burn area, the initial establishment of species appears promising. However, future persistence will vary depending on local site conditions and the occurrence of the next wildfire in relation to the development of a soil seed bank. Consequently, long term monitoring in multiple restoration sites is needed to help managers determine the success of their treatments and effectively plan for future restoration projects.