J. Range Manage.
53:106–113 January 2000

Reassessment of revegetation strategies for Kaho‘olawe Island, Hawai‘i

ALAN D. ZIEGLER, STEVEN D. WARREN, J. LYMAN PERRY AND THOMAS W. GIAMBELLUCA

Alan Ziegler is a doctoral candidate in the Department of Geography, 2424 Maile Way, 445 Porteus Hall, University of Hawai‘i, Honolulu, Hawai‘i 96822; Steven Warren is a research scientist, Land Management Laboratory, US Army Construction Engineering Research Laboratories, Box 9005, Champaign, Ill. 61826-9005; Lyman Perry is State Forester, Division of Forestry and Wildlife, State of Hawai‘i, Box 4849, Hilo Hawai‘i, 96720; Thomas Giambelluca is a professor of Geography at the University of Hawai‘i, Honolulu, Hawai‘i 96822.

Abstract

This work investigates 2 US Army Construction Engineering Research Laboratory revegetation experiment sites (Phase I and II) on Kaho‘olawe Island, Hawai‘i (USA) to determine the long-term success of several revegetation strategies and to identify species that are best suited for future restoration activities in the highly eroded central plateau region of the island. Only the Phase I treatments receiving the highest rates of phosphorus and nitrogen fertilizer and the Phase II strategy (moderately high fertilizion, and landscaping) produced enough cover to begin providing protection from erosion processes. Buffelgrass (*Cenchrus ciliaris* L.), glycine (*Neonotonia wightii* (Wight & Arnott) Verdc.), Natal redtop (*Rhynchelytrum repens* (Willd.) Hubb.), and siratro (*Macroptilium atropurpureum* (DC) Urb.) appear to be resilient to the harsh island conditions, which include strong winds, low annual rainfall, acute erosion, and a nutrient-depleted soil profile. Although all 4 species offer some protection against erosional processes, none are particularly desirable for long-term restoration of the island. Glycine and siratro, both of which volunteer readily in planting sites, are considered invasive in that they may smother other more desirable species, particularly less competitive natives. Finally, native woody species are shown to have difficulty in surviving on the island without special attention to planting and maintenance.

Key Words: Island restoration, long-term monitoring, ecology

Resumen

Este trabajo investiga 2 sitios experimentales de revegetación del Laboratorio de Investigación e Ingeniería de Construcción del Ejercito de E.U.A. (fase I y II) localizados en Kaho‘olawe Island Hawai‘i (E.U.A.). El objetivo fue determinar el éxito a largo plazo de varias estrategias de revegetación e identificar las especies mas apropiadas para actividades futuras de revegetación en regiones altamente erosionadas de las mesetas centrales de la isla. Solo los tratamientos de la fase I que recibieron altas cantidades de fertilización fosforada y nitrogenada, y las estrategias de la fase II, fertilización moderadamente alta y manejo del paisaje produjeron cobertura suficiente para iniciar la protección contra el proceso de erosión. El "Buffelgrass" (*Cechurus ciliaris* L.),"Glycine" (*Neonotonia wightii* (Wight & Arnott) Verde) "Natal redtop" (*Rhynchelytrum repens* (Willd) Hubb.) y "Siratro" (*Macroptilium atropurpureum* (DC) Urb.) parecen ser resistentes a las condiciones adversas de la isla, las cuales incluyen fuertes vientos, baja precipitacion anual, erosión aguda y un perfil de suelo pobre en nutrientes. Aunque las 4 especies ofrecen algo de protección contra el proceso de erosivo, ninguna es particularmente deseable para una recuperación a largo plazo de la isla. "Glycine" y "Siratro", ambas colonizan rápidamente los sitios de plantación, y son consideradas invasivas, ellas pueden suprimir otras especies más deseables, particularmente las nativas menos competitivas. Finalmente las especies leñosas muestran tener dificultad para sobrevivir en la isla sin atención especial para plantarlas y mantenerlas.

Prior to European contact, the Hawaiian island of Kaho‘olawe (Fig. 1) had become important to native Hawaiians as a site for religious practices, astronomical and navigational training, tool making, fishing, and agriculture as early as 1000 A.D. (Kaho‘olawe Island Conveyance Commission 1993). Original dry scrub forest vegetation of the island may have given way to a grassland in some areas as a result of agricultural practices of Hawaiians, especially burning. Substantial erosion may have occurred on the island as early as the 1500s (Kirch 1982). Severe vegetation loss and soil loss were greatly enhanced following the introduction of goats in 1793. Following the onset of western style ranching in the 1850s, the 1880s overgrazing by large herds of goats and sheep had led to significant wind and gully erosion. At about that time, kiawe (*Prosopis pallida* (Humb. & Bonpl. ex Willd.) Kunth) was introduced by ranchers to check soil loss, but erosion problems continued to worsen throughout a period during which Kaho‘olawe was designated a forest reserve (1910–1918) and during the subsequent return to ranching. Although ranching was discontinued when the U.S. Navy took control of the island for training purposes in 1941, feral goats remained, continuing to thwart restoration efforts until they were finally eradicated in the early 1990s (cf., Giambelluca et al. 1997). By this time, the

Acknowledgments. We would like to thank the following folks for their support in the investigation: John R. Egan, S. Kanani Garcia, Fred Richardson, and Allison A. Chun-Smith (field data collection; historical research); Julsun Pacheco and Renee Louis (cartography); Malli Aradhya and Alexis Y. Lee (vegetation analysis), Stephanie Aschmann (consultation), Ross A. Sutherland (statistical analyses), and the U.S. Department of Navy, Army, and Air Force Explosive Ordnance Personnel. We especially thank Keoni Fairbanks and Paul Higoshino (Kaho’olawe Island Reserve Commission) for their support in all phases of the project. Field research was partially funded by the Kaho’olawe Island Reserve Commission. Alan Ziegler is supported through a Horton Research Grant from the Hydrological Section of the American Geophysical Union and an Environmental Protection Agency STAR fellowship.
Manuscript accepted 17 May 1999.

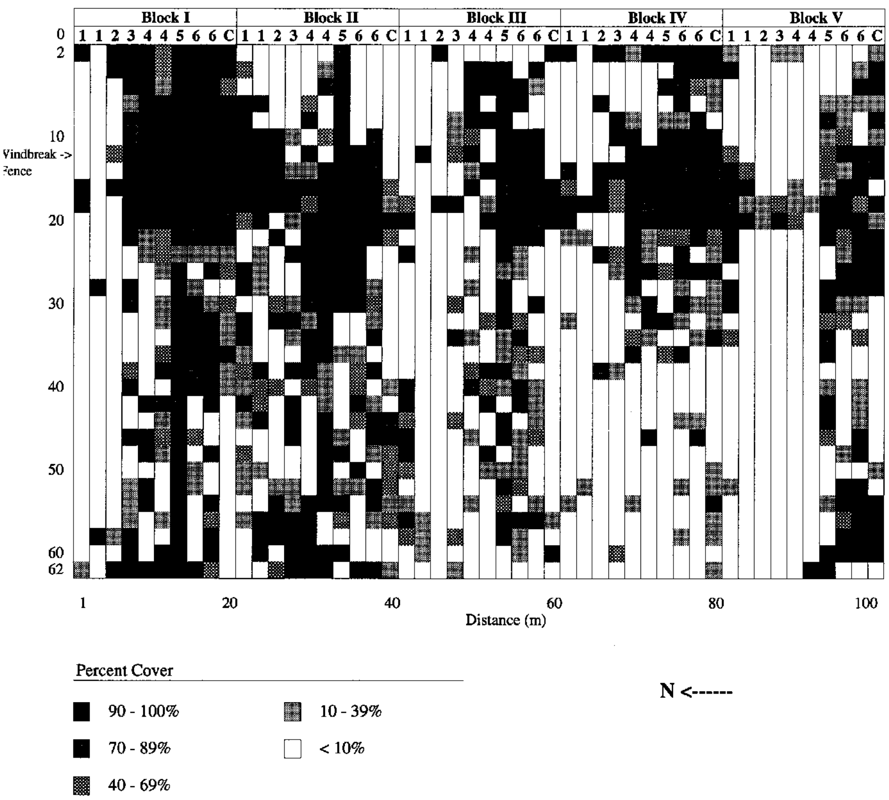

Fig. 2. Spatial distribution of ground cover in the Phase I planting area. The darkest squares correspond to areas of highest cover. Treatment planting strips and treatment blocks are labeled at the top of the diagram. Treatments are described in Table 2.

seed for the state of Hawai'i. Buffelgrass, bermudagrass, Guinea grass and glycine were used because of apparent success during the 1970s. Yellow bluestem, plains bristlegrass and buffalograss were selected for their drought tolerance on the mainland United States. Fifty strips (2 x 62 m) were treated with various combinations of fertilizer, jute netting, and seed. Fertilizer selection was based on an earlier study that determined phosphorus to be a major limiting nutrient on the island (Warren et al. 1988) and evidence that tropical soils in general are often low in nitrogen (Manrique 1993). The use of a high concentration of phosphorus was due to the abundance of iron and aluminum oxides and hydroxides, which are well known for their propensity to bind phosphorus and make it unavailable to plants. The treatments are summarized in Table 2.

The plantings were conducted in 5 adjacent, identical blocks, with treatments 1, 4, and 6 repeated within each block (Fig. 2). Therefore, these 3 treatments were replicated 10 times; all other treatments and the control, 5 times. The planting strips were laid out parallel to the prevailing wind direction. A windbreak fence was constructed perpendicular to the strips about 12 m from the windward end. Initial assessment of Phase I, about 15 months following planting (Warren and Aschmann 1993), revealed: (i) treatments consisting of moderate and high fertilizer rates (i.e., T4, T5, and T6 in Table 2) were the most effective; (ii) jute netting and windbreak fencing significantly enhanced plant coverage, but may be prohibitively expensive; (iii) buffelgrass, common bermudagrass, and weeping lovegrass (*Eragrostis curvula* (Schrad.) Nees, probably a contaminant in one of the other grass seed stocks) were the most successful 'planted' species in becoming established; and (iv) Australian creeping saltbush (*Atriplex semibaccata* R. Br.), although

Table 2. Six treatments and control associated with the CERL Phase I planting.

Identifier	Treatment[1]
T1	Seed only
T2	Seed and jute netting
T3	Seed and fertilizer rate 1
T4	Seed and fertilizer rate 2
T5	Seed, fertilizer rate 2, and jute netting
T6	Seed and fertilizer rate 3
C	Control

[1]Fertilizer rate 1 = 3.6 kg ha^{-1} N plus 17.1 kg ha^{-1} P_2O_5; Rate 2 = 62 kg ha^{-1} N plus 291 kg ha^{-1} P_2O_5; and Rate 3 = 123 kg ha^{-1} N plus 582 kg ha^{-1} P_2O_5 (Warren and Aschmann 1993).

not planted, responded favorably to seedbed preparation and fertilization. The windbreak fence ruptured a short time after planting, thus contributing less protection to the restoration sites than intended, particularly for Blocks II and III.

Additionally, within the CERL Phase I project area, 310 native woody plants (Table 3) were planted in 3 rows, perpendicular to the treatment strips, at 0, 12.3, and 60 m from the beginning of the planting area (Warren and Riggins 1991). This planting was conducted in December 1988. One hundred plants were planted at equal intervals in the first row; 100 and 110, in rows 2 and 3, respectively (Table 3). Row 2 is located ≈ 0.3m leeward of the windbreak fence. Monoammonium phosphate fertilizer was added to approximately half the plants in each row. No formal investigation has been made of the survivorship of these plants.

Phase II was a larger-scale revegetation effort, conducted in January and November 1990, utilizing a chisel plow seeder to scarify and plant an 8-ha watershed, having a pre-planting vegetative cover of 1.4% (Warren and Riggins 1991). The seeding mixture included buffelgrass, common bermudagrass, weeping lovegrass, and Italian ryegrass (*Lolium multiflorum* Lam.). Fertilization at a rate of 70 kg ha^{-1} N plus 179 kg ha^{-1} P_2O_5 was applied to the furrows created by the chisel plow (Warren and Aschmann 1993). The initial

Table 3. Native woody species planted in CERL Phase I (from Warren and Riggins 1991). Numbers reflect total species planted only; they do not indicate planting order.

Species	Row 1[1]	Row 2	Row 3
wiliwili (*Erythrina sandwicensis* Degener)	21	22	59
'ūlei (*Osteomeles anthyllidifolia* (Sm.) Lindl.)	10	10	9
'a'ali'i (*Dodonea eriocarpa* Sm.)	20	20	19
koa (*Acacia koa* A. Gray)	20	20	5
ko'oloa'ula (*Abutilon menziesii* Seem.)	19	10	6
ma'o (*Gossypium tomentosum* Nutt. ex Seem.)	10	18	12
TOTAL	100	100	110

[1]Rows 1, 2, and 3 are located at 0, 12.3, and 60 m respectively from the beginning of the planting area (shown in Fig. 2).

cumulative effects of ranching, decades of uncontrolled grazing by feral goats, and military use had left one third of the island barren, with large areas completely without topsoil (cf. Loague et al. 1996, Nakamura and Smith 1995). Today, this largely barren plateau is commonly referred to as the "hardpan". Hardpan vegetation consists mainly of introduced species including kiawe, tamarisk (*Tamarix aphylla* (L.) H. Karst.), buffelgrass (*Cenchrus ciliaris* L.), Natal redtop (*Rhynchelytrum repens* (Willd.) Hubb.), lantana (*Lantana camara* L.), koa haole (*Leucaena leucocephala* (Lam.) de Wit), and pitted beardgrass (*Bothriochloa pertusa* (L.) *A. Camus*). Additionally, native pili or twisted beardgrass (*Heteropogon contortus* (L.) P. Beauv. ex Roem. & Schult.), ‘ilima (*Sida fallax* Walp.), and indigenous (status uncertain) ‘uhaloa (*Waltheria indica* L.) are moderately abundant.

Restoration of soil and vegetation, especially native species, is a prerequisite for the Kaho‘olawe Island Reserve Commission's (1995) vision for the future of Kaho‘olawe. During the past few decades, various entities have initiated projects on Kaho‘olawe, including research-oriented or pilot studies, and other direct attempts at improving the vegetative cover or arresting soil erosion. Two studies undertaken in 1988 and 1990 by the U.S. Army Construction Engineering Research Laboratories (CERL) investigated the use of exotic grass seeding, various treatments of fertilizer, windbreak fencing, and jute netting (Warren and Aschmann 1993). In this work, we reassess the CERL plantings to determine: (i) changes in individual species coverage and overall species composition among various treatments and planting blocks since the initial assessment; and (ii) native and exotic species most capable of persisting on this barren windswept area, following revegetation efforts.

Materials and Methods

1988–1991 Investigations

The CERL vegetation trials were initiated at 2 sites on the hardpan in 1988 to identify effective, economical techniques for revegetation. Scarcity of hardpan vegetation (< 2% at time of planting) results in part from low annual rainfall totaling only approximately 370 mm (Ziegler and Giambelluca 1997). More importantly, the paucity of vegetation cover results from significant overgrazing by feral goats and

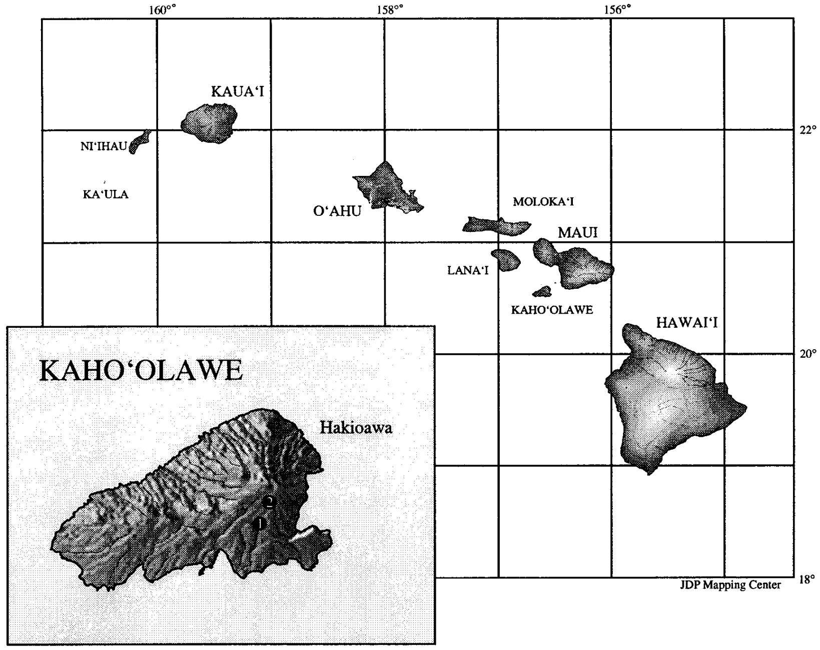

Fig. 1. Kaho‘olawe, the 8th largest island in the Hawaiian archipelago, rests in the rainshadow of Mt. Haleakalā on Maui Island to the northeast. Research was conducted within two areas associated with the U.S. Army Corps of Engineers Construction Engineering Research Laboratory (CERL) planting Phases I and II.

the ensuing large-scale erosion. Today the soil surface, which is probably lower than the original by > 2 m, is best described as the Bw horizon of the Kaneloa and Puu Moiwi Oxisol soil series (cf. Nakamura and Smith 1995). Soil in this general area is slightly acidic, and low in phosphorous, calcium, and zinc (Table 1). Salinity is not problematic; calcium and magnesium levels are high. Total nitrogen is low for ideal plant growth. Bulk density of the disturbed barren soils is high (1.2 g cm^{-3}), and partly as a result, saturated hydraulic conductivity is only about 120 mm hour^{-1}. This area is the source area of significant overland flow eroding large gullies on the slopes extending down the plateau to the coastline (Loague et al. 1996).

During Phase I, a seed mixture of one legume (glycine [*Neonotonia wightii* (Wight & Arnott) Verdc.]) and 6 exotic grasses (buffelgrass, yellow bluestem [*Bothriocloa ischaemum* (L.) Keng], plains bristlegrass [*Setaria leucopila* (Scribn. & Merr.) K. Schum.], buffalograss [*Buchloë dactyloides* (Nutt.) Engelm.], common bermudagrass [*Cynodon dactylon* (L.) Pers.], and Guinea grass [*Panicum maximum* Jacq.]) was sown. The choice of exotic species was necessitated by the absence of commercial sources of adequate quantities of native

Table 1. Chemical and physical characteristics of surface soils within the general area of the Phase I and II planting sites on Kaho‘olawe.

Soil Characteristics[1]	Units	Value
pH		6.8
P	ppm	15
K	ppm	325
Ca	ppm	839
Mg	ppm	543
Total N (TN)	%	0.1
Organic carbon (OC)	%	1.2
OC/TN	—	9.7
Zn	ppm	0.3
Electrical conductivity (EC)	mmhos cm^{-1}	0.3
Saturated hydraulic conductivity	mm hour^{-1}	117.5
Field bulk density	g cm^{-3}	1.16
Soil moisture at saturation	g g^{-1}	0.47

[1]pH, P, K, Ca, Mg, TN, OC, Zn, and EC data are means of 32 surface (0–10 cm) samples (from Ziegler and Smith 1998). All other values were determined as a weighted mean of CERL O-group and V-group lands in the Giambelluca et al. 1997.

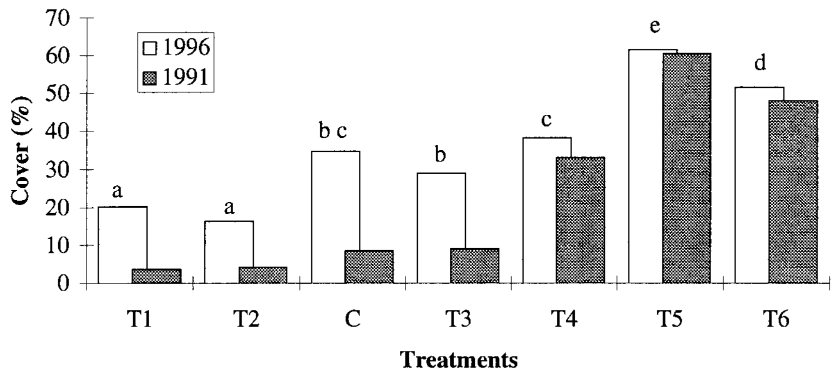

Fig. 3. Percent cover within the 6 treatments and the control in the Phase I area for the 1991 assessment (Warren and Aschmann 1993) and the study reported herein. For the 1996 values, similar letters indicate cover values are not statistically different (ANOVA, $\alpha = 0.05$). Treatments are described in Table 2. Increases since 1991 for Treatments T1, T2, T3, and the control are significant (t-test, $\alpha = 0.05$).

results of a field survey conducted in January 1992 revealed the following: (i) average foliar coverage was 55% compared to 6% in outside control areas; (ii) weeping lovegrass contributed 31% of the total foliar coverage; and (iii) success of the project, relative to Phase I, was attributed, at least in part, to an increased ratio of N to P_2O_5 in the fertilizer and the use of Italian ryegrass to provide a fast-growing protective vegetation cover (Warren and Aschmann 1993). The success of Phase II compared with Phase I might be attributed to better growing conditions at the former, such as better wind protection or more rainfall. Furthermore the landscaping conducted at the Phase II site prior to planting may have influenced soil moisture by damming overland flow, thus retaining more water on-site for plant use. Plowing also breaks up the hard surface crust, decreases the soil bulk density, increases porosity (especially macroporosity), thus leading to increased infiltration and more favorable conditions for root growth.

1996 Measurements

At the Phase I site, vegetative cover of all plant species was measured in June and August 1996 using the relevé sampling method (Mueller-Dombois and Ellenberg 1974). This methodology follows that of Warren et al. (1988) who surveyed the site initially in 1988 and then again in 1991, 25 months after planting (Warren and Aschmann 1993). For the 1996 survey, 50 transects (62 m in length) were established along the central axis of each treatment strip and sampled using a 0.25 m^2 frame. At 2-m intervals along each transect individual species coverage and bare ground was visually estimated within the sampling frame using the Braun-Blanquet scale (Mueller-Dombois and Ellenberg 1974). Briefly, with this technique, numbers from 1 to 10 are assigned for each species and bare ground. The Braun-Blanquet values correspond to ranges of cover values. Coverages were quantified by assigning the midpoint values of cover ranges (i.e., 1 = 0.5%, 2 = 3.0%, 3 = 7.5 %, 4 = 17.5%, 5 = 37.5%, 6 = 62.5%, 7 = 82.5%, 8 = 92.5%, 9 = 97.0%, and 10 = 99.5%). Individual species coverage within a given treatment strip was computed as the mean of 31 sampling locations. Because Braun-Blanquet values are not additive, total foliar coverage within a treatment strip was computed as the residual of the bare cover values (i.e., 100% - percent bare ground).

For sampling in the Phase II site, we utilized the boot-step method (Cook and Stubbendieck 1986), which was employed in surveys conducted in 1987 and 1991 (Warren et al. 1988). Briefly, this method involves identifying the plant species present at the tip of the toe of each "boot step" on a randomly walked path through the study area. Species coverage is computed as the percentage of times the species was encountered. To increase comparability with the prior assessment, we attempted to follow the route sampled by Warren et al. (1988) between specified markers.

The depth of "soft soil" above the hardpan surface was measured as an indicator for sediment depth on the Phase I site. This measurement involved recording the depth a 0.01 m diameter rod could be pushed into the soil surface before reaching the resistant hardpan below. Sediment depth was sampled at 2 m intervals on 12 transects, running parallel to the planting strips. The transects were established every 5 m, beginning from the northern end of the planting site. This measurement was used to ascertain how the windbreak fence may have contributed to sediment accumulation within the planting area and to investigate correlations between sediment depth and vegetation cover.

Three-factor analysis of variance (ANOVA) was used to assess the effects of (1) planting treatments, (2) treatment block location, and (3) location with respect to the windbreak fence on total vegetation cover in the experiment area. If ANOVA tied-P values were less than 0.05 during testing of each individual factor, 1-factor ANOVA followed by post-hoc testing with Fisher's Protected Least Square Difference test (FPLSD) was employed to identify groups that were statistically indistinguishable. The one sample t-test was used to evaluate changes since the initial assessment in percent cover for the 7 treatments and the 5 blocks. Finally, the nonparametric Spearman Rank Correlation Coefficient was computed to show the influence of sediment depth and fertilizer application rates on percent cover.

Results and Discussion

CERL Phase I

Total foliar coverage in the Phase I planting area was 36%, compared with 24% cover determined in 1991 by Warren and Aschmann (1993). Fig. 2 depicts the current distribution of vegetative cover within the 6,200 m^2 planting area. A total of 20 species (6 sown; 14 volunteer) were present, with buffelgrass, glycine, Natal redtop, and siratro (*Macroptilium atropurpureum* (DC) Urb.) having the greatest coverages (Table 4). The 16 other species present had cover values $\leq$1%. Each of the 4 most common species in our survey increased in coverage since 1991. Only 2 species, common bermudagrass and Australia creeping saltbush, decreased substantially since 1991. Australian creeping saltbush is a pioneer species on Kaho'olawe that dies back after producing seed (approximately 2 years). The decline of this species between 1991 and 1996 suggests competition may be preventing propagation of new saltbush plants. Buffalograss and plains bristlegrass, which were originally planted in 1988 and present in the 1991 assessment, were absent in our survey. Buffelgrass and glycine, and 2 volunteer species, Natal redtop and siratro, demonstrate the greatest ability to persist on the hardpan for periods of several years.

In general, treatments with the highest fertilizer rates (i.e., T4, T5, and T6) still had the highest cover values since the initial assessment (Fig. 3). Total plant cover for these 3 treatments increased only slightly since 1991, while cover for the control and treatments T1, T2, and T3 increased significantly (t-test, $\alpha = 0.05$). Cover for the lowest fertilizer treatment (T3) was not statistically different from the control—nor was the higher fertilizer T4 treatment. Cover for the 2 non-fertilizer treatments (T1 and T2), however, was significantly less (ANOVA, $\alpha = 0.05$), perhaps because the control plots were located adjacent to, and thus influenced by, the high fertilizer plots (i.e., T6, see Fig. 2). In general, buffelgrass appeared to respond favorably to all levels of fertilizer treatments (T3-6, Table 4); and glycine responded well to the highest levels of fertilization and jute netting (T5 and T6).

Jute netting (T2) alone did not produce significant cover increases, demonstrating the importance of fertilizing the nutrient-poor soil of this area. The fertilizer treatments contained various application rates (also various ratios) of P- and N-based fertilizer (Table 2). The general trend was as total application rate increased vegetative cover increased—and there was no indication that a threshold had been reached such that increasing N and P would not promote greater cover. Nor were important limiting micronutrients, such as zinc, included in the tested fertilizer mixtures.

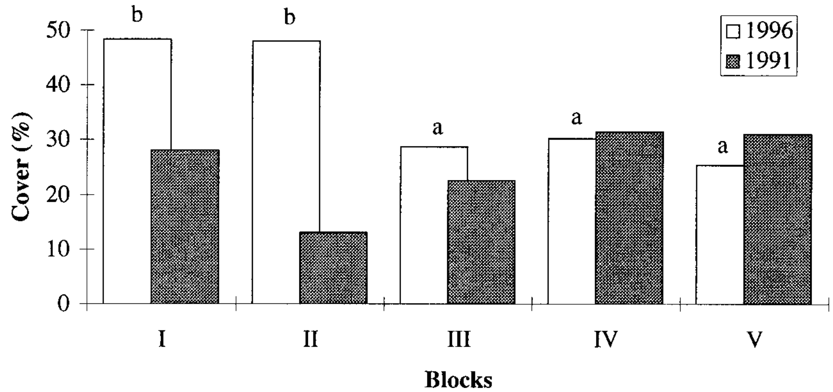

Fig. 4. Percent cover in the 5 planting blocks in the Phase I area for the 1991 assessment (Warren and Riggins 1991) and the study reported herein. For the 1996 values, similar letters indicate cover values are not statistically different (ANOVA, $\alpha = 0.05$). Changes for all Blocks, except IV, since 1991 are significant (t-test, $\alpha = 0.05$).

Prior laboratory and field studies suggest a ground cover of approximately 40 to 60% is needed to provide significant protection from erosion detachment and transport processes (e.g. DePloey et al. 1976, Morgan et al. 1986, Rogers and Schumm 1991). This threshold varies depending on soil hydrological/physical properties, rainfall characteristics, slope, and vegetation type. As a rough estimate of the erosion control effectiveness of the various treatments, the nonlinear relationship between groundcover and sediment transport by runoff reported by Dadkhah and Gifford (1980) is useful. This relationship suggests that treatments T4, T5, and

Table 4. CERL Phase I total ground coverage (%) of plant species for the initial assessment (1991) and this study (1996); and coverage within the seven fertilizer treatments for 1996.

			Total Coverage		1996 Coverage by Treatments[2]						
N/E[1]	Species	Common Name	1991	1996	T1	T2	T3	T4	T5	T6	C
	PLANTED		(%)								
E	*Bothriochloa ischaemum* (L.) Keng	yellow bluestem	t	t				t			
E	*Buchloë dactyloides* (Nutt.) Engelm.	buffalograss	t								
E	*Cenchrus ciliaris* L.	buffelgrass	7	9	4	4	12	10	12	12	4
E	*Cynodon dactylon* (L.) Pers.	common bermudagrass	4	t	t	t	t		t	t	tr
E	*Eragrostis curvula* (Schrad.) Nees[3]	weeping lovegrass	1	t	t	t	t	t	2	t	tr
E	*Neonotonia wightii* (Wight & Arnott) Verdc.	glycine	2	8	2	3	6	9	17	12	7
E	*Panicum maximum* Jacq.	Guinea grass	t	t	t			t	t	1	tr
E	*Setaria leucopila* (Scribn. & Merr.) K. Schum.	plains bristlegrass	t								
	NOT PLANTED										
E	*Atriplex semibaccata* R. Br.	Australian creeping saltbush	8	t		t	t	t	t	t	tr
E	*Chamaecrista nictitans* (L.) Moench	partridge pea		t			t	t			
E	*Conyza bonariensis* (L.) Cronq.	hairy horseweed		t						t	
E	*Digitaria pentzii* Stent	pangola grass		t	t		t	t		t	tr
E	*Emilia fosbergii* Nicolson	pualele		t	t		t	t	t	t	tr
E	*Macroptilium atropurpureum* (DC) Urb.	siratro		3	4	1	1	2	1	3	4
E	*Nicotiana glauca* R.C. Graham	tree tobacco		t				t			
E	*Rhynchelytrum repens* (Willd.) Hubb.	Natal redtop		4	2	3	2	5	8	5	4
E	*Sonchus oleraceus* L.	pualele		t			t				t
E	*Tridax procumbens* L.	coat buttons		t	t						
N	*Waltheria indica* L.	‘uhaloa		t	t	t	t	t	t		tr
E	*Asclepias physocarpa* (E. Mey.) Schlechter	balloon plant		t		t		t		t	
E	*Bothriochloa pertusa* (L.) A. Camus	pitted beardgrass		t			t				
E	*Xanthium strumarium* L. var *canadense* (Mille.) Torr. & A. Gray	cocklebur		‘t’			t	t	t		
TOTAL[4]			24	36	20	16	29	38	61	52	36

[1]N is native; E is exotic; ‘t’ (trace) means present at less than 1%.
[2]Treatments are described in Table 1.
[3]This species was accidently present in the seeding mixture.
[4]Total values are computed as 100% - percent bare ground.

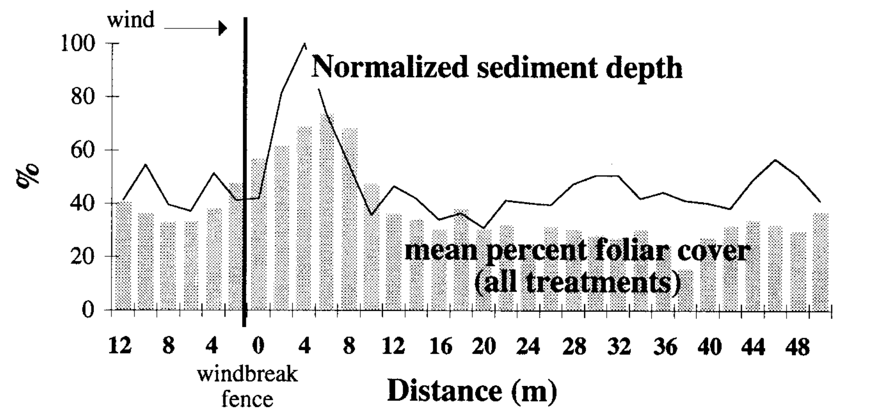

Fig. 5. Mean percent cover and mean normalized sediment depth (expressed as a percent) within the Phase I area. The Y-axis is percent for both cover and normalized sediment depth. A windbreak fence was originally constructed at 12 m.

T6 would reduce sediment output by 65, 79, and 75%, respectively. All other treatments would reduce output by ≤ 60%.

Blocks I and II had significantly higher cover than Blocks III, IV, and V (Fig. 4; ANOVA, $\alpha = 0.05$). In a prior assessment, Warren and Riggins (1991) reported that Blocks II and III, which were badly damaged by water erosion, had significantly lower foliar cover than the remaining blocks. Blocks II and III have largely recovered from the initial erosion damage. There is a slight increase in elevation across the study area from north to south (from Block I to V). The additional runoff that originally damaged Blocks II and III may now be contributing to their vegetative cover. Additionally, runoff water could be transporting P from treatments 3, 4, and 5 downslope, and thus contributing to the success of the other treatments and the control.

Three factor ANOVA indicated that differences in total vegetative cover are not independent of: (1) treatment, (2) planting block, or (3) distance from the windbreak fence; and differences in cover among treatments (or blocks, or distances) are not independent of the other 2 factors. With respect to distance, for 1-factor ANOVA, distances before and after the windbreak fence were classified into 5 groups: (1) 0 to 12 m windward of the fence; (2) 0 to 12 m leeward; (3) 13 to 24 m leeward; (4) 25 to 36 m leeward; and (5) 37 to 48 m leeward. Three statistically indistinguishable groups were identified, with {0 to 12 m leeward (64%)} > {windward (38%)} > {13 to 24 m, 25 to 36 m , 37 to 48 m leeward (27%, average of three groups)}. This relationship, which is apparent in Fig. 5, suggests the windbreak fence had a positive influence on promoting vegetative growth, probably by decreasing strong winds and creating sediment deposition areas where seeds could germinate.

In support, sediment depth was greatest 4 to 8 m leeward of the fence. The small peak at approximately 4 m windward of the fence is probably also related to deposition by wind. These distances are in reasonable agreement with literature values for sediment deposition both windward and leeward of a 1.2 m fence (cf., Morgan 1995). The sediment peak near the beginning of the planting area (10 m windward) may be that deposited leeward of a row of tamarisk trees (another revegetation project, cf., Giambelluca et al. 1997). Figure 5 shows the spatial relationship between sediment cover and sediment depth (normalized by dividing all values by the maximum depth, 11.5 cm; expressed as a percent). The 2 are positively correlated (tied-P value = 0.10; Spearman Rank Correlation). In Fig. 6, higher application rates of fertilizer are also shown to produce higher vegetative cover. Thus, sediment depth and fertilizer application rate both have a positive influence on cover. Figure 6 additionally shows that as fertilizer application rate increases the correlation between sediment depth and cover decreases (i.e., tied-P values increase toward one). This trend suggests fertilization is critical. Entrapment of windblown sediments may be beneficial for plant establishment, but this benefit pales in comparison to fertilization, particularly at higher rates.

Survival of Native Species in Phase I

Of the 310 native woody species planted in the Phase I site, only 14 (of 103 planted) wiliwili trees survive today. Nine are located immediately in the lee of the windbreak fence line (Row 2; Blocks I and IV); the remaining 5, in Row 3 (Blocks I and II), 60 m from the beginning of the planting area. These data reflect the difficulty of establishing native woody species on some parts of the island without careful attention to planting and maintenance, especially for plants other than wiliwili. The marginal success within Row 2 indicates that windbreak fencing may be beneficial for the establishment of some tree species.

Table 5. CERL Phase II species cover (%) for the planting year and at the time of this study.

N/E[1]	Species	Common Name	1988[2]	1996
			- - - - (%) - - - -	
	PLANTED			
E	*Cenchrus ciliaris* L.	buffelgrass		18
E	*Cynodon dactylon* (L.) Pers.	common bermudagrass		
E	*Eragrostis curvula* (Schrad.) Nees[3]	weeping lovegrass		17
E	*Lolium multiflorum* Lam.	Italian ryegrass		
	NOT PLANTED			
E	*Atriplex semibaccata* R. Br.	Australian creeping saltbush	1	2
E	*Asclepias physocarpa* (E. Mey.) Schlechter	balloon plant		t
E	*Bothriochloa pertusa* (L.) A. Camus	pitted beardgrass	't'	
E	*Casuarina equisetifolia* L.	common ironwood		t
E	*Chamaecrista nictitans* (L.) Moench	partridge pea		5
E	*Conyza bonariensis* (L.) Cronq.	hairy horseweed		t
E	*Emilia fosbergii* Nicolson	pualele		t
E	*Neonotonia wightii* (Wight & Arnott) Verdc.	glycine		12
E	*Lantana camara* L.	lantana		t
E	*Leucaena leucocephala* (Lam.) de Wit	koa haole		1
E	*Rhynchelytrum repens* (Willd.) Hubb.	Natal redtop		16
N	*Waltheria indica* L.	'uhaloa		1
	TOTAL		1	73

[1]N is native; E is exotic; 't' (trace) means present at less than 1%.
[2]1988 is at the time of planting; total cover was determined to be 55% in 1992 (individual species data are not available).

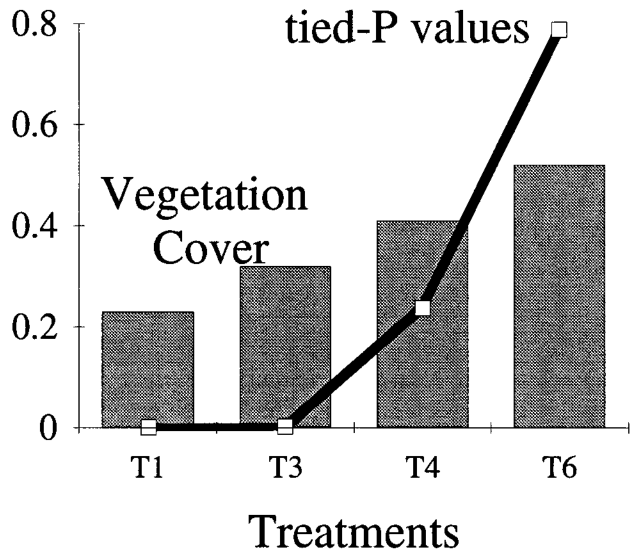

Fig. 6. The influence of fertilizer application rate on (1) total vegetation cover (expressed as a fraction) within a treatment (bars), and (2) the tied-P values for the Spearman Rank Correlation Coefficient (line) for total cover and sediment depth. The Y-axis contains values ranging from 0 to 1 for both cover and tied-P values. As fertilizer application rate increases cover increases. Meanwhile the correlation between sediment depth and cover decreases (i.e., tied-P value increase), indicating fertilizer application rate is more important in determining cover than is sediment depth. Treatments are described in Table 2.

Finally, ‘uhaloa (*Waltheria indica* L.) was the only woody native species to volunteer in either planting phase (Table 4, 5), demonstrating a lack of native seed sources to foster germination of new plants.

CERL Phase II

Total foliar coverage in the Phase II planting watershed has increased from 1% at planting in 1988 to 55% in January 1992, and finally to 73% in August 1996 (Table 5). Exotic grasses buffelgrass, weeping lovegrass, and Natal redtop, and the exotic viney legume glycine are now the most abundant species (18, 17, 16, and 12%, respectively). The latter 2 species were not sown. Glycine appears to have been a contaminant in the hay mulch used to stabilize terraces that were constructed across the site. In addition, 7 species absent in the 1992 survey were volunteers. Two species planted during Phase II, common bermudagrass and Italian ryegrass, were absent from our survey. Common burmudagrass similarly decreased at the Phase I site from 4% in 1991 to <1% in 1996, suggesting it is not suitable for revegetation. The inclusion of Italian ryegrass was credited in an earlier study (Warren and Aschmann 1993) for contributing to the success of Phase II because it established a fast-growing protective cover. Its disappearance in 1996 suggests it is not resilient to the harsh conditions and/or was outcompeted by one of the more dominant volunteers. Buffelgrass, the most abundant species in the Phase I site, was also the most abundant in the Phase II planting area. Weeping lovegrass, accidentally introduced in small quantities during Phase I, but intentionally planted during Phase II, was the second most abundant species (17%). Additionally, glycine and Natal redtop were more abundant in Phase II than Phase I; siratro however, one of the most abundant Phase I species, was not found in the Phase II area.

Conclusion

Vegetation within planting strips receiving large fertilizer inputs had the highest cover, demonstrating the benefits of phosphorus and nitrogen fertilization. However, there was no indication that appropriate fertilizer rates and combinations have been achieved to promote the greatest cover. The significant cover increases in the strips receiving little or no fertilizer may be artifacts of: (i) vegetation spreading from several large clumps centered around strips with high fertilizer application rates; (ii) enhanced plant growth in sediment deposition areas created by the presence of the windbreak fence; or (iii) growth promoted by run-on water transporting nutrients from treatments strips with higher fertilizer rates. In terms of providing adequate cover to reduce surface erosion processes, only treatments T4, T5, and T6 in Phase I and the Phase II strategy are potentially effective.

Four species, buffelgrass, glycine, Natal redtop, and siratro appear resilient to the harsh conditions on the windswept hardpan. Glycine and buffelgrass respond well to high rates of fertilization. Glycine, which was intentionally excluded from the planting mixture in Phase II because it was believed to smother other species, was still one of the most abundant species in the Phase II survey. The presence of glycine may result from contamination in the seed mixture, and/or dispersal, from on-island sources, including the Phase I site. Siratro, because it is similar to glycine in habit, is probably not a desirable revegetation species for Kaho‘olawe, despite its ability to volunteer and persist on the hardpan. Italian ryegrass and common bermudagrass do not appear to be successful long-term revegetation species. However, Italian ryegrass may be useful as a starter that will yield to more desirable species once growing conditions become more favorable (i.e., wind protection established, increased infiltration, increased organic matter). Survival of native woody species can be very low without the combination of other revegetation strategies such as rhizobial inoculation, windbreak fencing, protective vegetative cover, and/or carefully applied fertilization.

Future work should focus first on identifying appropriate species for island restoration. This should involve finding both fast starters and persistent long-term survivors. If nonnative species are to be used, care should be taken to select non-invasive species. Finally, planting strategies and fertilizer mixtures, determined from plant nutrient/rhizobial requirements of selected revegetation species and soil nutrient data, should be determined to promote quick establishment of pioneer species and long-term growth of other species resilient to the harsh climate conditions.

Literature Cited

Cook, C.W. and J. Stubbendieck. 1986. Range Research: Basic Problems and Techniques. Society for Range Management, Denver, Colo., 317 pp.

Dadkhah, M. and G.F. Gifford. 1980. Influence of vegetation, rock cover, and trampling on infiltration rates and sediment production. Water Resour. Bull. 16(6): 979–986.

De Ploey, J., J. Sawat., J. Moeyersons. 1976. The differential impact of some soil factors on flow, runoff creep and rainwash. Earth Surf. Process. 1:151–161.

Giambelluca, T.W. J.R. Egan, K. Garcia, J.L. Perry, F. Richardson, A.A. Chun-Smith, A.D. Ziegler. 1997. Lessons Learned: Kaho'olawe. Restoration Efforts Prior To 1996. Final Report. Kaho'olawe Island Reserve Commission, Honolulu, Hawii.

Kaho'olawe. Island Conveyance Commission. 1993. Kaho'olawe. Island: Restoring a cultural treasure. Final report to the Congress of the United States. xiv + 158 pp.

Kaho'olawe Island Reserve Commission. 1995. Kaho'olawe. Use Plan. State of Hawaii. 45 leaves.

Kirch, P.V. 1982. The impact of the prehistoric Polynesians on the Hawaiian ecosystem. Paci. Sci. 36(1):1–14.

Loague, K., D. Lloyd, T.W. Giambelluca, A. Nguyen, and B. Sakata. 1996. Land misuse and hydrological response: Kaho'olawe, Hawai'i. Pac. Sci. 50(1):1–35.

Manrique, L.A. 1993. Soil Management and Conservation in the Tropics. Manrique International Agrotech, Honolulu, Hawaii. 215 pp.

Morgan, R.P.C. 1995. Soil Erosion and Conservation. Second ed. Longman, Essex, England. 198 pp.

Morgan, R.P.C., H.J. Finney, H. Lavee, E. Merritt, and C. Noble. 1986. Plant cover effects on hillslope runoff and erosion: Evidence from two laboratory experiments. *In:* A.D. Abrahams (Editor), Hillslope Processes. Binghamton Symposia in Geomorphology No. 16. Allen and Unwin, London. pp. 77–90.

Mueller-Dombois, D. and H. Ellenberg. 1974. Aims and Methods of Vegetation Ecology. New York. John Wiley and Sons. 547 pp.

Nakamura, S. and C. W. Smith. 1995. Soil Survey of Island of Kahoolawe, Hawaii. U.S. Department of Agriculture, Natural Resources Conservation Service and the United States Department of Navy, Pacific Division, Naval Facilities Engineering Command. Washington, D.C.

Rogers, R.D., and S.A. Schumm. 1991. The effects of sparse vegetative cover on erosion and sediment yield. J. Hydrol. 123:19–24.

Warren, S.D. and S. G. Aschmann. 1993. Revegetation strategies for Kaho'olawe. Island, Hawaii. J. Range Manage. 46(5):462–466.

Warren, S.D. and R.E. Riggins. 1991. Rehabilitation of Kao'olawe. Unpublished Second Status Report. U.S. Army Construction Engin. Res. Lab, Environ. Div., Campaign, Ill.

Warren, S.D., E.G. Vachta, and W.L. Banwart. 1988. Rehabilitation proposal for Kaho'olawe Island, Hawaii: an interim report. U.S. Army Construction Engin. Res. Lab, Environ. Div, Campaign, Ill.

Ziegler, A.D. and A.A. Chun Smith 1998. Soil Nutrient Properties on Kaho'olawe. Island, Hawai'i. Technical Report #1998-ADZ01, Geomorphology Lab, Geography Dept., U. Hawaii Manoa. Prepared for Kaho'olawe. Island Reserve Commission, Honolulu, Hawaii.

Ziegler, A.D. and T.W. Giambelluca. 1997. The influence of revegetation efforts on hydrologic response and erosion, Kaho'olawe. Island, Hawai'i. J. Land Degrad. Develop.