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INFLUENCE OF REVEGETATION EFFORTS ON HYDROLOGIC RESPONSE AND EROSION, KAHOʻOLAWE ISLAND, HAWAIʻI

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ABSTRACT

Measurements of soil physical and hydrological properties provide the first evaluation of the success of revegetation efforts in reducing surface runoff and accelerated erosion on the largely barren plateau region of Kahoʻolawe Island, Hawaiʻi. Saturated hydraulic conductivity and sorptivity data, collected within four of the largest restoration sites, suggest revegetated areas have significantly higher infiltration capacities compared with those of the bare areas surrounding the project sites. Furthermore, comparison of modeled steady-state infiltration capacity to one-min rainfall intensities demonstrate erosion-producing Horton overland flow is very rare on the vegetated areas compared with the barren landscape. Thus, recently, established vegetation forms zones of high infiltration capable of absorbing both rainwater and surface flow exported from upslope areas. However, the current areal extent and spatial arrangement of vegetation is not sufficient to significantly reduce watershed-scale runoff and erosion. © 1998 John Wiley & Sons, Ltd.

KEY WORDS: island restoration; revegetation assessment; runoff response; erosion control

INTRODUCTION

Severe degradation of vegetation and ensuing accelerated soil erosion on Kahoʻolawe Island, Hawaiʻi (Figure 1) have resulted from decades of agricultural misuse, overgrazing by feral goats, and detonation of live ordnance by the US military (KICC, 1993). During the 1970s native Hawaiians protested the military use of Kahoʻolawe. In 1977 most large-scale ordnance testing was discontinued, and in the following years a handful of pilot conservation projects were initiated. In 1994 Kahoʻolawe was returned to the State of Hawaiʻi by the US Government, which additionally authorized $400 million to remove unexploded ordnance and support revegetation efforts to control the acute erosion that threatens Kahoʻolawe's terrestrial and marine ecosystems and Hawaiian cultural sites (KICC, 1993). If appropriated, most of this money will go toward ordnance removal; therefore, the funds available for future revegetation efforts must be used efficiently to achieve (a) maximum erosion protection, and (b) restoration of the landscape to that of an acceptable previous era – including the reintroduction of desirable (i.e. native *vs.* exotics) plant and animal species.

Beginning in the late 1970s, several groups initiated revegetation projects of Kahoʻolawe, including efforts to plant a large-scale windbreak, re-establish native dryland forest vegetation, and identify various treatments of grass seeds, fertilizer, mulching, and wind abatement most suitable to the island's harsh environment. Collectively, the focus of these prior restoration projects was to reduce runoff and concomitant accelerated erosion by promoting vegetative growth. All the projects were successful to varying degrees in establishing vegetative cover, promoting limited growth within their boundaries and immediate surroundings, and trapping sediment transported by both wind and overland flow (Giambelluca, *et al.*, 1997). However, to this date, limited physical data have been collected to demonstrate that the revegetation efforts have mitigated runoff or erosion in the restoration areas. The objective of this soil investigation, therefore, is to determine, within four of the largest revegetation sites on Kahoʻolawe, changes in soil hydrological and physical properties that have resulted from restoration activities. Changes within existing small-scale

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restoration sites are important indicators of how basin-scale revegetation efforts could influence changes in runoff and erosion processes.

BACKGROUND

Physical Setting

Today many areas on Kaho'olawe are vegetatively depauperate. Approximately one-third of the island is denuded; the remainder is dominated by introduced species including kiawe (*Prosopis pallida*), tamarisk (*Tamarix aphylla*), buffelgrass (*Cenchrus ciliaris*), Natal redtop (*Rhynchelytrum repens*), lantana (*Lantana camara*), koa haole (*Leucaena leucocephala*), and pitted beardgrass (*Bothriochloa pertusa*). Additionally, native pili grass (*Heteropogon contortus*), 'ilima (*Sida fallax*), and indigenous (status uncertain) uhaloa (*Waltheria indica*) are moderately abundant. The scarcity of vegetation results in part from limited water availability, as Kaho'olawe ($\approx$117 km^2) lies in the rainshadow of Mt. Haleakalā on Maui, about 40 km to the northeast (Figure 1). Mean annual rainfall is only approximately 371 mm, with 67 per cent coming between November and March (Figure 2). More importantly, the paucity of vegetation cover results from significant overgrazing by feral goats and the ensuing large-scale erosion that created the barren surface of the central plateau region, commonly referred to as 'the hardpan'. Today this surface, probably lower than the original soil surface by >2 m, is the source area of significant overland flow eroding large gullies on the

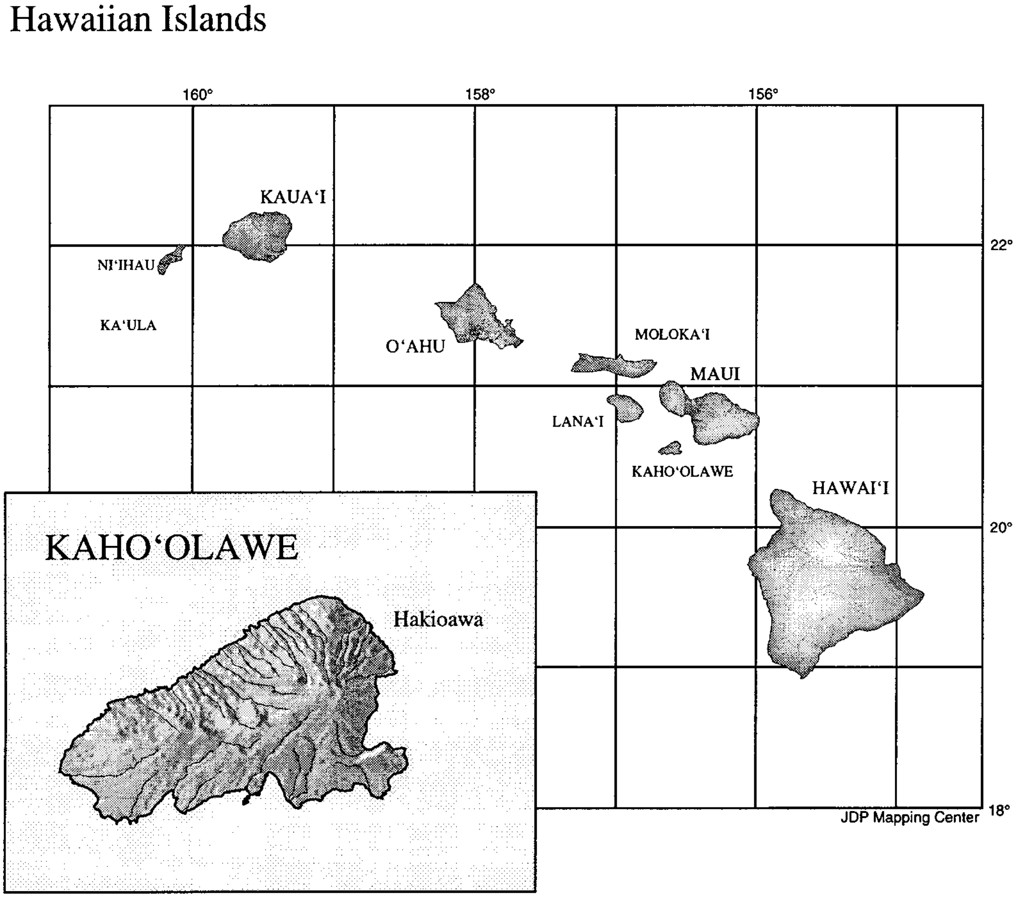


Figure 1. The Hawaiian Islands. Kaho'olawe, the eighth largest island in the Hawaiian archipelago, rests in the rainshadow of Mt. Haleakalā, on Maui Island to the northeast

slopes extending down the plateau to the coastline. Loague, *et al.* (1996) predicted Horton overland flow on all catchments associated with the hardpan plateau for 10 simulated rainfall events. Furthermore, they estimated that island-wide surface runoff by the Horton mechanism can be as great as 20 per cent of rainfall.

Environmental Degradation on Kaho'olawe

Hawaiians first inhabited Kaho'olawe *c.* AD 900; and probably as a result of their agricultural practices, dryland scrub forest eventually gave way to a savanna-type grassland (cf. Kirch, 1982; Allen, 1987; State of Hawai'i, 1990). Accelerated soil erosion became problematic after introduction of Western agricultural techniques, particularly ranching (cf. Spriggs, 1987). Erosion resulting from excessive grazing by cattle, sheep, and goats prompted replanting in the late 1880s (cf. KICC, 1993). Soil loss from wind erosion was reported by 1910, during which time Kaho'olawe was designated a Forest Reserve (Hosmer, 1910). Ranching resumed in 1918, then continued until the US Navy took possession of the island for training prior to World War II. Bombing and small ordnance testing is likely to have exacerbated environmental degradation and contributed to the loss of Hawaiian cultural sites; however, the extent of the impacts from these activities is debated (cf. USN, 1979; KICC, 1993; Warren and Aschmann, 1993). Nevertheless, during most of the Navy stewardship, an uncontrolled feral goat population was allowed to overgraze the island, contributing more to erosion than did bombing. The goats were finally eradicated in about 1991 (cf. Giambelluca, *et al.*, 1997).

Revegetation Efforts on Kaho'olawe

Since 1910 nine major restoration/revegetation projects have been attempted to Kaho'olawe (reviewed in Giambelluca, *et al.*, 1997). The first efforts focused on preventing the loss of topsoil for agriculture/ranching. For instance, Australian saltbush (*Atriplex semibaccata*) was introduced on hardpan areas during the

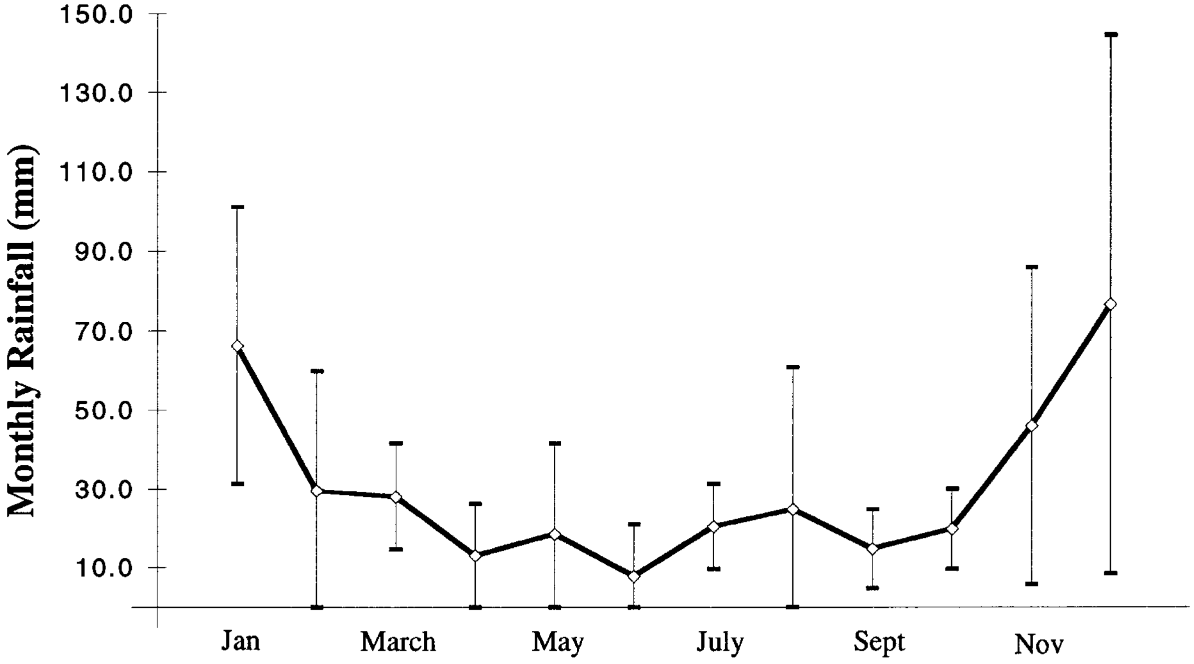


Figure 2. Mean monthly rainfall on Kaho'olawe for November 1989 to October 1996. Approximately 67 per cent of the annual rainfall total fell between November and March. These estimates are a synthesis of a November, 1989 to December, 1993 dataset recorded near the coast at Hakioawa, and March, 1994 to October, 1996 data from our tipping bucket raingauge in Hakioawa catchment near Lua Keālialuna (rain gauges numbers 1 and 2 respectively in Figure 3). The large error bars (± one standard deviation about the mean) reflect (a) naturally high rainfall variability, which is typical of most dry areas; and (b) the very short rainfall record. Annual rainfall is approximately 371 mm

period 1910–18; and over the next three decades, thousands of native and exotic trees were planted with only limited success (cf. Ashdown, 1979; Spoehr, 1992). Later projects focused on protecting archaeological sites, curbing massive gullying, improving the 'harsh environment on the island' (e.g., Wong, 1978; USN, 1989), and identifying both native and exotic vegetation species most adaptable to the growing conditions of Kaho'olawe (e.g., Whitesell, 1971; Whitesell and Wong, 1974). Other projects were initiated with the intention of re-establishing a native dryland forest. Recently, two restoration studies were conducted using experimental designs. The first consisted of several small-scale trial plantings of exotic grasses to identify effective treatments of fertilizer, mulching, and wind abatement (Warren and Aschmann, 1993); the second was an attempt to identify microbial and mineral constraints to re-establishing the native wiliwili tree (*Erythrina sandwicensis*) (Nakao, *et al*., 1993). Prior to the present study, no physical data have been reported to verify if any of these nine prior revegetation projects have mitigated runoff or erosion within their respective areas.

METHODS

Overview of the Experimental Design

To investigate the influence of revegetation efforts on reducing overland flow generation and accelerated erosion on Kaho'olawe, we measured saturated hydraulic conductivity (K_s), sorptivity (S), bulk density (ρ_b), pH, relative soil strength, organic matter content, and water-stable aggregation (WSA). Soil data were collected within and adjacent to four revegetation project sites during May, July, and September, 1996. Because we were unable to conduct sufficient soil measurements within each restoration area to perform project-specific analyses, measurements for similar land-use types within all sites were combined to create 11 basic cover categories (Table I). Following preliminary analyses of the hydrologic data, we reduced the total number of categories to three: (B) bare, highly eroded/degraded areas, (V) vegetated areas or depositional areas created by plants-trapping sediments, and (O) other non-vegetated, open areas affected by revegetation efforts such as tilling or application of Geojute$^{\text{TM}}$ rolled erosion control system. All group O and V sites are located within restoration sites. Because no measurements were made prior to the revegetation project, the B-group landcovers were used to represent the landscape at the time of planting; hence, group B serves as the control. We then compared the group B data to those of groups O and V to assess the influence of revegetation activities on hydrologic response and erosion.

Table I. Descriptions of the three landcover groups

Landcover class	Landcover description	Group†
Areas representative of the landscape before vegetation		
RD	Road surface, either on track or less compacted in-between track surfaces	B
HP	Bare 'hardpan' area outside of revegetation project sites	B
SH	Sediment deposition zone in hardpan area	B
Areas directly affected by revegetation efforts		
SS	Scarified/plowed area characterized by loose gravel or sediment deposition	O
EC	Bare sediment deposition area covered by a rolled erosion control system (Geojute$^{\text{TM}}$)	O
TO	Trees or large shrubs growing in open area, without groundcover below	V
SB	Australian saltbush growing on the 'hardpan'	V
NV	Within/under native vegetation plantings	V
EV	Within/under exotic vegetation (usually Natal redtop, partridge pea, other grasses)	V
SV	Sediment deposition zone created by trapping of sediments by vegetation	V
TW	Within tamarisk windbreak planting strip	V

†The eleven landcover classes were reduced to three groups based on field observations. Sample size for groups B, O, and V are 60, 14, and 56, respectively.

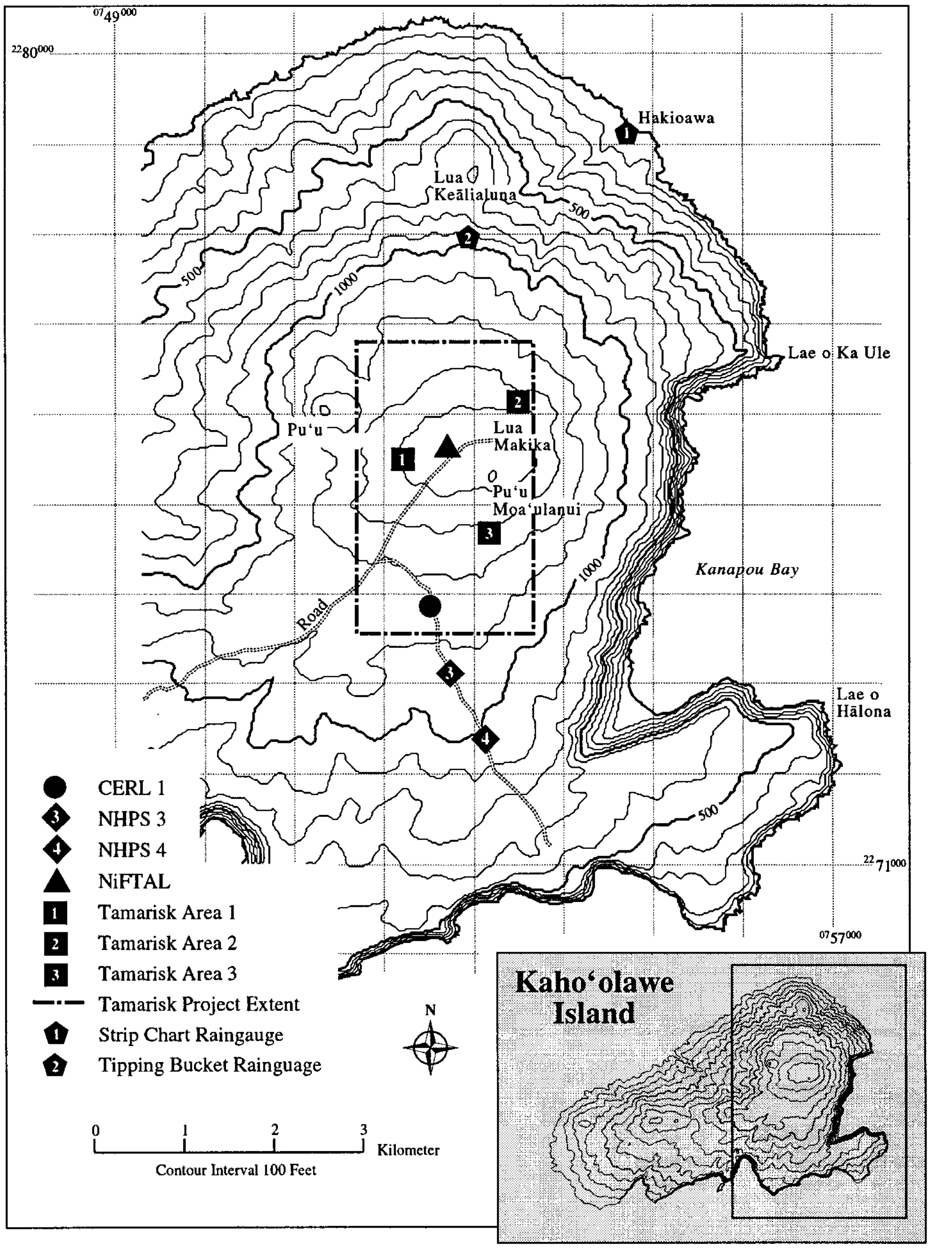


Figure 3. Eastern Kaho'olawe. Research was conducted within four prior revegetation sites located on the central denuded plateau, commonly referred to as 'the hardpan'. The four project areas include the Native Hawaiian Plant Society (NHPS) planting sites 3 and 4, the US Army Construction Engineering Research Laboratory (CERL) planting phase 1, the Tamerisk Windbreak Project, and the Nitrogen Fixing Trees and Legumes Project (NiFTAL)

Study Site Descriptions

The four projects included in this investigation are all located within the same general area on the denuded hardpan region of the island (Figure 3). The soil of this area is largely the Bw horizon of an exhumed Paleosol, dominated by the two similar Kaneloa and Puu Moiwi soil series (Table II, Nakamura and Smith, 1995). Most of the soil surface appears to be a ferralitic duracrust (cf. Thomas, 1994) with some areas

Table II. Chemical and physical characteristics of the Kaneloa and Puu Moiwi soil series on Kaho'olawe (synthesized from Nakamura and Smith, 1995)

Soil characteristics†	Units	Kaneloa	Puu Moiwi
Soil texture	–	silty clay loam	silty clay loam
pH in water (1:1)	–	6·6–7·8	6·6–7·7
Organic matter	$g\ kg^{-1}$	5·0–10·0	5·0–10·0
Exchangeable Ca^{2+}	cmol (+) kg^{-1}	3·61	3·19
Exchangeable Mg^{2+}	cmol (+) kg^{-1}	2·88	2·58
Exchangeable K^{+}	cmol (+) kg^{-1}	1·27	0·97
Kaolinite/halloysite	–	moderate	small to moderate
Gibbsite	–	moderate to large	small to moderate
Permeability	$mm\ h^{-1}$	15–50	15–50
Available water capacity	–	0·10–0·14	0·10–0·14
Field bulk density	$g\ cm^{-3}$	1·10–1·30	1·10–1·30
Particle density¥	$g\ cm^{-3}$	2·88	2·88
Porosity§	–	55–62	55–62
Liquid limit	–	40–50	40–50
Plastic index	–	10–20	10–20
USLE K erodibility factor	–	0·17	0·17
Shrink–swell potential	–	low	low
Drainage class	–	well-drained	well-drained
Typical surface material	–	duracrust/durapan	duracrust/durapan
Depth to bedrock‡	m	>1·5	>1·5

†Data are for the uppermost soil horizon (Bwl; 15–20 cm).
¥Data for Molokai silty clay loam (Soil Conservation Service, 1976).
§Porosity = (1–bulk density/particle density)*100.
‡Parent material for both series is strongly weathered volcanic ash over strongly weathered basic igneous rock.

resembling the 'tabular' durapan plates described by Blank and Fosberg (1991). In general, this windswept region is the source of significant overland flow that contributes to severe gully erosion processes occurring both on the relatively flat (0–5 per cent) plateau and particularly on the steeper slopes (>15 per cent) extending down to the coastline. The following provides a brief history and description of the project sites investigated:

(1) The Native Hawaiian Plant Society (NHPS) plantings were an exploratory attempt to re-establish native dryland forest vegetation on Kaho'olawe (Figure 3). Between 1985 and 1989 several thousand plants (34 species) were established in two 0·4 ha plots (sites 3 and 4). After surface tilling to approximately 0·5 m, mixed species were planted in contours, with low creeping varieties situated <2 m apart to promote ground cover. We conducted 22 measurements within the NHPS site 4, and four within the NHPS site 3. Discontinuous vegetative cover in these restoration sites is now approximately 30 and 15 per cent, respectively, compared to less than 5 per cent in adjacent control areas. Vegetation often occurs as elevated clumps, around which surface runoff flows. Because of initial tilling, all non-vegetated lands within these project sites correspond to group O in our classification (see Table IV).

(2) The US Army Construction Engineering Research Laboratory (CERL) exotic grass plantings were undertaken to identify effective treatments of fertilization, mulching, and wind abatement to best facilitate future grass plantings. The project was conducted within three separate areas (referred to as 'phases') from 1988 to 1991; and then evaluated in 1991 (Warren and Aschmann, 1993). Prior to planting, all sites were tilled to 0·1 m. We conducted 19 measurements within a 6200 m^2 area associated with phase I (CERL 1, Figure 3). Total vegetation cover in this area is now approximately 36 per cent (i.e., group V lands; group O lands occupy 75 per cent); before planting, cover was approximately 1 per cent (Warren and Aschmann, 1993). Despite revegetation, several open areas that allow Horton overland flow (HOF) generation exist within the project site.

(3) The Nitrogen Fixing Trees and Legumes (NiFTAL) Project on Kaho'olawe was conducted by researchers from the University of Hawai'i, The Nature Conservancy, and the US Navy, to identify microbial and mineral constraints to re-establishing the native wiliwili tree. Between 1989 and 1991 the project site was prepared by tilling, then seedlings were planted within subplots corresponding to different nitrogen-source treatments. Additionally, 'left-over' trees were established with the native shrubs in areas outside the main NiFTAL site and within the planting area of CERL phase II. We conducted measurements at eight locations within an auxiliary planting area ($<1{\cdot}0$ ha) (Figure 3). All measurement sites within this project area correspond to groups O and V landcovers.

(4) The objective of the Tamerisk Windbreak Project was to bring a halt to current soil erosion problems on the island by improving the harsh, barren environment, thus promoting growth of vegetation. In the initial phase of the project, conducted by The State of Hawaii Department of Land and Natural Resources Division of Forestry and Wildlife and the US Navy, several windbreak rows of predominantly tamarisk (*Tamarix aphylla*) were planted in near-parallel strips approximately 75 m apart within a 6 km^2 area. The area was not tilled prior to planting; however, the holes for planting the trees were created using explosive charges. We made measurements at 64 locations near the center, the N.E. corner, and S.W. corner of the Windbreak Project area (Figure 3). Vegetative ground cover within the tamarisk planting area (excluding the planted trees) is approximately 37 per cent, compared to 23 per cent for outside control areas. Because the Tamarisk Windbreak Project area includes lands of long, moderate slopes (>100 m; 5–10 per cent), many major erosion features (e.g., deep rills and gullies with head-cutting, exposed saprolite, lag deposits, and pedestals) occur within and immediately adjacent to the tamarisk lines. Only landcover groups V and B are found in this project area.

In addition to observations made within or adjacent to the four restoration project areas, we made measurements at four locations near raingauge station number 2 above Lua Keālialuna, and on road surfaces at 10 locations.

Measurements of Soil Properties

Surface bulk density (ρ_b), the ratio of dry mass to the bulk volume of the soil, was determined from soil cores collected from the upper 3 cm with a 3·325 cm^3 corer. The dry-mass determinations were made after oven-drying for 24 h at 105 °C. As an index for relative strength for the soil surface, 5–9 measurements were taken at many of the measurement locations using a pocket penetrometer (Bradford, 1986). Soil sampled from the upper 3 cm was separated using a Tyler (Mentor, OH) Ro-tap sieve shaker to estimate the geometric mean aggregate diameter (GMAD) of the material at each site. The samples were shaken through a nest of sieves to isolate fractions into the following aggregate size ranges: 2·00–4·00, 1·00–2·00, 0·25–1·00, 0·063–0·25, and $<0{\cdot}063$ mm. After shaking, visible rock fragments were removed from the two largest sieves prior to massing. The GMAD was calculated using the method defined by Kemper and Rosenau (1986). In addition, two soil erodibility indices were calculated from the sieved samples, the aggregate fraction $\geqslant 1{\cdot}0$ mm and the aggregate fraction $<0{\cdot}063$ mm. Loss on ignition (LOI) was determined as a proxy for organic matter content. Briefly, for this technique, 30 g of finely ground aggregates were oven-dried (24 h at 105 °C), then dried in a muffle furnace at 400 °C over night. The LOI values were determined as the ratio of the mass lost through 'muffle-drying' to the oven dry mass. Finally, soil pH was determined in the laboratory from 1:1 mixtures of soil and distilled water using an Oakton^{TM} pH meter.

Saturated Hydraulic Conductivity and Sorptivity

Horton overland flow occurs as a result of prolonged rainfall at an intensity greater than the infiltration capacity of the soil (Horton, 1933). Rainfall in excess of infiltration accumulates in small surface depressions, eventually overflowing them if rainfall continues. The HOF mechanism is generally thought to be rare in fully vegetated, undisturbed areas because of high infiltration rates. However, in areas where infiltration has been reduced by human activity, such as vegetation removal or compaction, the Horton mechanism can generate a significant amount of overland flow. In this respect, the compacted, largely bare surfaces of the barren plateau region of Kahoʻolawe are generally regarded as significant source areas for HOF (cf. Loague, *et al.*, 1996). To examine the influence of revegetation efforts on HOF generation, we determined saturated hydraulic conductivity (K_s) and sorptivity (S) on various landcover types from infiltration measurements taken *in situ* with a Vadose Zone Equipment Corporation (Amarillo, TX) disk permeameter.

Modeling Steady State-Infiltration Capacity

Infiltration capacity (f) is the maximum rate at which water can be absorbed by the soil. In an event where HOF occurs, the infiltration capacity acts as the partitioning mechanism of rainfall. At times when rainfall intensity is less than the infiltration capacity, infiltration will occur at a rate equal to the rainfall intensity; but when rainfall intensity exceeds the infiltration capacity, infiltration will equal the infiltration capacity, and the excess rainfall will be ponded on the surface. According to the Horton hypothesis, infiltration capacity is initially high, then decreases during a rainfall event, eventually approaching a more or less constant value. To calculate infiltration curves for three landcover categories considered in this study, we used a modification of Philip's (1957) equation:

$$f = \tfrac{1}{2}St^{-1/2} + \tfrac{1}{2}K_s \tag{1}$$

This is the same equation used previously by Loague, *et al.* (1996) in their simulation of HOF on Kahoʻolawe. In this equation, the infiltration capacity approaches one-half K_s (steady-state infiltration capacity, f_s) as time increases after rainfall initiation. An assumption of this model is that ponding begins at the start of the storm.

Water-Stable Aggregate Experiments

Aggregate stability is the resistance of soil aggregates to failure when subjected to disruptive forces. Bryan (1968, 1974) and Luk (1979) found indices of water-stable aggregation (WSA) determined from wet-sieving to be highly correlated with soil loss from laboratory erosion plot experiments. These correlations suggest that as aggregate stability increases soil erodibility decreases. To ascertain how the Kahoʻolawe revegetation projects may have decreased soil erodibility compared with that of the surrounding landscape, we examined WSA indices determined using a technique described by Sutherland and Ziegler (in press). Briefly, the two-phase method involved shaking 10 g of 2·00–4·00 mm air-dried aggregates with 100 ml of water with a wrist-action shaker. Shaking was followed by gently washing the samples through a nest of sieves to isolate the WSA fractions in the aggregate diameter ranges 2·00–4·00, 1·00–2·00, 0·25–1·00, 0·063–0·25, and $<0{\cdot}063$ mm. From these data three indices of water-stable aggregation were computed, the geometric mean aggregate diameter (Kemper and Rosenau, 1986), per cent of water-stable aggregates greater than 0·25 mm (WSA fraction $\geqslant 0{\cdot}25$ mm), and WSA fraction $<0{\cdot}063$ mm.

Statistical Analysis

All data for each landcover type were examined using one-way analysis of variance (ANOVA), followed by *post hoc* multiple comparison testing using Fisher's Protected Least Significant Difference test (FPLSD) at $\alpha = 0{\cdot}05$. Prior to statistical testing, K_s, and S were log-transformed to stabilize the variances as suggested by Ott (1984).

RESULTS AND DISCUSSION

Soil Hydrologic Properties

Results of ANOVA testing ($\alpha = 0{\cdot}05$) indicate K_s values for all three landcover types were statistically different from each other, with vegetated areas (group V) having the highest values; and bare hardpan areas

Table III. Descriptive statistics of soil hydrologic properties for three landcover types

Group n†	B (40–48)	O (12–14)	V (44–50)
K_s (mm h^{-1})			
Arithmetic mean	50·7^{a}§	76·6^{b}	258·6^{c}
Coef. var.‡	0·89	0·32	0·76
Median	39·0	76·9	217·0
Minimum	4·0	31·5	1·6
Maximum	207·2	110·4	778·1
S (m s$^{-1/2}$)			
Arithmetic mean	1·4E-3^{a}	1·1E-3^{a}	1·7E-3^{a}
Coef. var.‡	0·58	0·40	0·86
Median	1·3E-3	1·2E-3	1·2E-3
Minimum	5·2E-4	3·2E-4	8·0E-5
Maximum	4·5E-3	1·8E-3	6·2E-3
Θ_n Arithmetic mean	0·18^{a}	0·18^{a}	0·21^{b}
Θ_0 Arithmetic mean	0·46^{a}	0·46^{a}	0·49^{a}

B = bare; O = other bare areas associated with restoration efforts; V = vegetated.

K_s is saturated hydraulic conductivity; S, sorptivity; Θ_n, *in situ* volumetric soil moisture; Θ_0, soil moisture at saturation.

†n varies for each property tested due to measurement error, or difficulty in performing a particular measurement at all sites.

§Mean values in each ROW with the same letter are statistically indistinguishable (ANOVA; $\alpha = 0{\cdot}05$). K_s and S were log transformed before statistical testing.

‡Coef. var. = std. dev./arithmetic mean (dimensionless).

(group B), the lowest values (Table III). Saturated hydraulic conductivity is a useful index for assessing benefits of revegetation because K_s largely controls the infiltration of rainwater, i.e., in general, the greater K_s, the less likely it is that HOF will be generated. Descriptive statistics of K_s on the three surface covers are shown in Table III; Figure 4 shows the probability density function (pdf) of K_s values for each land-use type. These data show vegetated areas have much higher K_s values than bare areas and other lands affected

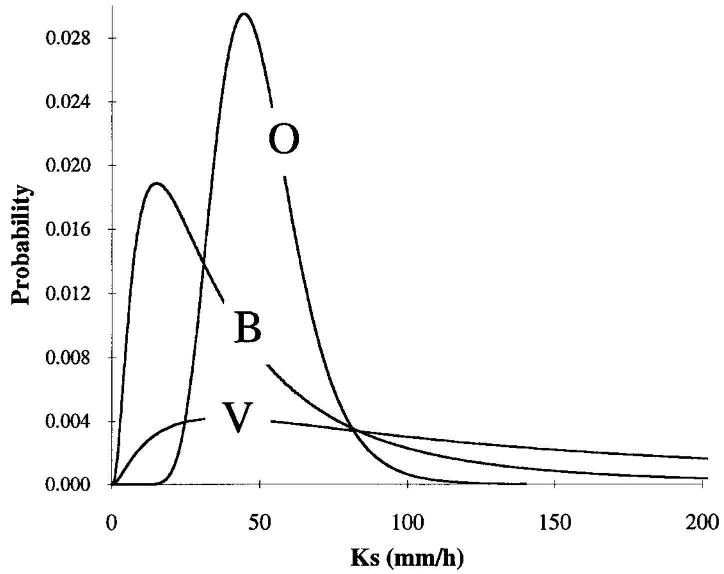


Figure 4. The probability density function (pdf) of measured K_s values for the three landcover categories: (B) bare, highly eroded/degraded areas; (V) vegetated areas or depositional areas created by plants trapping sediment, and (O) other non-vegetated, open areas affected by revegetation efforts. These curves were generated under the assumption that the pdf of hydraulic conductivity is log normal (see reviews by Freeze, 1975 and Dahiya, *et al.*, 1984)

by revegetation (group O). In addition, the K_s values of the unvegetated group O lands fall within the upper range of those found on bare hardpan lands, indicating that tilling the surface alone is not an effective long-term strategy for improving infiltration.

In contrast to distinct K_s groupings for each of the three landcover groups, volumetric soil moisture (Θ_n), soil moisture at saturation (Θ_0), and S did not differ significantly in most cases (Table III). Of these three properties, volumetric soil moisture is a particularly important variable because Θ_n indicates water availability for plant usage during dry conditions (all data were collected during May, July, and September, for which rainfall averaged 25·7 ± 4·1 mm (± one standard deviation)). The ANOVA ($\alpha = 0{\cdot}05$) indicated no differences among the Θ_n values taken during the three normally dry months. Mean volumetric soil moisture for all combined landcover groups during this period was 0·19. Finally, although sorptivity, like K_s, is an important parameter in the calculation of infiltration (i.e., the first term in Eq. 1), the influence of surface cover on S is not apparent in these data.

Overland Flow Generation on Kaho'olawe

Comparing measured rainfall intensity to modeled steady-state infiltration capacity (Eq. 1 with median S and K_s values, Table III) is a useful first-order indicator of the potential for HOF generation on each of the three land-surface types. For example, periods when rainfall intensity (p) is greater than infiltration capacity (f) represents times when excess rainfall (r) could be generated. Excess rainfall, defined as:

$$r = \begin{cases} p - f & p > f \\ 0 & p \leqslant f \end{cases} \tag{2}$$

is the source of HOF once surface storage is overcome. In Figure 5, median modeled steady-state infiltration capacity on revegetated areas was never exceeded by measured one-min rainfall intensities, suggesting HOF

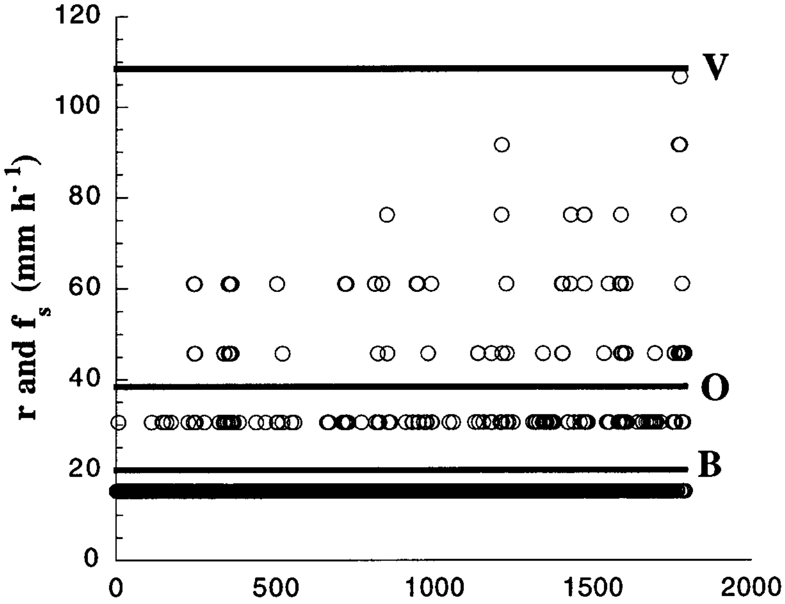


Figure 5. One-min rainfall intensity values (r) for the periods 3/94 to 5/95 and 3/96 to 10/96 (note the gap is due to equipment failure) are superimposed on modeled steady-state infiltration capacities (f_s) for each of the three landcover types (B refers to bare areas; V, vegetated areas; and O, other non-vegetated, open areas affected by revegetation efforts). Steady-state infiltration capacities were calculated from Eq. 1 using median values for sorptivity (S) and saturated hydraulic conductivity (K_s). Rainfall values that exceed f_s represent periods when excess rainfall, and hence overland flow, could occur. Of the total 1792 non-zero rainfall values in the dataset, 14 per cent exceed f_s of the B-group lands; 5 per cent, for group O lands

is infrequent on these surfaces. In contrast, 81 and 248 of the possible 1792 one-min rainfall intensity values exceed f_s on the O- and B-group lands, respectively. Again, although O lands have been somewhat improved by revegetation activities, they are not as effective as vegetated areas in mitigating HOF generation.

Figure 6 depicts modeled excess rainfall generation during one of the largest, continuous rainfall events in the dataset ($\approx$5 h; 66 mm; maximum 10-min intensity $\approx$ 46 mm h^{-1}). The gray line corresponds to 10-min rainfall intensities. The black lines are modeled infiltration capacities determined from K_s values corresponding to 20 probability classes of the K_s cumulative density function (cdf) for each landcover. These 20 f curves therefore represent the range of infiltration capacity existing within a respective landcover group, i.e., each line represents 5 per cent of the areal extent of a given group. The thick black line is the infiltration capacity calculated with the median K_s value (Table III). Median S values were used in all calculations of f. Excess rainfall occurs when the rainfall curve exceeds one or more of the infiltration capacity curves; the more f curves exceeded, the greater the proportion of the total land surface capable of generating HOF. During this rainfall event, HOF is predicted on approximately 40 per cent and 25 per cent of bare areas at 60 and 220 min respectively. In contrast, the infiltration-capacity curves for areas affected by revegetation (V and O lands) are much higher than the rainfall intensity, again demonstrating these lands are much less likely to generate HOF than the bare areas. Furthermore, within the rainfall collection period (3/94 to 5/95 and 3/96 to 10/96) no storms produced 10-min rainfall intensities that exceeded any of the 20 infiltration-capacity curves for V- or O-group lands.

The frequency of predicted HOF generation on bare areas was much smaller than were anticipated, given that this area of the island is believed to be a significant source area for HOF. While our rainfall record is short, and some error is involved in calculating infiltration parameters from permeameters (cf. Smetten, *et al.*, 1995), we feel the discrepancy is most likely related to the overland flow generation mechanism operating in this area. During rainfall, enhanced surface sealing from raindrop impact (Ekern, 1950; McIntyre, 1958) may reduce the infiltration capacity much more than predicted by Eq. 1, thereby generating overland flow sooner and/or at lower rainfall intensities than indicated by the K_s and S values derived from the permeameter measurements (note, wetting from a disk permeameter does not induce the same force as raindrop impact). If overland flow is initiated by an enhanced sealing process, the benefits of establishing a protective vegetative groundcover to intercept raindrop impact may be as important as those gained by increasing the hydraulic conductivity of the soil.

Some of the B- and O-group sites with relatively high K_s are sediment deposition areas underlain by more compacted, less permeable surfaces $\approx$ 5–30 mm below the sediment surface. In such cases, sustained rainfall with intensities less than surface infiltration capacities could produce overland flow as the pore space of the sediment layer approaches saturation and water 'perched' on the compacted underlying hardpan surface flows laterally. With this in mind, runoff reduction on open sediment deposition zones is probably less than on vegetated zones where groundcover may be deep-rooted and/or provide protection from raindrop impact. Similarly, some vegetated sites may also generate overland flow sooner than indicated by their high infiltration capacities, especially sites where the vegetation occurs as small isolated patches growing on sediment trapped atop the less permeable hardpan (i.e., low infiltration capacity if roots have not penetrated deeply). An example of this phenomenon is provided by Australian saltbush (*Atriplex semibaccata*), a species noted by others as an important pioneer for revegetation of Kaho'olawe because it establishes on the hardpan and traps sediment, thereby providing favorable growing areas where new plants can germinate (cf. Giambelluca, *et al.*, 1997). Currently Australian saltbush is the most abundant species in the control areas outside the Tamarisk Windbreak Project site, comprising roughly 15 to 25 per cent of the vegetation cover. However, despite the ability of Australian saltbush to trap sediment, saturated hydraulic conductivity of the soil surface below individual saltbush plants is not necessarily high. In fact, two of the lowest K_s measurements (both <6 mm h^{-1}) within the entire data set were made beneath the creeping assemblages of Australian saltbush. The large range in K_s beneath Australian saltbush probably results from the areas close to the root system having much higher infiltration than the areas where the plant has trapped sediment on the less permeable, hardpan surface.

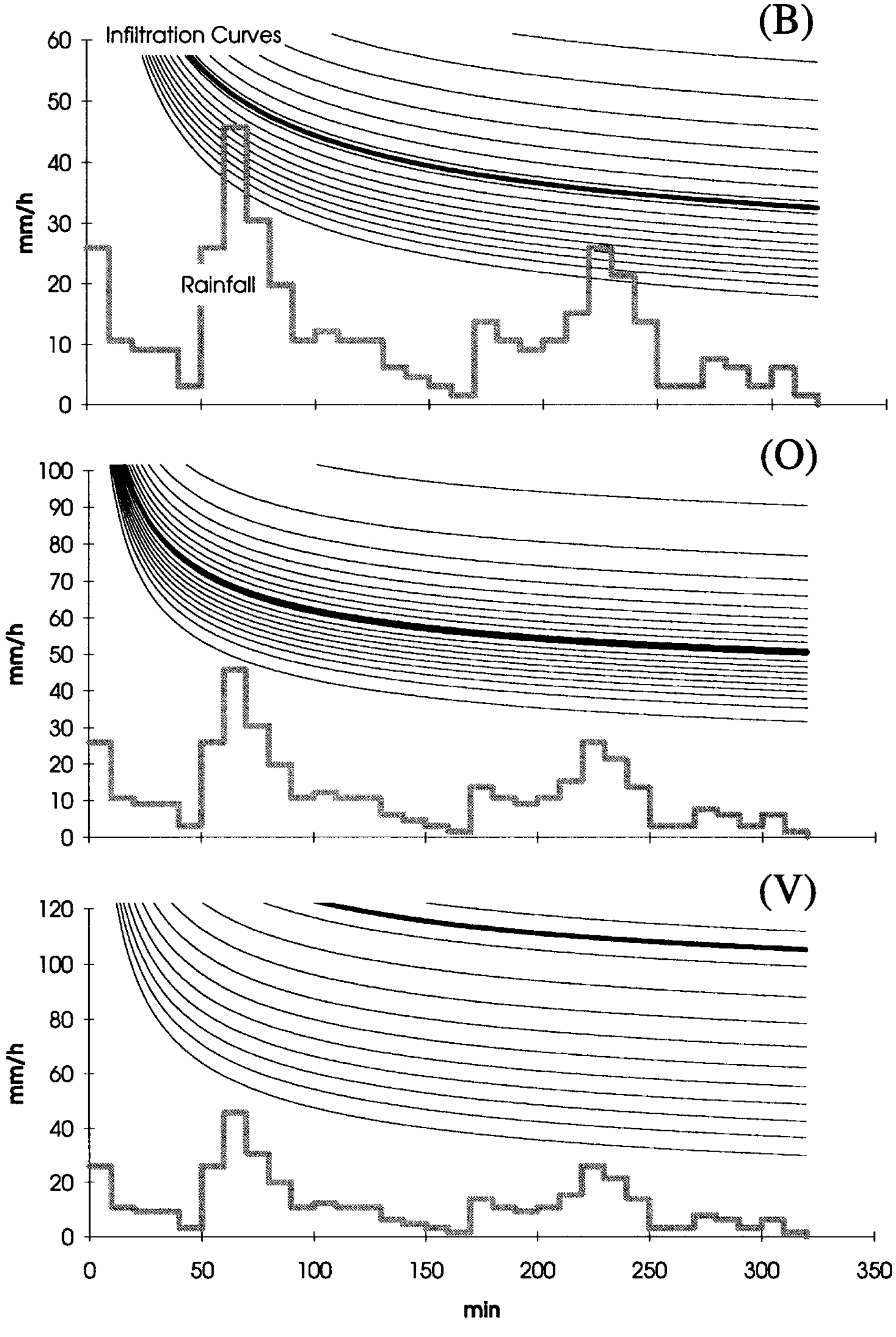


Figure 6. Conceptualization of excess rainfall generation during an approximately 5 h, 66 mm storm event on Kaho'olawe. Excess rainfall, the source for HOF, occurs when rainfall intensity (gray line) exceeds one or more of the infiltration capacity curves (thin black lines). The infiltration capacity curves were calculated with Eq. 1 using median S values and K_s values associated with 20 probability classes of the K_s cumulative density function; therefore, each curve corresponds to 5 per cent of the areal extent of a given landcover category (B refers to bare areas; V, vegetated areas; and O, other non-vegetated, open areas affected by revegetation efforts). The thick black line is the infiltration capacity calculated with the median K_s value

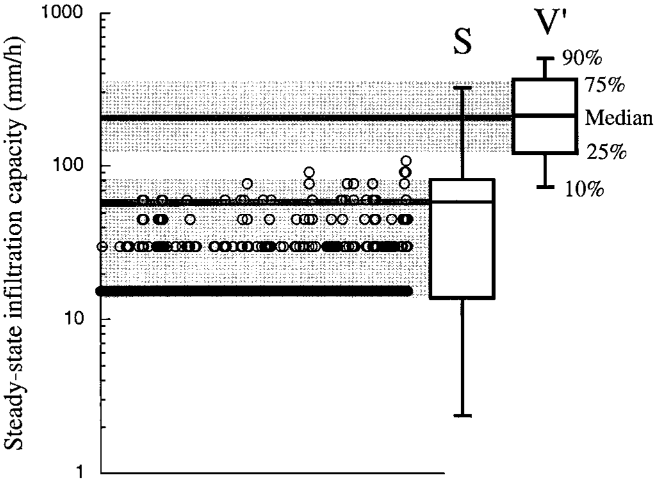


Figure 7. Modeled steady-state infiltration capacity (f_s) values for areas occupied by Australian saltbush (S) compared with those of all other vegetated lands (V'). Each box plot indicates values below which 10 per cent, 25 per cent, 50 per cent (median), 75 per cent, and 90 per cent of the corresponding f_s value are found. The shaded area highlights the middle 50 per cent of the distribution. One-min rainfall intensities (circles) show that overland flow is more likely to be generated within saltbush sites than within the other vegetated areas

Compared with the other vegetated areas, K_S of the saltbush sites was statistically the lowest (ANOVA, $\alpha = 0{\cdot}05$). Figure 7 is a box plot comparison of modeled steady-state infiltration-capacity (Eq. 1) values for saltbush sites (S) to the other vegetated sites (V'; saltbush excluded). The shaded regions represent 50 per cent of the f_s data values centered around the median (horizontal line within the box). To show the hydrological implications of differences in steady-state infiltration capacity, the box plots are superimposed on the rainfall data record. Again, no rainfall intensity values fall within the shaded region of the vegetation group. In contrast, all the one-min intensities fall within or above the shaded region of the saltbush group. Although the sample size for the saltbush data is small ($n = 7$), this comparison suggests that areas below saltbush are more likely to generate overland flow than the other vegetated areas. In terms of creating larger, long-lasting areas of high infiltration where other species can germinate, Australian saltbush may not be as useful for large-scale revegetation efforts as was hoped.

Spatial Pattern of Vegetation

The hydrologic data suggest infiltration under most vegetation is very high compared with adjacent non-vegetated areas. Therefore, when vegetation is planted in small sparse patches, a mosaic of high- and low-infiltration areas is created on the landscape. If the areal extent of the groundcover is sufficient, and if the vegetation 'plots' are arranged in a way capable of intercepting overland flow, the high infiltration rates of the vegetated areas may be sufficient to absorb water that does not infiltrate in the adjacent open areas of low K_S. In general, the areal extent and spatial arrangement of planted vegetation in the project areas visited in this study was not sufficient to reduce basin-scale overland flow production significantly.

In some respects the treeline plantings of the Tamarisk Windbreak Project provide a continuous vegetated zone of high infiltration capable of intercepting overland flow transported from adjacent areas. However, in many cases the overland flow paths run parallel to the tree lines. Nonetheless, the hydrological benefits are greatly increased in areas where volunteer grasses and small shrubs have established between the tree lines. For example, mean vegetative cover is approximately 37 per cent within the treeline planting area, compared to 23 per cent outside (Giambelluca, *et al.*, 1997). The hydrological implication of this vegetative increase is shown in Figure 8. In general, vegetation cover (thick line) is greatest near a given treeline (between 10 m windward and 20 m leeward); and although cover is less at distances greater than 20 m leeward, it is nearly

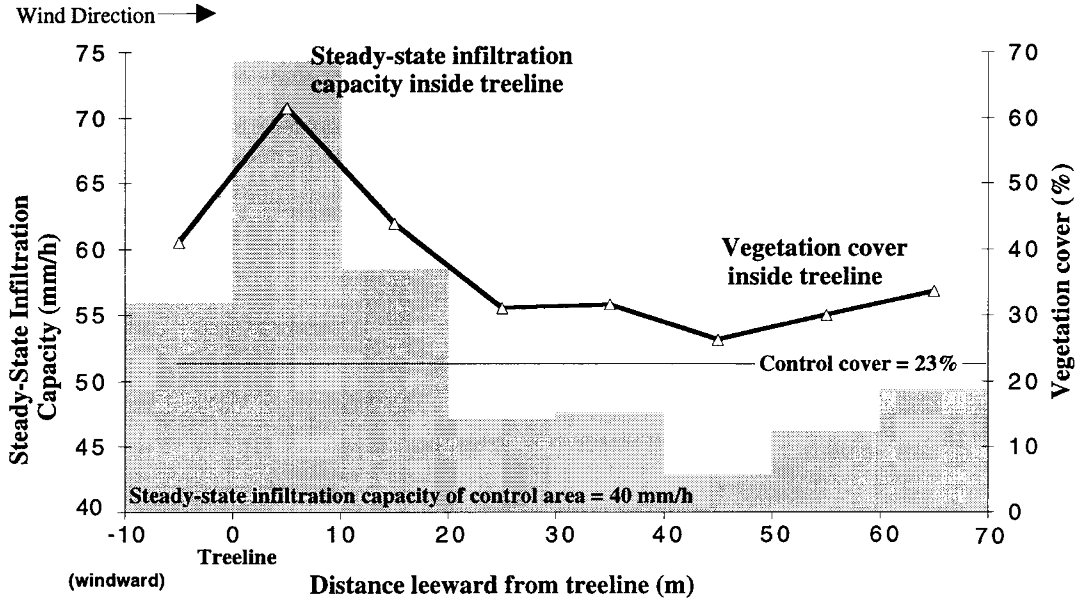


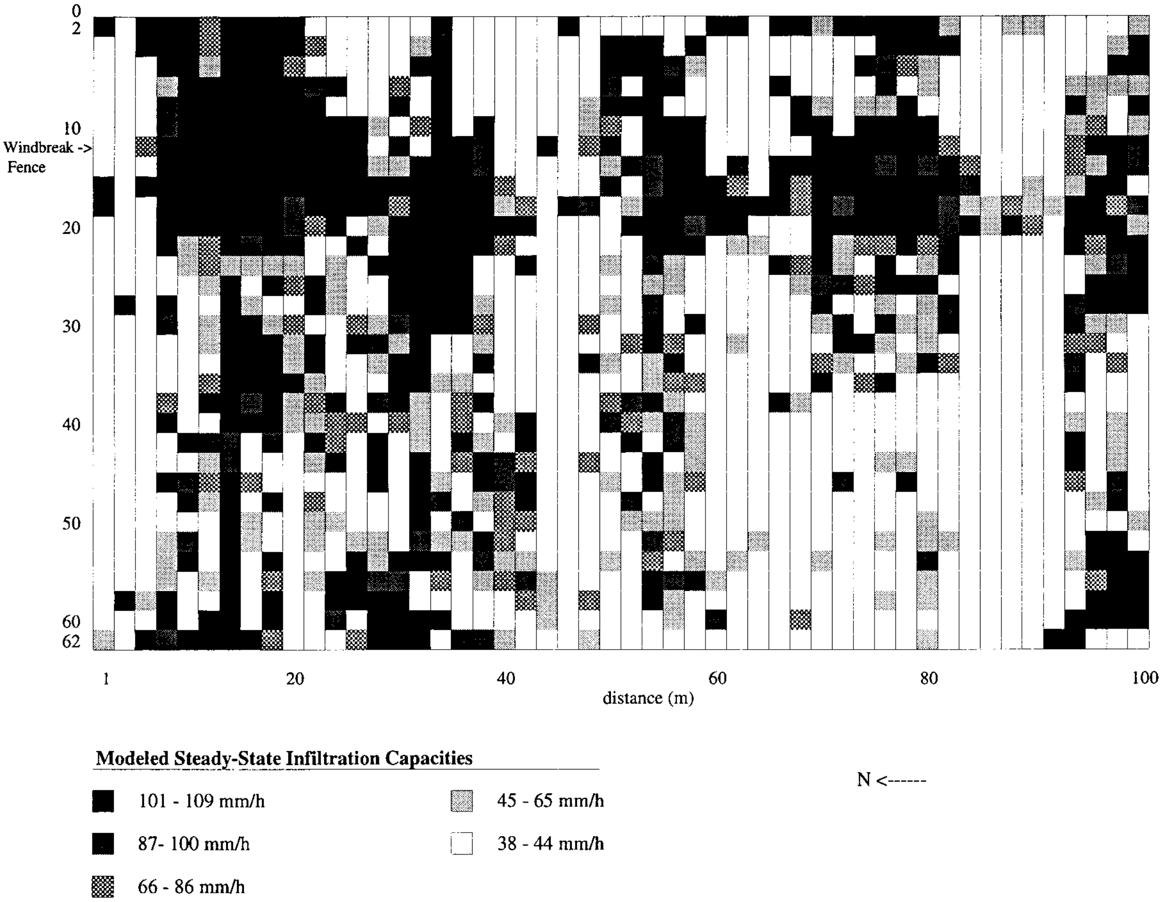
Figure 8. Increase in steady-state infiltration capacity (f_s, gray bars) resulting from the increase in vegetation coverage (black line with triangles) within a typical tamarisk treeline. In the Tamarisk Windbreak Project area most treelines are 75 to 80 m apart; therefore, the 10 m interval on the windward side of the treeline is representative of the interval following 70 m (not shown). Vegetation cover at all 10 m intervals (except 40–50 m) is significantly greater than the 23 per cent cover in control areas on the degraded plateau. Steady-state infiltration capacity within the treeline is calculated as the area-weighted average of modeled f_s for groups B (bare) and V (vegetated), where respective f_s are calculated with Eq. 1 (approximately 19·5 and 108·5 mm h^{-1}). Steady-state infiltration capacity of the control (40·0 mm h^{-1}) was calculated assuming a vegetation coverage value of 23 per cent

always significantly greater than the 23 per cent coverage of the control. This cover increase produces a concomitant increase in steady-state infiltration capacity (the gray bars minus 40·0 mm h^{-1}, the steady-state infiltration capacity of the control, estimated for bare lands using Eq. 1). On average, modeled steady-state infiltration capacity has increased by 12·5 mm h^{-1} within the 80 m zone around the treeline; 23·0 mm h^{-1} in the smaller zone from 10 m windward to 20 m leeward of each treeline. This conceptualization, however, generalizes the true spatial arrangement of vegetation, which as mentioned above, currently does not block many overland flow paths because it is discontinuous.

The hydrological benefits of the CERL planting can also be predicted by estimating the change in steady-state infiltration capacity since planting (Figure 9). Assuming a vegetation cover of 2 per cent (Warren and Aschmann, 1993), mean modeled f_s within the 6200 m^2 site was 22·0 mm h^{-1} before planting (Eq. 1 for B and V lands). Figure 9 shows the current spatial distribution of modeled steady-state infiltration capacity. The two darkest colors represent areas of high f_s resulting from 70 to 100 per cent cover; white represents areas of low f_s (0–10 per cent cover). Because this project site was tilled before planting, no Group B areas are present; thus, all f_s values are calculated based on group V and O values of K_s and S (Table III). The weighted mean steady-state infiltration capacity within the CERL site has therefore increased by about 190 per cent to 63·7 mm h^{-1}, a one-hour volume increase of 259 m^3 for the whole project area. Despite the substantial increase in mean f_s within the project site, the presence of extensive rill networks suggests the extent of vegetation cover does not prevent overland flow generation, especially in the S.W. corner (Figure 9); nor does the spatial distribution prevent overland flow from crossing through the project area.

Water-Stable Aggregate Experiments and Erodibility

Organic matter is part of a complex interaction of physical, chemical, and biological reactions that creates and maintains a well-aggregated soil (Harris, *et al.*, 1965). The WSA experiments were conducted from the



Mean modeled steady-state infiltration capacity before revegetation was 22.0 mm/h

Figure 9. Spatial distribution of steady-state infiltration capacity (f_s) within the CERL grass planting site. White areas correspond to areas of lowest f_s resulting from limited vegetation cover ($\leqslant 10$ per cent). The two darkest colors represent areas of higher f_s, resulting from 70–100 per cent cover. The areas of highest cover, and hence highest steady-state infiltration capacity, tend to be located a few meters windward of where a windbreak fence was once located. The large areas of low f_s between 60 and 90 m are areas where prevalent overland flow paths exit the southwest corner of the project site. Since planting, the average steady-state infiltration capacity of this site has increased from approximately 22·0 to 63·7 mm h^{-1}

premise that the establishment of vegetation might decrease erodibility on the degraded, largely unvegetated hardpan area by increasing the organic matter in the soil. The significantly higher amounts of organic material within vegetation sites (inferred from the LOI data, Table IV) suggest that these areas may be creating greater aggregate stability (e.g., by producing organic cements and/or enmeshing aggregates through root growth, Harris, *et al.*, 1965). To test this hypothesis, we examined the aggregate stability of soil collected within the three land covers.

The results of our WSA experiment do not support the hypothesis. For example, three WSA indices, GMAD, WSA fraction $\geqslant 0{\cdot}25$ mm, and WSA fraction 2·00 to 4·00 mm, were not statistically different among the cover groups. We speculate that the three cover groups have similar WSA indices because (a) the aggregates were already strongly cemented by iron and aluminum oxides, and (b) the time since planting has not been long enough for organic material to affect aggregate stability. For these reasons, and because no true control for comparison currently exists on the hardpan region (i.e., an undisturbed, uneroded soil profile),

Table IV. Mean values of physical soil properties for the three landcover types

Class	n†	ρ_b (g cm^{-3})	strength (kgf cm^{-2})	GMAD (mm)	% aggregates ≥1·0 mm	% aggregates <0·063 mm	LOI (%)	pH
B	(30–59)	1·17^{b}	3·94^{b}	0·891^{b}	46·4^{b}	7·6^{a}	13·6^{a}	5·9^{a}
O	(4–14)	1·14^{b}	0·56^{a}	0·883^{b}	45·4^{b}	6·3^{a}	12·9^{a}	6·6^{b}
V	(30–56)	0·97^{a}	1·10^{a}	0·780^{a}	32·4^{a}	7·1^{a}	15·3^{b}	6·8^{b}

B = bare; O = other bare areas associated with restoration efforts; V = vegetated.

ρ_b is bulk density, GMAD is geometric mean aggregate diameter, and LOI is loss on ignition. The aggregate fractions are for air-dried soil samples.

†n varies for each property tested due to measurement error, or difficulty in performing a particular measurement at all sites.

‡Mean values within the same COLUMN with the same letter are NOT significantly different (ANOVA; $\alpha = 0{\cdot}05$).

Table V. Mean values of water-stable aggregate (WSA) indices

Class	Puu Moiwi and Kaneloa Oxisols	Lualualei Vertisol
GMAD (mm)	0·962†	0·479‡
WSA fraction > 0·25 mm	79·8	33·8
WSA fraction 2·0–4·0 mm	39·1	1·5
WSA fraction < 0·063 mm	11·0	21·3

†n = 98 for the Puu Moiwi/Kaneloa soil samples; groups B, O, and V combined.

‡n = 16 for the Lualualei soil (based on Ziegler and Sutherland, in review).

WSA indices may not be reliable indicators of changes in soil erodibility on the barren hardpan area of Kahoʻolawe.

The WSA data, combined with other data of physical soil properties (Table IV), suggest that the degraded soil of the plateau in its current state is no longer highly erodible by typical forces that cause aggregate failure. For example, relative soil strength (3·9 kgf cm^{-2}, Table IV) of this surface is substantially higher than that of O and V surfaces (0·6 and 1·1 kgf cm^{-2}, respectively). High values for this index indicate shear stress must also be high for sediment detachment to occur. In the WSA experiments, nearly 80 per cent of the material remaining after shaking in water and sifting was greater that 0·25 mm (Table V), indicating (a) minimal slaking (aggregate destruction by escaping air molecules during the initial rapid wetting period, cf. Truman, *et al.*, 1990), which is typical of duracrust/durapan material; and (b) the wetted material is also resistant to detachment impacts and shearing forces by overland flow. In comparison, WSA indices calculated by the same technique for the Lualualei Vertisol (Ziegler and Sutherland, in review), an erodible soil type also found on Kahoʻolawe, were significantly lower (e.g., GMAD = 0·479 mm *vs*. 0·962 mm; WSA fraction ≥0·25 mm = 33·8 per cent *vs* 79·8 per cent; Table V). Collectively, our data indicate the material now dominating the hardpan is probably more resistant to detachment by raindrop impact and low velocity overland flow than indicated by their reported erosion factors (USLE $K = 0{\cdot}17$, Table II; Nakamura and Smith, 1995).

CONCLUSIONS AND RECOMMENDATIONS

Analyses of our hydrologic data demonstrate that revegetated areas associated with four restoration studies/projects on Kahoʻolawe have reduced the likelihood of runoff generation within their immediate areas. For example, comparison of rainfall intensity with modeled steady-state infiltration capacity suggests the revegetated areas infrequently generate overland flow compared with the bare hardpan surfaces that dominated the project sites before replanting. Other non-vegetated areas associated with the restoration projects, such as plowed/tilled areas and lands covered by rolled erosion control systems where vegetation did not become established, also have greater steady-state infiltration capacities than surrounding bare hardpan areas. However, modeled steady-state infiltration capacities in these areas are statistically lower than those for the revegetated areas, suggesting that such activities alone are less effective in reducing runoff than establishing vegetative cover. The revegetated areas form zones of high infiltration capable of infiltrating both rainwater and surface flow exported from adjacent bare lands actively producing overland flow. However, this 'sponging' effect does not currently prevent runoff from crossing the immediate project areas because the existing vegetation cover does not effectively block overland flow paths. Finally, although the effects of the revegetation projects in reducing the erodibility of the soil within the revegetation sites could not be ascertained in this study, the geomorphologic data suggest the most important role of revegetation efforts in reducing erosion appears to be decreasing large-scale overland flow, which, once channelized, is capable of eroding the hardpan surface by gullying processes.

The goal of our research was not to quantify how each project affected basin-scale runoff *per se*, but to determine within the collective project sites, small-scale changes in hydrologic/geomorphologic properties that might lead to large-scale reduction in runoff and erosion. This approach was necessary because the revegetation projects, with the exception of the Tamarisk Windbreak Project, are small-scale revegetation studies that were not designed specifically to affect basin-scale hydrologic response. Our study was hampered by a dearth of hydrological and geomorphological baseline data from which to judge project successes. To facilitate future investigations of this nature, we suggest baseline values be established on Kaho'olawe for (a) hydrologic variables, including available water content; (b) soil chemistry variables (e.g., cation exchange capacities, nutrient data, organic matter content); and (c) rates of infiltration, sediment detachment (raindrop and hydraulic), and gully migration. Long-term monitoring of the baseline variables should be integral components of any future restoration efforts.

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