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HYDROPHYSICAL DEGRADATION ASSOCIATED WITH HIKING-TRAIL USE: A CASE STUDY OF HAWAI'ILOA RIDGE TRAIL, O'AHU, HAWAI'I

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ABSTRACT

Recreational activities can have significant impacts on geomorphic and hydrologic processes in drainage basins, often out of proportion to their areal extent. With increased stress on hiking trails nationwide, there is a need to characterize the impacts of human trampling on soil properties. We examine an 810 m segment of Hawai'iloa Ridge Trail (O'ahu, Hawai'i, USA). Soil compaction and surface erosion on moderate to steeply sloping sites have degraded the trail environment. Bulk density, penetration resistance, and vane shear strength were significantly higher on the trail than in adjacent undisturbed areas, with median differences ranging from 29 to 120 per cent. With compaction and exposure of subsoil on the trail, void ratio, air-filled porosity, saturated hydraulic conductivity, effective and preferential porosity were significantly lower, with relative change values ranging from 23–93 per cent. No significant changes were noted in meso- or micro-porosity, but macropores with a radius of $>110\,\mu m$ decreased significantly by 58 per cent for on-trail locations. This comprehensive dataset indicates that hiking stress is deleterious to the soil–hydrologic system. Data point to a trail system that would be dominated by Hortonian overland flow and this was supported by field evidence during a storm event. Increased runoff has incised rills on some trail segments and there is evidence that run-on to adjacent side slopes has lead to accelerated erosion. Management on most trails in Hawai'i, including the one studied, is limited, but from our data it is apparent that on-trail sites directly influenced by an overhanging canopy of rapidly growing (aggressive) exotics were least impacted due to increased organic contributions to the surface and root network development. These data will allow land managers to more effectively address the potential geomorphic and hydrologic impacts of recreational land use. Copyright © 2001 John Wiley & Sons, Ltd.

KEY WORDS: hiking trail degradation; compaction; Hawai'i; recreational impacts; macropore disruption; management; penetration resistance

INTRODUCTION

The demand for lands dedicated to outdoor recreational uses has increased greatly since World War II (Toy and Hadley, 1987). Over 30 years ago, Dotzenko *et al.* (1967) suggested that expanding populations, increased income and greater leisure time created more intensive use of recreational areas. More recently, Ferris *et al.* (1993) noted that significant increases in recreational use in the UK and Ireland was a function of increased leisure time per capita, a greater proportion of the population who wish to pursue outdoor activities, higher incomes and greater mobility.

Recreational activities such as hiking, camping, mountain biking, four-wheeling, and horseback riding impose significant stresses on the environment. Long-term recreational use leads to changes in vegetation, soil microbial communities, soil morphology, micromorphology, soil chemistry and hydrophysical properties (Dotzenko *et al.*, 1967; Bryan, 1977; Shoba and Sokolov, 1982; Jim, 1987a,b; Stewart and Cameron, 1992; Sun and Liddle, 1993; Yorks *et al.*, 1997; Zabinski and Gannon, 1997; Ivonin and Avdonin, 2000). Quantification of recreational impacts is now necessary as a prerequisite to the scientific management of natural areas (James *et al.*, 1979).

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Objectives of this study are to: (i) examine the impact of recreational hiking on a variety of soil hydrophysical and chemical variables and (ii) identify a small number of sensitive variables that can be used by land managers to assess the degree of stress imposed by recreational impacts.

MATERIALS AND MEASUREMENTS

Study Area and Characteristics

A hiking trail on O'ahu, Hawai'i was selected for investigation. Hawai'iloa Ridge Trail is 13 km east of Honolulu, with a trail-head elevation of 340 m above sea level (asl) and extends for about 3 km along the ridgetop, intersecting the Ko'olau summit ridge at 770 m asl. The trail is incised into the remnants of the Ko'olau shield volcano that forms the eastern spine of O'ahu. Observations during trail reconnaissance trips indicated evidence of trail degradation, such as rill incision, bedrock exposure, minimal vegetation, absence of a litter layer and root exposure. Trail management has been minimal with only flow channels excavated into the trail to direct overland flow to off-trail side slope locations. An 810 m portion of the trail was field surveyed with a Sokkia Set 5 Total Station at approximately 5 m intervals (Figure 1).

Average annual rainfall for the trail area is approximately 2000 mm (Giambelluca *et al.*, 1986). The plant community is as an 'ūlei (*Osteomeles*) shrubland (Wagner *et al.*, 1990) with some patches dominated by ironwood (*Casuarina equisetifolia*), especially peaks, and others by strawberry guava (*Psidium cattleianum*). An inventory of trees and shrubs found within 2 m of the trail center for the 40 sites is given in Bussen *et al.* (1998). The Lahaina soil series is characteristic of the trail, and taxonomically it is a Rhodic Eutrustox (oxisol), very fine, kaolinitic, isohyperthermic silty clay, well suited only for herbaceous plants and shrubs (Foote *et al.*, 1972). Kawano and Holmes (1958) found the Lahaina soil (0–25 cm depth) to be composed of 62.7 per cent clay, have a plastic limit of 32.6 per cent, a liquid limit of 48.5 per cent, and a plasticity index of 15.9 per cent. They also reported organic carbon (OC) content was 1.25 per cent (Walkley-Black), and particle density was 2.86 Mg m^{-3}.

Chemical and Hydrophysical Soil Property Measurements

Most recreational impact studies, particularly those focusing on hiking trail impacts have measured only a limited number of chemical and hydrophysical variables. To more effectively quantify the impact of hiking on soil properties a wider array of variables needs to be measured. In this study a paired (on versus off), post-impact, systematic transect-oriented sampling framework was employed. Samples were collected and measurements taken at 40 sites, 20 m apart, and selected locations are shown in Figure 1. At each of the 40 sites paired samples were

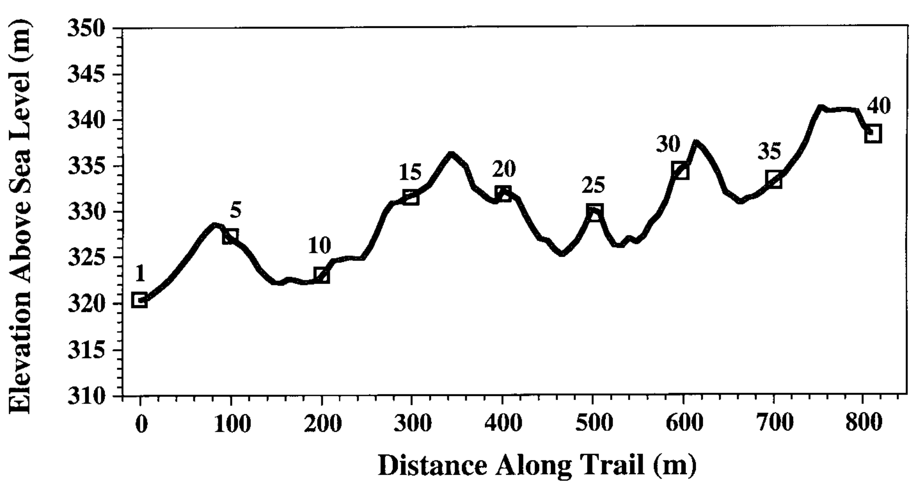

Figure 1. Hawai'iloa Ridge Trail profile, 10 times vertical exaggeration.

Table I. Field and laboratory methods used for soil chemical, hydrophysical, and morphological analysis

Soil variable	Units	Sites	Method/Reference
Chemical property			
Organic carbon (*OC*)	%	80	Modified Walkley–Black (Heańes, 1984)
pH in water	–	60	Electrode, 1:5 soil–water mixture (Buurman *et al.*, 1996)
Hydrophysical property			
Air-filled porosity ($Ø_{air}$)	$m^3\ m^{-3}$	80	Derived variable from core data (Hillel, 1982)
Bulk density (ρ_B)	$Mg\ m^{-3}$	80	Core method, 5.1 cm depth (Blake and Hartge, 1986)
Effective porosity ($Ø_{Eff}$)	$m^3\ m^{-3}$	30	Derived from moisture characteristic curve (MCC), pore diameter $>10\ \mu m$ (Ahuja *et al.*, 1984; Klute, 1986)
Gravimetric water content (θ_g)	%	80	Core dried (105 °C, 24 h) and equation in Gardner (1986)
Mesoporosity ($Ø_{Meso}$)	$m^3\ m^{-3}$	30	Derived from moisture characteristic curve (MCC), pore diameter 3.0–30 µm (Klute, 1986; Mbagwu, 1997)
Microporosity ($Ø_{Micro}$)	$m^3\ m^{-3}$	30	Derived from moisture characteristic curve (MCC), pore diameter 0.2–3.0 µm (Klute, 1986; Mbagwu, 1997)
Penetration resistance (*PR*)	MPa	80	CN-970 proving-ring penetrometer, 30° cone, 5.47 cm length, 6.47 cm^2 base (Bradford, 1986; ASAE, 1998)
Pore size distribution	%	30	Apply capillary equation (Equation 2) to MCC data (Hillel, 1982)
Porosity (Ø)	$m^3\ m^{-3}$	80	Derived from ρ_B and a particle density of 2.86 $Mg\ m^{-3}$ (Hillel, 1982)
Preferential porosity ($Ø_{Pref}$)	$m^3\ m^{-3}$	30	Derived from moisture characteristic curve (MCC), pore diameter $>30\ \mu m$ (Klute, 1986; Mbagwu, 1997)
Saturated hydraulic conductivity (K_s)	$mm\ h^{-1}$	32	Disc permeameters (Ziegler and Giambelluca, 1997)
Saturated porosity ($Ø_s$)	$m^3\ m^{-3}$	30	Distilled water saturation method (Klute, 1986)
Vane shear strength (τ_v)	kPa	80	E285 torvane, depth of 'foot' ≈ 5 mm
Void ratio (*e*)	–	80	Dervied using equation in Hillel (1982)
Volume of solids (V_s)	m^3	80	Derived using equation in Hillel (1982)
Volumetric water content (θ_v)	$m^3\ m^{-3}$	80	Core dried (105 °C, 24 h) and equation in Gardner (1986)
Morphological property			
Down-trail slope	%	40	Clinometer
Across-trail slope	%	40	Clinometer
Saleh roughness factor (SRF)	%	40	Chain method and Equation (3) (Saleh, 1993)

collected, i.e. 40 on-trail and 40 undisturbed off-trail. The occurrence of excessive tree roots or bedrock outcrops led to minor deviations from the regular 20 m sampling interval. At all on-trail and off-trail sites, 5.1 cm by 4.7 cm diameter soil cores were collected using a standard stainless steel corer. Loose organic surface litter encountered at most off-trail sites was carefully removed before sampling.

The variables measured in the field, laboratory or derived are listed in Table I, and these were selected following an extensive examination of the recreational impact, agronomy/soil science and forestry literature. To compare on- and off-trail sites, and to compare our results to published data we compute the relationship shown in Equalion (1):

$$\text{Relative percent change} = \left(\frac{\text{Disturbed site} - \text{undisturbed site}}{\text{undisturbed site}}\right) \cdot 100 \tag{1}$$

At 15 on-trail and off-trail sites additional 5.1 cm depth cores were extracted for development of soil moisture characteristic curves using standard procedures described in Klute (1986). Eight matric potentials (ψ) were selected with a range from -1.9 to -1500 kPa. These data were used to derive several variables listed in Table I. Effective porosity was computed as the difference in water content between $\psi = 0$ kPa (saturation) and -30 kPa, sometimes referred to as field capacity (Ahuja *et al.*, 1984). Preferential porosity was computed as the difference in water content between $\psi = 0$ kPa (saturation) and -10 kPa (Mbagwu, 1997). Mesoporosity was computed as the difference in water content between $\psi = -100$ kPa and -10 kPa, and microporosity between $\psi = -1500$ kPa and -100 kPa (Mbagwu, 1997). In a non-shrinking soil, the soil moisture characteristic curve allows calculation of the effective pore-size distribution using the capillary equation (Hillel, 1982; Dunn and Phillips, 1991):

$$r = -[2\gamma \cdot \cos \alpha_a]/[\rho \cdot g \cdot \psi] \tag{2}$$

where r = equivalent pore radius (m), γ = surface tension of water at 20 °C (kg s^{-2}), α_a = wetting angle of the water and the pore wall (assumed ≈ 0, therefore $\cos \alpha_a = 1$), ρ = density of water at 20°C (kg m^{-3}), g = acceleration due to gravity (m s^{-2}) and ψ = suction of water, negative hydraulic pressure (m). Using Equation (2) the distribution of pores (per cent) in each of six pore radii classes were determined: >110 µm, 50–110 µm, 15–50 µm, 1.5–15 µm, 0.1–1.5 µm, and <0.1 µm.

Morphometry

Cross-trail and down-trail slopes were measured with a clinometer. The chain method (Saleh, 1993) was used to measure cross-trail roughness at each of the 40 on-trail sampling sites. A small link chain was carefully laid at right angles across the degraded trail section, making sure that the chain fit tightly to the surface undulations. The resulting chain length was compared to the straight line distance. A Saleh roughness factor (SRF) was computed as

$$\mathrm{SRF} = 100 \cdot \left[1 - \left(\frac{\text{Straight line distance } (m)}{\text{Undulating surface distance } (m)}\right)\right] \tag{3}$$

The SRF is potentially a useful method for land managers as it has been shown to be closely correlated to estimates made by a multi-pin roughness meter (Saleh, 1993). Gilley and Kottwitz (1995) also found changes in surface roughness induced by tillage and rainfall appeared to be adequately reflected by SRF. Merrill (1998) also indicated that the chain concept offers the prospect of integrative field roughness measurement that is sensitive to scale and fractal character. Thus, a rougher or more highly incised trail segment would be characterized by a larger SRF value. Though simple in concept we found defining either edge of the hiking path presented the most challenging aspect of using this method. Clustered patches of short grass or herb growth were often interspersed with partially disturbed soil. The trail edge delimitation was a qualitative judgment based on very localized observation of transitional soil conditions at the surface and remnant vegetation.

Statistical Analyses

Descriptive statistics were summarized for all variables based on trail location. Many variables were highly skewed and non-normally distributed, therefore the median was used as a measure of centeral tendency and the median absolute deviation from the median (MAD) was used as a robust measure of dispersion (see Helsel and Hirsch, 1992). Box plots were used to graphically illustrate the dichotomy between on- and off-trail locations for selected variables. The central portion of the box plot represents 50 per cent of the distribution, with the central line in the box being the median and the shaded area the 95 per cent confidence band about the median. Circles represent 'outliers' as identified by an empirical rule, and asterisks represent 'extreme outliers' as identified by an empirical rule (Frigge *et al.*, 1989).

The Wilcoxon (paired) signed rank test was used to examine differences between on-trail and off-trail sites at $\alpha = 0.05$. Spearman's rank order correlation coefficient (r_s) was used to examine monotonic relationships between selected variables with an α-level of 0.05. Canonical discriminant analysis (CDA) was used to assess combinations of variables that best separate the mean vectors of two or more groups of multivariate observations relative to the within-group variance (Rencher, 1992). Two datasets were examined using CDA, the first being the complete set that included eight non-redundant variables for all on- and off-trail sites (ρ_B, θ_g, θ_v, τ_v, Ø_{air}, OC, PR and e; see

Table I for symbol descriptions). The second dataset included 15 on- and off-trail locations where K_s and core water retention data were available; this dataset included 14 non-redundant variables (i.e. variables from the complete set plus: $Ø_{Eff}$, $Ø_{Pref}$, $Ø_{Meso}$, $Ø_{Micro}$, $Ø_s$ and K_s).

RESULTS AND DISCUSSION

Visual trail observations during a rainfall event on March 23, 1997 (25 mm in 24 h) indicated significant runoff by Hortonian overland flow, and sediment transport throughout the sloping segments. In gently sloping areas and in areas at the base of moderate to steep slopes significant ponding was observed. On-trail overland flow generation during this event was influenced by high antecedent moisture status, with rainfalls of about 20 and 40 mm on March 16 and 17, respectively.

Trail Morphometry and Roughness

Median on-trail slope was 6.0 ± 3.7 per cent ($\pm$ MAD) with a range from 1 to 47 per cent (Table II). Slopes were classified as steep ≥ 15.0 per cent, moderate 7.0–14.9 per cent, and gradual ≤ 6.9 per cent after Jubenville and O'Sullivan (1987). Gradual slopes accounted for 60 per cent of the on-trail locations, moderate slopes for 20 per cent, and steep slopes 20 per cent. Across-trail slope was 8.3 ± 7.0 per cent, with a median width of 1.0 ± 0.3 m (mean = 1.6 m) Unlike some studies, development of secondary or feeder trails was not a problem since the narrow ridge-top and steep side slopes prevented hikers from off-trail wandering.

The median trail SRF value was 5.1 ± 3.1 per cent, with a range from 0–35 per cent (Table II). The only other hiking trail roughness data known to the authors are from western Montana (DeLuca *et al.*, 1998). They found a significant positive linear relationship between surface roughness and sediment yield from plots under simulated rainfall. Though comparable SRF data are not available from the hiking trail literature, we can look to other human disturbed environments for comparative data. Gilley and Kottwitz (1995) present SRF data for an initially smooth agricultural soil that was subsequently disrupted by a variety of tillage operations: (i) anhydrous ammonia applicator, SRF = 12.4 ± 9.2 per cent (mean $\pm$ 1 standard deviation); (ii) a planter, SRF = 13.0 ± 5.1 per cent; (iii) a field cultivator, SRF = 23.9 ± 5.0 per cent; (iv) a disc, SRF = 28.2 ± 5.8 per cent; (v) a moldboard plow, SRF = 30.9 ± 5.9 per cent; and (vi) a chisel plow, SRF = 34.6 ± 3.5 per cent. Our hiking trail SRF data are typically much lower than those for the agriculturally disturbed soil, but 20 per cent of the trail locations had SRF values ≥ 12.4 per cent (similar to the lowest mean associated with a tillage operation), and 10 per cent had SRF values ≥ 25 per cent. The on-trail locations with the highest roughness values were those with the most highly incised surfaces. The SRF was found to be positively correlated with down-trail slope ($r_s = +0.40, p = 0.017$). One-way ANOVA, followed by post-hoc testing, indicated that gradual slopes had significantly lower SRF-values than the moderate and steeply sloping sites. As slope increases the importance of trail incision by surface runoff processes would increase, while on flatter slopes roughness would be dominated less by erosion, and more by hiker tread preferences. Additionally, flatter toe slopes are sites of sediment deposition and exhibit limited evidence of rilling.

Vegetation and Chemical Properties

Reduction in soil organics would have deleterious impacts on biotic activity, and may lead to higher rates of surface erosion since the binding power of organics is lost and aggregates become more susceptible to breakdown and transport. Soane (1990) identifies six mechanisms by which organics may influence the ability of the soil to resist compactive loads, such as: (i) binding forces between particles and within aggregates; (ii) elasticity; (iii) dilution effect; (iv) filament binding effect; (v) effect on electrical soil charge; and (vi) effect on friction (Soane, 1990). Off-trail organic carbon (OC) was significantly higher than on-trail, 5.7 ± 2.5 per cent versus 2.8 ± 1.3 per cent, equivalent to a decrease of 51 per cent (Table II; Figure 2a). No comparable hiking trail data are available, but the decrease of organics from Hawai'iloa Ridge Trail are similar to those reported for other recreational activities: (i) camping in Rocky Mountain National Park, CO, 29–31 per cent (Dotzenko *et al.*, 1967); (ii) 38 per cent for

Table II. Statistical data summary for soil chemical, hydrophysical and morphological variables and results of Wilcoxon paired sample test of on- and off-trail samples

Soil variable	Units	On-trail[1]	Off-trail[1]	Relative difference (%)[2]	*p*-value[3]
Chemical property					
Organic carbon (*OC*)	%	2.79 ± 1.33 (0.50 – 23.46)	5.70 ± 2.45 (0.31 – 21.06)	– 51.1	< 0.0001
pH in water	–	5.2 ± 0.6 (4.3 – 6.7)	5.8 ± 0.5 (4.6 – 7.1)	– 10.3	0.031
Hydrophysical property					
Air-filled porosity ($Ø_{air}$)	$m^3\ m^{-3}$	0.274 ± 0.071 (0.102 – 0.635)	0.362 ± 0.081 (0.041 – 0.641)	– 24.3	0.003
Bulk density (ρ_B)	$Mg\ m^{-3}$	1.04 ± 0.12 (0.40 – 1.45)	0.80 ± 0.08 (0.40 – 1.09)	+ 29.3	< 0.0001
Effective porosity ($Ø_{Eff}$)	$m^3\ m^{-3}$	0.148 ± 0.025 (0.092 – 0.434)	0.191 ± 0.042 (0.042 – 0.417)	– 22.5	0.028
Gravimetric water content (θ_g)	%	37.7 ± 4.2 (11.1 – 77.7)	42.8 ± 7.2 (24.0 – 86.6).	– 12.0	0.003
Mesoporosity ($Ø_{Meso}$)	$m^3\ m^{-3}$	0.078 ± 0.017 (0.054 – 0.122)	0.083 ± 0.018 (0.053 – 0.150)	– 6.0	0.46
Microporosity ($Ø_{Micro}$)	$m^3\ m^{-3}$	0.385 ± 0.020 (0.268 – 0.473)	0.382 ± 0.030 (0.322 – 0.437)	+ 0.8	0.82
Penetration resistance (*PR*)	MPa	1.45 ± 0.14 (0.89 – 1.82)	0.66 ± 0.20 (0.17 – 1.16)	+ 118.2	< 0.0001
Porosity (Ø)	$m^3\ m^{-3}$	0.637 ± 0.042 (0.494 – 0.861)	0.720 ± 0.028 (0.618 – 0.860)	– 11.5	< 0.0001
Preferential porosity ($Ø_{Pref}$)	$m^3\ m^{-3}$	0.100 ± 0.024 (0.041 – 0.333)	0.149 ± 0.026 (0.022 – 0.354)	– 32.9	0.042
Sat. hydraulic conductivity (K_s)	$mm\ h^{-1}$	19 ± 10 (8 – 148)	254 ± 161 (20 – 600)	– 92.5	0.0004
Saturated porosity ($Ø_s$)	$m^3\ m^{-3}$	0.589 ± 0.035 (0.456 – 0.822)	0.624 ± 0.025 (0.509 – 0.779)	– 5.6	0.031
Vane shear strength (τ_v)	kPa	56.4 ± 12.3 (22.1 – 88.3)	29.9 ± 9.8 (4.9 – 47.1)	+ 88.5	< 0.0001
Void ratio (e)	–	1.76 ± 0.28 (0.98 – 6.19)	2.57 ± 0.36 (1.62 – 6.16)	– 31.6	< 0.0001
Volume of solids (V_s)	cm^3	32.3 ± 3.7 (12.4 – 45.1)	25.0 ± 2.5 (12.4 – 34.0)	+ 29.4	< 0.0001
Volumetric water content (θ_v)	%	36.0 ± 4.30 (11.8 – 47.2)	36.3 ± 6.2 (14.9 – 57.7)	– 0.9	0.47
Morphological property					
Down-trail slope	%	6.0 ± 3.7 (0.9 – 46.6)	–	–	–
Across-trail slope	%	8.3 ± 7.0 (0.9 – 43.8)	–	–	–
Saleh roughness factor (SRF)	%	5.1 ± 3.1 (0.0 – 35.1)	–	–	–

[1]Median values are tabulated with ± values representing median absolute deviations from the median (MAD); values in parentheses are the minimum and maximum values.
[2]The median relative percent change from on-trail to off-trail was calculated using Equation (1); positive values indiciate on-trail > off-trail and negative values indicate off-trail > on-trail.
[3]*p*-values were calcuated using the Wilcoxon (non-parametric) paired test, with values less than 0.05 indicating a statistically significant difference between on- and off-trail sites.

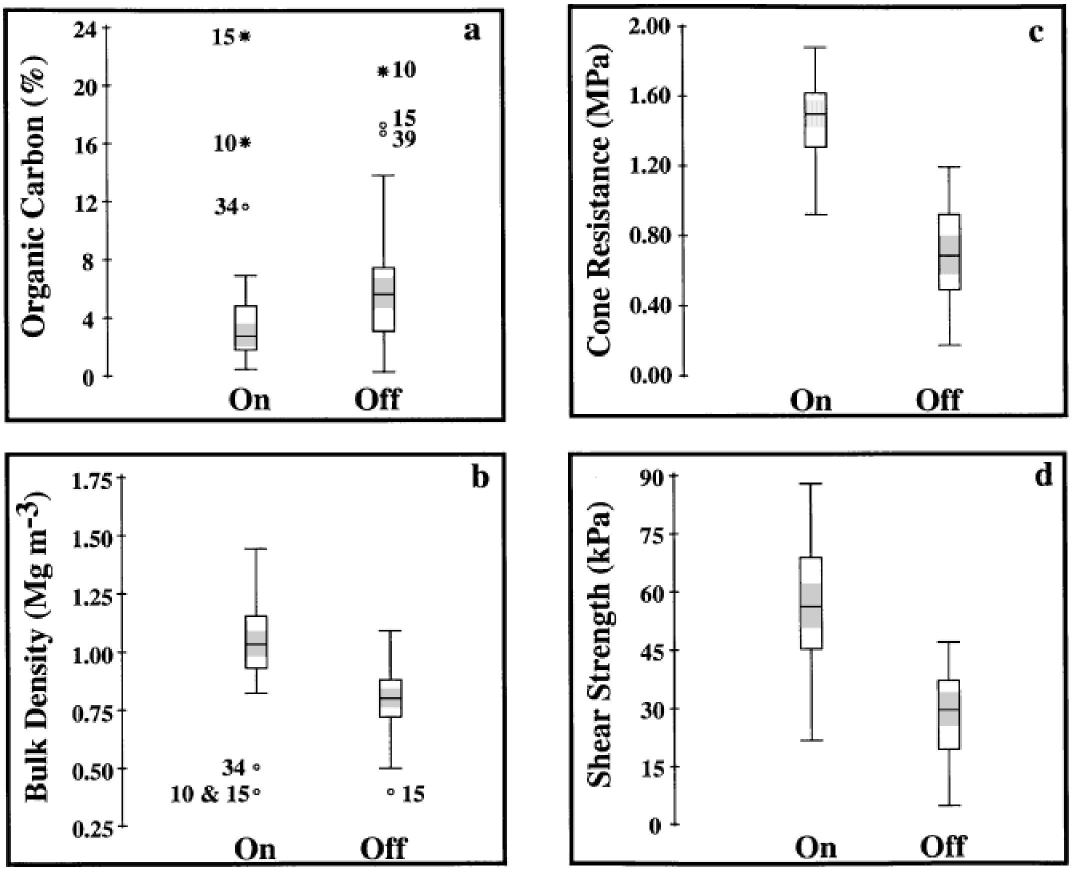

Figure 2. Selected side-by-side box plots of on- and off-trail soil variables: (a) organic carbon (*OC*); (b) bulk density (ρ_B); (c) penetration resistance (*PR*); and (d) vane shear strength (τ_v). Note the numbers associated with the outliers represent sample site locations.

off-road vehicles in San Francisco Bay area, CA (Wilshire *et al.*, 1978); (iii) 42 per cent for areas influenced by heavy picnicking in Shing Mun Country Park, Hong Kong (Jim, 1987b); and (iv) 54 per cent for heavy use of campsites in northeastern Iowa (Dawson *et al.*, 1978).

The OC content for on-trail sities #10 (180 m from start of transect) and #15 (280 m) were identifieid as extreme (high) outliers, with values of 16 and 24 per cent respectively (Figure 2a). Additionally, their off-trail OC contents were high, 21 and 17 per cent. These sites are the ones most direictly influenced by an ironwood canopy, and the impact of this tree species on other soil variables will be explored more fully later in this paper. The ratio of OC on-trail to off-trail with distance along the study section (Figure 3a) indicates that most (85 per cent) of the locations had greater OC off-trail than on-trail. Two sites at the base of slopes #2 (20 m) and #7 (120 m; Figure 1) accumulated sediment and organic material from upslope and had ratios > 1.0.

Soil pH (Table II) data indicated that on trail soils were significantly more acidic (5.2 ± 0.6) than off-trail soils (5.8 ± 0.5). Increased acidity of on-trail soil may suggest an increased exposure of the more acidic subsoil on the hiking trail and/or selective removal of fine particles by surface erosion and their preferential transport of basic cations. No comparable pH data are available from the hiking trail literature.

Impacts on Soil Hydrophysical Variables

Bulk density is the soil variable most frequently incorporated into studies examining the influences of anthropogenic practices on the environment. Its value in deciphering hiker impacts has been nicely shown in experimental trampling studies. For example, Weaver *et al.* (1979) determined soil surface ρ_B, after a specified

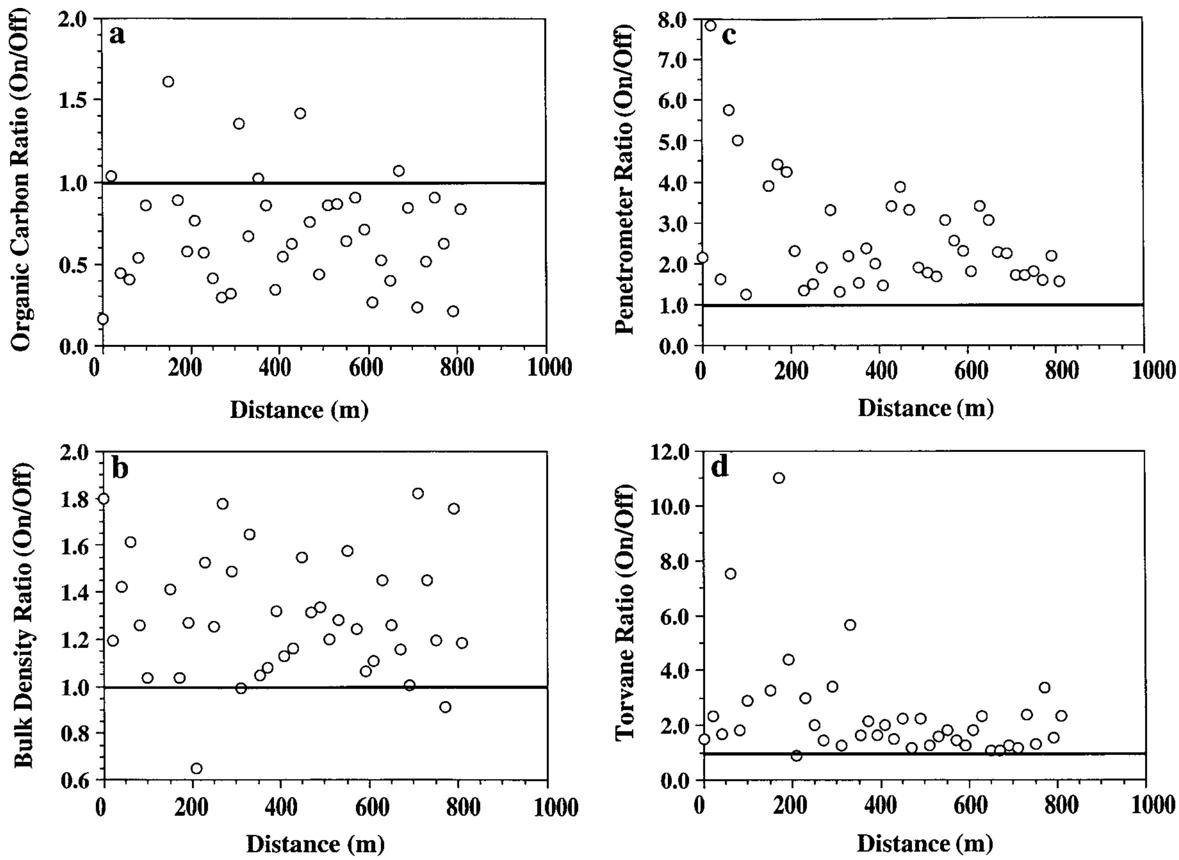

Figure 3. Selected on-trail to off-trail ratio plots with distance for (a) organic carbon (*OC*); (b) bulk density (ρ_B); (c) penetration resistance (*PR*); and (d) vane shear strength (τ_v).

number of hiker passes (0, 300, 600 and 900), to be 1.01, 1.09, 1.11 and 1.18 Mg m^{-3}, respectively, with relative changes increasing with intensity from 7.9 to 16.8 per cent. We also found ρ_B-values of on-trail sites were siginifcantly greater than adjacent off-trail sites (Table II; Figure 2b). The relative increase was 29 per cent, similar to those reported in the literature for other hiking trails, camping activities (heavy use areas), and impacts of off-road vehicles; but higher than those associated with picnicking, skid trails and grazing (Table III).

The ρ_B-values for on-trail sites 10, 15 and 34 were considered outliers (Figure 2b) and on the low side, with values between 0.4 and 0.5 Mg m^{-3}. These sites have obviously been influenced by the overhanging tree canopy, through additions of organics via fallen leaves and root biomass. Correlation analysis suggests a significant negative relationship between ρ_B and OC ($r_s = -0.52, p = 0.001$), i.e. as the OC of the surface soil increases ρ_B-values decrease. Organic carbon is one of the important factors influencing the susceptibility of a soil to compaction. If on-trail compaction is to be minimized, management efforts must be focused on preventing significant declines in this critical soil structure stabilizing factor.

Trail compaction resulted in a significant decrease in porosity (Ø, 12 per cent) but the void ratio (e) decreased by 32 per cent (Table II). Air-filled porosity ($Ø_{air}$), not commonly reported in the recreational research literature, also decreased significantly with trampling by 24 per cent. Hillel (1982) reports $Ø_{air}$ data from a livestock trampling study that found a relative decrease of 58 per cent between grazed and ungrazed areas.

For agricultural soils, Anderson *et al.* (1980) stated that the penetrometer is the most widely used instrument for assessing *in situ* soil strength. This is also true for studies conducted to assess impacts on the soil surface by recreational activities. In our study penetration resistance (*PR*) increased significantly from 0.66 MPa off-trail to

Table III. Average values for relative change (Δ) in surface bulk density (ρ_B), penetration resistance (PR), and infiltration rate (IR) between disturbed and undisturbed land uses

Impact	Location	Δ in ρ_B (%)	Δ in PR (%)	Δ in IR (%)	Reference[1]
Skid trail	Ochoco National Forest, OR[2]	9 to 16	18 to 143	–	1
Grazing	Alberta, Canada[2]	9 to 17	21 to 84	–	2
Camping	Grand Canyon National Park, AZ[2]	26	300	– 73.2	3
Camping	Northeast Iowa[2]	30	–	–	4
Skid trail	Coastal Plain, Mississippi[2]	10 to 20	–	– 65 to – 90	5
Camping	Rocky Mt. National Park, CO[3]	32 to 46	–	–	6
Grazing	Utah[2]	15 to 22	200 to 422	–	7
Camping	Central AZ[3]	2 to 25	–	–	8
Camping	Rushing River Provincial Park, Canada[2]	–	99 to 209	– 95 to – 100	9
Camping	Sai Kung Country Park, Hong Kong[2]	6 to 34	80	–	10
Picknicking	Shing Mun Country Park, Hong Kong[3]	5	33	– 97	11
Camping	Ottawa National Forest, MI[2]	23 to 46	–	–	12
Hiking	Pat Sin, Hong Kong[2]	–	90	–	13
Camping	South Carolina[2]	75	460	–	14
Camping	Delaware Water Gap National Recreation Area[2]	16 to 22	361 to 520	–	15
Camping	Boundary Water Canoe Area, MN[2]	20 to 40	–	–	16
Camping	Rushing River Provincial Park, Canda[2]	34	–	– 95	17
Wagon + animals	Wadsworth Trail, MN[2]	6	39	– 48	18
Hiking	Russia[2]	33 to 101	230 to 875	– 96 to – 100	19
Hiking	St. James Walkway, New Zealand[2]	60	–	–	20
Hiking + vehicles	Queensland, Australia[2]	–	103 to 400	–	21
Hiking	Jatsun Sacha, Ecuador[2]	40	–	–	22
Hiking	La Selva, Costa Rica[2]	12	–	–	22
Off-road vehicles	San Francico Bay area, CA[2]	34	–	– 97	23
Camping	Illinois[2]	–	144 to 183	–	24
Hiking	Hawai'iloa Ridge Trail, O'ahu	29	118	– 93	25

[1]1, Allbrook (1986); 2, Chanasy and Naeth (1995); 3, Cole (1986); 4, Dawson *et al.* (1978); 5, Dickerson (1976); 6, Dotzenko *et al.* (1967); 7, Gifford *et al.* (1977); 8, Green (1998); 9, James *et al.* (1979); 10, Jim (1987a); 11, Jim (1987b); 12, Legg and Schneider (1977); 13, Leung and Neller (1995); 14, Lockaby and Dunn (1984); 15, Marion and Cole (1996); 16, Marion and Merriam (1985); 17, Monti and Mackintosh (1979); 18, Sharrett *et al.* (1998); 19, Shoba and Sokolov (1982); 20, Stewart and Cameron (1992); 21, Sun and Liddle (1993); 22, Wallin (1995) and Wallin and Harden (1996); 23, Wilshire *et al.* (1978); 24, Young and Gilmore (1976); 25, this study.
[2]Impact relative to undisturbed site.
[3]Impact relative to lightly disturbed site.

1.45 MPa on-trail, equivalent to an increase of 118 per cent (Table II). The box plot (Figure 2c) shows the distinct difference in the distributional data for the two environments. Additionally, the ratio of *PR* on-trail to off-trail clearly indicates that all on-trail sites exceeded their adjacent off-trail site values, with a maximum difference of about eight-fold (Figure 3c). Using a lower limit of 1 MPa for *PR* suggested by Whalley *et al.* (1995) as deleterious to the rate of root elongation, 95 per cent of the on-trail sites ($n = 38$) would be adversely impacted, while only 12.5 per cent of the off-trail sites ($n = 5$) would be so impacted.

Several recreational studies have shown that the influence of human activities on soil property response is non-linear, with most change occurring during the initial low levels of use (i.e. Bryan, 1977; Cole, 1988; Kuss and Hall, 1991; DeLuca *et al.*, 1998). Cole (1998) found *PR* (pocket-type) increased asymptotically with trampling intensity, with a 0.6 kg cm^{-2} increase after about 40 passes per year vs. about 3 kg cm^{-2} with 1600 passes per year. Data from Kuss and Hall (1991) also showed a similar trend, with an increase in *PR* (pocket-type) of 0.94 kg cm^{-2} with 100 passes, 1.55 kg cm^{-2} increase with 400 passes, and 2.18 kg cm^{-2} increase with 800 passes on an experimental hiking trail system. Comparisons of relative changes in *PR* data from this study with others are shown in Table III; they are informative, but must be viewed with caution, as our data were integrated over a depth of 5.5 cm with a cone basal area of 6.5 cm^2. Relative changes in *PR* data from Hawai'iloa Ridge Trail are similar in magnitude to those reported for other human impacts, and they are significantly higher than the relative change values reported for ρ_B. This may suggest that PR is a more sensitive variable when assessing human impacts.

Quinn *et al.* (1980) found (i) the shearing action of the foot contributes far more to vegetation 'wear' and footpath damage than does its compressive action and (ii) the greatest shearing action occurs on steeper slopes. The hand-held torvane was used to assess the vane shear strength (τ_v) of the trail and undisturbed surface layer to tangential stresses. Trail τ_v-values were significantly higher than off-trail values, 56.4 kPa versus 29.9 kPa, 89 per cent higher (Table II). The differences are apparent from the side-by-side box plots (Figure 2d), and from the on/off ratio plot (Figure 3d). Only a few vane shear datasets exist in the site disturbance literature: Stewart and Cameron (1992) found an increase of 20 per cent with hiking; and Allbrook (1986) found increases of 11, 33, and 59 per cent for the centre of a skid trail (influenced by dragged logs), trail edge locations and skidder wheel ruts, respectively, compared to an undisturbed forest soil.

Together the *PR* and τ_v data indicate that the on-trail sites are stronger and more likely to resist normal (e.g. raindrop impacts) and tangential stresses (e.g. Hortonian overland flow). The strength increase has come about through a combination of processes such as compaction by trampling and/or erosion with the removal of the surface horizon and exposure of a more resistant subsurface horizon. On the one hand, increased surface strength would produce a less erodible soil, but subsequent surface property changes would increase the frequency of overland flow generation that may overcome the increased surface strength and lead to rill incision. If vertical incision is restricted by the compact surface, lateral corrasion may occur in some locations, regardless the path surface will act as a source area for overland flow generation. The increased strength of the trail soil surface will restrict root elongation and prevent seedling germination. These are critical areas of concern to land managers during rehabilitation.

In support of enhanced overland flow generation on the compacted trail surface, saturated hydraulic conductivity (K_s) data for 16 on-trail and off-trail sites indicaite significantly lower values for trampled locations (Table II). Data for on-trail sites are typically 13-fold lower than their neighboring off-trail sites. Box plots (Figure 4a) indicate a much wider spread of values for off-trail sites than on-trail, and the on-off-site spatial plot (Figure 5a) shows all sites with ratios < 1.0. Wallin and Harden (1995), and Ziegler and Giambelluca (1997) indicate that paths and other compacted surfaces such as unpaved roads can act as important areas for generation of Hortonian overland flow. Flow generated on-trail can serve as a source of run-on water for off-trail locations and increase the potential for channel incision. Despite trails occupying a very small portion of the surface area of drainage basins, they can play a disproportionally important role hydrologically and geomorphologically.

Changes in the soil surface conductivity to ponded water has typically been measured on recreational areas using single or double ring infiltrometers, not with disc permeameters, making direct comparisons difficult between studies. Nevertheless, final infiltration rate data were used when available to compute relative per cent change values for disturbed and undisturbed areas (Table III). The relative decrease of 93 per cent for on-trail sites measured in this study is similar to those reported in the literature.

Thirty samples (15 on- and 15 off-trail) were used to quantify the trampling effects on pore-related variables, including $Ø_{Eff}$, $Ø_{Meso}$, $Ø_{Micro}$, $Ø_{Pref}$, and $Ø_s$ (Table II). Macropore indices ($Ø_{Eff}$ and $Ø_{Pref}$) were found to be significantly greater off-trail than on-trail. The side-by-side box plots for $Ø_{Pref}$ indicate again the unusual nature of sites 10 and 15 (Figure 4b). The on/off ratio plot for $Ø_{Pref}$ (Figure 5b) reinforces the pattern of higher $Ø_{Pref}$ values off-trail. Figure 6 displays the proportion of pores in each of six size classes, with bars representing median values and error bars are MAD values. The data show that the largest pore radii ($> 110\ \mu m$) are the ones most dramatically influenced by trampling with a decrease from 18 to 8 per cent (relative decrease of 56 per cent). Little difference was observed in the pore radii from about 0.1–110 μm for all on- and off-trail sites, with the smallest pores ($< 0.1\ \mu m$) showing an increase from 48 per cent for the off-trail site to 56 per cent for the on-trail sites. Whalley *et al.* (1995) noted that mechanical stress destroys the largest soil pores first; though there is some compensatory increase in the numbers of small pores, there is still a dramatic effect on soil transport properties

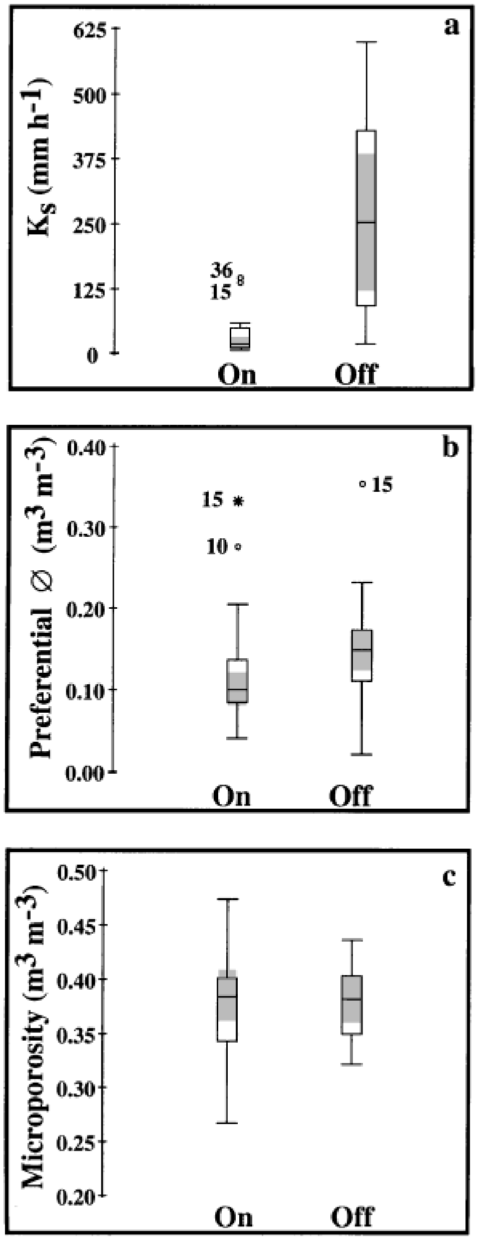

Figure 4. Selected side-by-side box plots of on-trail and off-trail soil variables: (a) saturated hydraulic conductivity (K_s); (b) preferential porosity ($Ø_{Pref}$); and (c) microporosity ($Ø_{Micro}$). Note the numbers associated with the outliers represent sample site locations.

because water conductivity varies as pore size squared. Additionally, as Luxmoore *et al.* (1990) point out, not all macroporosity is hydrologically active; it is likely that trampling not only significantly decreases macroporosity but also pore continuity. Thus, the decrease in macroporosity and removal of protective vegetation cover from Hawai'iloa Ridge Trail has lead to the significant decreases observed in the on-trail K_s-values.

There are no comparable pore size distribution data, derived from moisture characteristic curves, in the recreational literature. Limited campsite data exist on soil macroporosity measured using air. Legg and Schneider

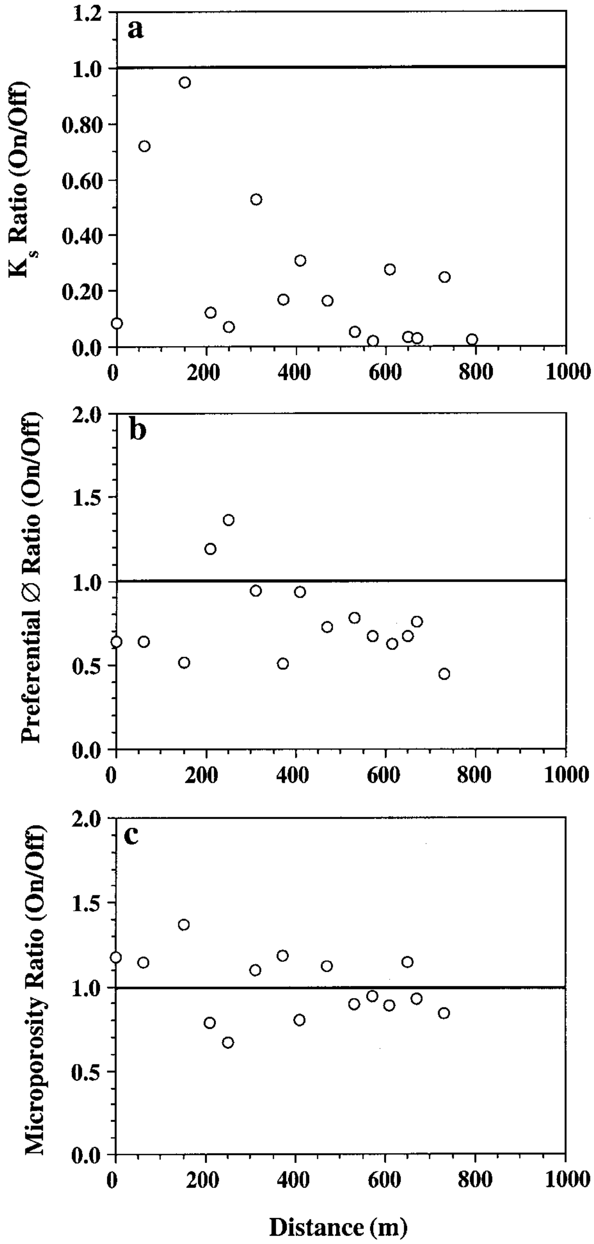

Figure 5. Selected on-trail to off-trail ratio plots with distance for (a) saturated hydraulic conductivity (K_s); (b) preferential porosity ($Ø_{Pref}$); and (c) microporosity ($Ø_{Micro}$).

(1977) found macroporosity (sizes of pores undefined) decreased with use-intensity in both hardwood and conifer forests with relative decreases ranging from 65–87 per cent. Dawson *et al.* (1978) also found comparable changes in macroporosity (again pore sizes not defined) in 13 public campgrounds, with a relative decrease of 64 per cent. Numerous studies on the influence of silvicultural and agricultural practices on pore size distribution have found significant decreases in 'macro' pores with compaction and concomitant decreases in infiltration (e.g. Ahuja *et al.*, 1984; Allbrook, 1986; Dunn and Phillips, 1991; Mbagwu, 1997).

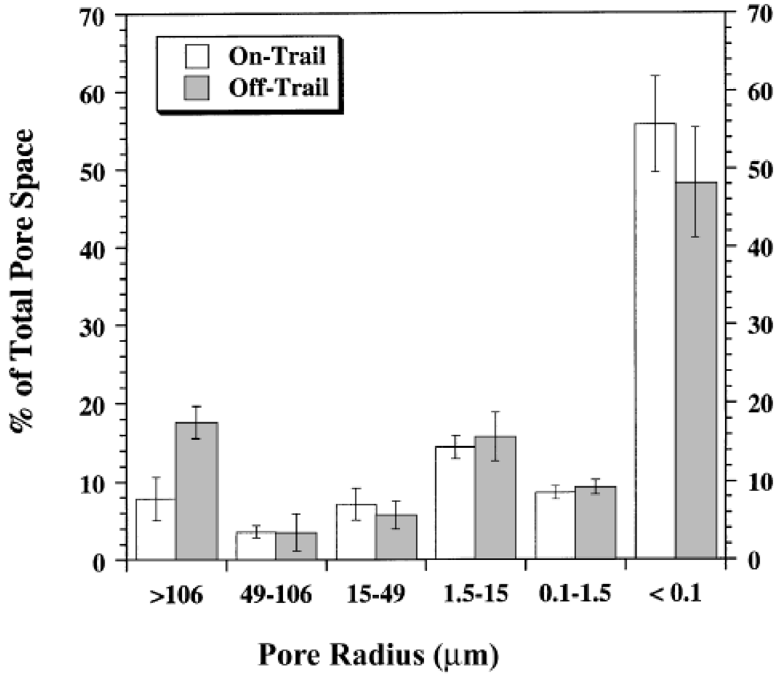

Figure 6. Distribution of soil pores (radii) in six classes for on- and off-trail sites. The bars represent median values, and error bars are median absolute deviations from the median (MAD).

Discrimination Between On- and Off-Trail Soil Properties

The second objective of this study was to identify a parsimonious set of variables that would allow the land manager to quantitatively identify the spatial and temporal impacts of hikers (or other forms of recreational activity). Forward stepwise CDA was used to quantitatively identify the most sensitive soil variables separating disturbed from undisturbed trail areas. Two datasets were examined, the first being eight variables measured or derived at all locations on-and off-trail ($n = 80$). Results indicate a four variable model correctly classified 95 per cent of all sites as either disturbed or undisturbed. The variables in order of sensitivity were: penetration resistance ($p < 0.0001$) > bulk density ($p = 0.005$) > vane shear strength ($p = 0.007$) > void ratio ($p = 0.02$). Each of the four significant variables were entered individually and discriminant analysis indicated that *PR* alone correctly categorized 92.5 per cent of the 80 sites, followed by ρ_B (82.5 per cent), τ_v (81.3 per cent) and e (75.0 per cent).

The second dataset examined contained fewer sites ($n = 30$) but more variables (14). A four variable model was identified that correctly classified 100 per cent of all sites, i.e. 15 on-trail sites were classified as on-trail, and 15 off-trail sites were correctly classified as off-trail. Sensitivity was again highest for penetration resistance ($p < 0.0001$) > saturated hydraulic conductivity ($p = 0.001$) > microporosity ($p = 0.02$) > gravimetric water content ($p = 0.03$). When entered separately *PR* correctly classified 93.3 per cent of the sites, followed by K_s at 80 per cent.

From an examination of the two datasets a land manager would benefit greatly from using a cone penetrometer to measure penetration resistance. This instrument would provide both a rapid and sensitive tool in assessing potential threshold trail impacts. Additionally, another advantage of this instrument is that cores do not need to be excavated and further time consuming laboratory analyses are not required.

CONCLUSIONS

Hiking activity on Hawai'iloa Ridge Trail has resulted in almost total removal of vegetation and the litter layer from the trail, and significant decreases in the soil organic carbon in the upper 5 cm. Trampling has caused compaction that has resulted in significant decreases in hydrophysical variables, such as macroporosity, porosity, void ratio, air-filled porosity and saturated hydraulic conductivity, and significant increases in bulk density, volume of solids, penetration resistance, and vane shear strength. In addition to compaction, evidence indicates that overland flow erosion occurs on some moderate to steeply sloping trail segments. This process would also adversely impact trail hydrophysical and chemical properties by exposing nutrient poor soil and denser subsoil (or regolith and bedrock). In total, the trail environment has undergone significant degradation.

On-trail sites with the least degradation in their chemical and hydrophysical variables were those associated with well established (aggressive) overhanging canopies of exotic species, notably ironwood and strawberry guava. The organics and root networks at these sites reduced the magnitude of deleteroius effects associated with compaction. Introduction of exotic species may be unfortunate from a native species competition perspective; however, it is clear that some degree of rehabilitation can be expected if trail managers could identify resilient vegetation types that grow quickly and contribute significant quantities of organic matter to the trail surface.

To assess the degree of trail degradation over time and space our results indicate that land managers should add the cone penetrometer to their tool-box. This instrument was found to provide the most sensitive assessment of trail degradation, and it can produce numerous measurements in quick order. Use of the cone penetrometer when combined with data on thereshold penetration resistance values for plant root growth or elongation rate could be effectively used in the management of trails or other recreational areas.

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