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# SOIL DEPTH CHARACTERISTICS AND EROSION ESTIMATES ALONG THE HAMAKUA COAST, ISLAND OF HAWAII

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## ABSTRACT

Soils were characterized on steep, cultivated fields used for sugarcane (*Saccharum officinarum L.*) production along the Hamakua Coast on the Island of Hawaii. Study objectives were to determine soil profile characteristics, obtain estimates of annual erosion rates and assess reductions in profile depth resulting from cultivation. Soil profile thickness, mass quantities of volcanic ash parent material, and soil organic C contents were determined for each soil. Annual soil losses (Mg $ha^{-1}$ $yr^{-1}$) from the fields through water erosion were estimated using the Universal Soil Loss Equation (USLE). Under the assumption that the USLE mass loss estimates were accurate, annual soil depth reductions were calculated. Slope gradients at the sites ranged from 17% to 32%, and depths to bedrock ranged from 0.8 m to 3.2 m. Based on estimated annual soil erosion rates, soil depth reductions ranging from 0.7 cm $yr^{1}$ to 6.6 cm $yr^{-1}$ were calculated for the sites. These annual soil losses would equate to profile depth reductions ranging from 56 cm to as much as 284 cm since the current mechanized cropping system was initiated approximately 43-44 years ago. Actual erosion losses at the sites are probably lower than these calculated estimates because the volcanic ash soils have unusually high resiliency to runoff and erosion. Removal of soil from the site during harvest operations further confounds accurate long-term soil profile reduction estimates. Accurate methods for estimating soil loss on steep, cropland soils of volcanic ash origin in Hawaii are needed because deterioration of these valuable finite resources must be averted.

## INTRODUCTION

The degrading effects of erosion threaten the continued productivity of our soil resources. Additionally, adverse effects of eroded sediment on surface water resources are problems that must be addressed in agricultural regions. Erosion is a naturally occurring process, generally maintained at an equilibrium rate in undisturbed ecosystems. This natural equilibrium rate is generally determined by the amount and intensity of rainfall, soil properties, and protective native vegetation cover. Removal of native vegetation and conversion of forest and rangeland to cropland often leads to accelerated erosion, orders of magnitude greater than the natural erosion rate prior to cultivation (Troeh et al., 1980). With continued cultivation and loss of surface soil through erosion, soil depth and fertility will eventually decline to the point that productivity is significantly reduced (Pierce et al., 1983).

Soils of the humid tropical and subtropical regions, particularly highly weathered Oxisols and those derived from volcanic ash deposits (Andepts), are generally far less susceptible to erosion than soils of temperate regions because of their favorable physical properties, including high aggregate stability, rapid infiltration rate, ample pore space, and moderate to high permeability (Sanchez, 1976; Uehara and Gillman, 1981). However, erosion is a greater problem in many humid tropical and subtropical regions because of steep topography, climatic extremes, and poor management practices (Hudson, 1971).

The Hamakua Coast on the northern slopes of Mauna Kea, Island of Hawaii, is a highly productive sugarcane growing region characterized by high annual rainfall, steep topography, and soils derived from volcanic ash. Despite favorable physical characteristics and tillage properties inherent to soils formed in volcanic ash, erosion is a serious problem on the steeper hillslopes used for sugarcane production along the Hamakua Coast. El-Swaify and Cooley (1980) reported that most of the soil loss from cropland along the Hamakua Coast occurred when fields were bare, during or shortly after harvest and field preparation for succeeding crops. Much of the sediment removed from the steeper areas was deposited on nearly-level to level field segments downslope before reaching delivery points where sediment sampling equipment was installed. However, reduction in effective soil depth on the steeper source areas was not assessed in this study. Recent research in other agricultural regions of the U.S. has shown that solum (A and B horizons) thickness reductions of as much as 60-70% can occur on certain segments of fields continuously cultivated for over 40 years (Aguilar et al., 1988; Kelly et al., 1988; Reganold et al., 1987).

The objectives of this study were to: 1) evaluate soil depths and soil organic C contents on steep hillslopes used for sugarcane production along the Hamakua Coast, and 2) obtain estimates of soil depth reduction occurring since mechanized harvesting of sugarcane (complete removal of vegetative cover) was initiated in the mid 1940's.

### Description of the study area

Soil parent materials along the Hamakua Coast consist of volcanic ash deposits overlying slightly weathered basalt. The volcanic ash deposits, identified locally as Pahala ash, are thought to be of late Pleistocene age (30,000 to 50,000 yr) and predominantly the result of explosive eruptions from Mauna Kea (Wentworth, 1938). The underlying basalt bedrock is of Pliocene age with the oldest flows surrounding the Kohala dome ($2^{+}$ m.y. B.P.) along the northwestern portions of the Hamakua Coast (Fig. 1).

Sterns and MacDonald (1946) surveyed the distribution and thickness of Pahala ash throughout the island. These individuals found depths ranging from over 6 m (20 ft.) to less than 0.6 m (2 ft.) along the sugarcane growing region of the Hamakua Coast. Ash deposit thicknesses reportedly decrease progressively toward the northeast and increase with elevation at any point along the coast (Fig. 1).

## MATERIALS AND METHODS

### Field methods

Ten sites were selected for study at elevations that represent the lower (1), mid (2) and upper (3) regions of sugarcane production within the Hamakua Coast (Fig. 2 and Table 1). Three sites were located at the wetter eastern edge of the Hamakua Coast near the village of Papaikou. Four sites were located at the central portion of the coast (three near the village of Laupahoehoe and one near Paauilo). Three additional sites were located within the drier northern portion of the coast adjacent to historic Waipio Valley.

Fields with slope gradient classifications of either D (15-25%) or E (>25%) were identified at each of the 10 sites. The segments of the hillslopes selected for study had uniform slope gradients from the top of the slope (usually originating at the field's upper boundary or at the base of a diversion channel wherein overland flow to downslope areas originated) to the point where runoff water either entered another diversion channel or the slope decreased and sediment deposition occurred. Slope length and gradient were determined for each site and a small pit was excavated at the mid-slope area of the field. Complete profile descriptions were compiled following procedures outlined in the USDA Soil Survey Manual (Soil Survey Staff, 1981) and the soils were classified to the family level according to the criteria outlined in Soil Taxonomy (Soil Survey Staff, 1975). Each profile was sampled by horizon to the contact of the underlying basalt bedrock. Twenty additional soil depth measurements were made approximately 5 m apart from one another in a grid pattern throughout the fields using a gas-powered soil auger in order to establish soil depth variability.

### Laboratory methods and statistical calculations

Bulk density (BD) was measured using the core method described by Blake and Hartge (1986). Three core samples were taken for each genetic horizon in the soil profile. Organic C content was determined by the modified Walkley-Black method (Nelson and Sommers, 1975). Quantities of Pahala ash soil were calculated by multiplying the bulk density of each soil horizon by its thickness and summing these to the underlying bedrock. Organic C contents (kg $m^{-3}$) were similarly calculated by multiplying horizon concentrations by bulk density and horizon thicknesses and summing to 1 m depth. Pore space was determined by the relationship: % Pore Space = 100 - (BD/Dp X 100). Particle density ($D_p$) was assumed to be 2.65 Mg $m^{-3}$ because most soil mineral constituents, including colloidal silicates comprising volcanic ash parent materials, have densities between the narrow range of 2.60 and 2.75 Mg $m^{-3}$ (Brady, 1984).

As the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978) is currently the empirical model used by the USDA Soil Conservation Service for estimating annual soil losses and subsequently recommending conservation practices on Hawaii cropland, estimates of annual soil loss resulting from water erosion were calculated with this empirical model. Revisions to the various factor components of the equation were recently made by various researchers (McCool and Foster, 1989; Porter et al., 1989; Renard, 1989; Romkens and Young, 1989; Weesies et al., 1989) and testing of this revised universal soil loss equation (RUSLE) is taking place throughout the continental United States. Proposed changes for RUSLE's application to Hawaii croplands are still being researched.

The USLE is expressed as: **$A = R * K * LS * C * P$**; where:

**A** is annual soil loss from the field (Mg $ha^{-1}$ $yr^{-1}$ or t $acre^{-1}$ $yr^{-1}$).
**R** is the rainfall energy factor, referred to as the Energy Index Factor (EI).
**K** is the soil erodibility factor.
**LS** is the slope length & gradient factor.
**C** is the cropping-management factor.
**P** is the erosion control practice factor.

The current USDA Soil Conservation Service technical guide for application of the USLE in Hawaii (USDA Soil Conservation Service, 1985) provides values for K, C, LS, and P-factors. We selected soil erodibility factors (K-factors) for the soil series associated with the site's soil mapping unit delineated in the soil survey for the Island of Hawaii (USDA Soil Conservation Service, 1973) after field verification that soil properties were within the range of the designated soil series. Rainfall erosivity factors (R-factors) recommended by Lo (1982), who recently refined existing iso-erodent maps for the State of Hawaii, were used in our calculations. R-factors were calculated from the following regression equation expressing the relationship between average annual $EI_{30}$ index (the product of storm kinetic energy and maximum 30-minute intensity) and the average annual rainfall at the sites (e.g. **$Y = 5.10X + 22.17$**, where $Y$ = average annual $EI_{30}$ index (R) and $X$ = average annual rainfall amount in inches).

Hamakua Sugar Corporation and Mauna Kea Agribusiness Corporation, the operators of the two sugar plantations on which our sites were located, provided average annual rainfall data from field weather stations in close proximity to each site. All calculated estimates of soil loss in t $acre^{-1}$ $yr^{1}$ were converted to the metric equivalent of Mg $ha^{-1}$ $yr^{-1}$.

USLE factor components used in our soil loss estimates are in Table 2. Applicable K-factors were either 0.05 for the soils with rapid permeability or 0.10 for those with moderately rapid permeability. C-factors varied with duration of sugarcane crop growth maturity period and the nature of the cropping system, either dryland or irrigated ($C = 0.15$ for 31-35 month, dryland; $C = 0.14$ for 36-40 month, dryland; $C = 0.16$ for 27-30 month, irrigated). P-factors were 1.00 for all sites with tillage practice consisting of straight up and down the hillslope, and 0.90 or 0.95 (depending on slope gradient) for cross slope tillage. For those sites with slope gradients greater than 24%, a P-factor of 1.0 was used regardless of tillage practices.

Based upon USLE estimates of annual soil mass loss (Mg $ha^{-1}$ $yr^{-1}$), rates of soil depth reduction (cm $yr^{-1}$) were obtained by first calculating the time (yr) necessary for complete removal of the entire ash mass (Mg $ha^{-1}$) and then dividing the total thickness (cm) of the ash by the calculated time (yr) for complete mass removal. Additionally, because the current sugarcane cropping practice was initiated approximately 43 years prior to our sampling, calculated depth reduction rates (cm $yr^{-1}$) were multiplied by 43 to obtain an estimate of profile depth reduction (cm) occurring since initiation of the cropping system with its mechanized harvesting practices.

## RESULTS AND DISCUSSION

Slope characteristics and soil mapping units for the selected study sites are in Table 3. Soils were Typic Hydrandepts at the wetter sites and Hydric Dystrandepts at the drier sites along the central and northern coastline portion of the Hamakua Coast. Steep slope gradients coupled with long slope lengths made the sites particularly susceptible to runoff and erosion.

### Soil depths & thickness of Pahala ash parent materials

Thickness of the Pahala ash parent materials was highly variable on the steep slopes evaluated (Table 3). At five of our sites the basalt bedrock underlying the Pahala ash deposits consisted of either a`a (clinkery, spinose surface) or pahoehoe (smooth, billowy surface) bedrock derived from Mauna Kea eruptions (Fig. 1). The slightly weathered nature of the basalt bedrock provided an abrupt, distinct boundary at its contact with the overlying Pahala ash soil at most sites, readily allowing accurate measurements of soil depth (Fig. 3a). But at the Kukuihaele 1 and 2 sites, soils are underlain by somewhat older basalt flows associated with the Kohala Dome (Fig. 1) and the contact between bedrock and ash contained highly fractured and disintegrated bedrock mixed in with silty clay mineral soil derived from the ash (Fig. 3b).

At three sites (Papaikou 2, Papaikou 3 and Laupahoehoe 3) a thin plastic clay lens was present between the Pahala ash parent material and the underlying basalt bedrock (Fig. 3c). This clay lens, observed in varying thicknesses at several localities throughout the Hamakua Coast, was identified as a paleosol originating from the accumulation of tropospheric dust (Jackson et al., 1971). The abrupt, distinct contact between the clay lens paleosol and the more recently deposited Pahala ash parent material at these two sites again readily allowed accurate measurements of the thickness of the Pahala ash soil.

The field at the Laupahoehoe 3 site had the most shallow soil (Table 3) and appeared to be severely eroded. Coarse fragments were present throughout the ground surface and the field had developed deep erosional rills at its lower reaches. The 0.17 m thickness of Pahala ash at this site is in sharp contrast with previously reported ash depths for the central portion of the Hamakua Coast (Stearns and McDonald, 1946) (Fig. 1). We measured soil depths on other fields in the vicinity with gentler slope gradients and found Pahala ash thicknesses ranging from 1.2 m (3.9 ft.) to 3.0 m (9.8 ft).

### Physical properties & organic carbon contents

Pahala ash parent materials weather to soil that ranges in texture from silty clay loam to silty clay (USDA Soil Conservation Service, 1973). In contrast to soils formed in other types of parent materials including alluvium, colluvium and residuum, the physical properties of the soils formed in Pahala ash tend to be relatively uniform with depth. These soils are thixotropic, becoming fluid when shaken, and have a very high proportion of pore space. The soils are generally very well drained and have low susceptibility to water erosion under natural vegetation. However, the surface soil displays an irreversible drying and aggregation to coarse sand/gravel-sized particles upon exposure through removal of native vegetation. These coarse aggregates are easily detached and readily transported by runoff from the steeper to level areas of the landscape in the cultivated fields. We observed the accumulation of these coarse mineral aggregates on depositional areas below our fields, particularly in the wetter eastern portions of the Hamakua Coast.

High organic C content and pore space are important factors related to a soil's resistance to water erosion. Table 4 shows the quantity of organic C and total pore space in the upper meter of soil at our ten study sites. Organic C in soils will generally decrease with continued cultivation due to accelerated erosion and mineralization. The higher content of organic C in the soil at the Kukuihaele 3 site as compared with the other sites reflects the site's shorter duration of cultivation. The comparatively low soil organic C content at the Laupahoehoe 3 site is likely due to extensive removal of organic-rich surface soil through erosion coupled with tillage-induced mineralization.

Total pore space within the upper 1 m at the Laupahoehoe 2 and Kukuihaele 1 sites was also reduced compared to the soil's total pore space at the other nine sites. We attribute this lower total pore space to the removal of Pahala ash by erosion and thus, a greater proportion of weathered basalt bedrock (Cr and C/R horizon material) within the soil's upper meter.

### Estimates of annual soil losses via water erosion

The average depth to consolidated bedrock was used as the lower boundary of the Pahala ash for calculations of soil loss over time from the fields. Calculated estimates of soil loss for our ten sites (Table 5) ranged from 50 Mg ha$^{-1}$ yr$^{-1}$ at the Papaikou 2 site (slope gradient 17%) to 254 Mg ha$^{-1}$ yr$^{-1}$ at the Laupahoehoe 1 site (slope gradient 32%). All sites with estimated annual soil losses >200 Mg ha$^{-1}$ yr$^{-1}$ had slope gradients approaching or exceeding 30% (Tables 3 & 5). These results reflect the USLE's emphasis on the importance of slope steepness in influencing runoff and erosion from cultivated fields. The Papaikou 2 site, despite having one of the highest R-factors, had a short slope length and low K-factor associated with the Hilo silty clay loam soil (Tables 2 and 3). Subsequently, the lowest annual soil losses were calculated for this site. With exception of the Kukuihaele 1 site, which had an extremely long slope and a 30% gradient, the drier Kukuihaele sites in northern portion of the coast had appreciably lower calculated soil loss estimates, largely due to the sites' lower R-factors.

Quantities of Pahala ash soil within the fields were divided by estimated annual rates of soil loss to arrive at estimates of time (yr) required for complete removal of ash parent materials (Table 5). These calculations were made under the assumption that the present cropping system will continue indefinitely. Further assumptions were that transformation of bedrock to soil is insignificant relative to rates of surface soil removal by erosion, and K-factors for the soils will remain essentially the same through time because of the parent material's uniform properties with depth.

Surprisingly, the estimated depth reductions that would have occurred in the 43 years of mechanized harvesting for the sites with very steep slope gradients are greater than their present profile depths. Particularly striking is the 284 cm depth reduction calculated for the Laupahoehoe 1 site; the 6.6 cm annual soil profile reduction rate calculated using USLE is much greater than soil loss attributed to the combined effects of all erosion mechanisms in other agricultural regions. The denudation rate attributed to water erosion at the Laupahoehoe 1 site is approximately 4.4 times greater than the 1.5 cm yr$^{-1}$ denudation rate reported for Iowa landscapes (Rhue, 1969) and 10 times greater than the 0.66 cm yr$^{-1}$ soil profile depth reduction rate (29 cm in 44 yr cultivation) reported for a sandy soil in North Dakota that, in addition to water erosion, is subject to high wind erosion (Kelly et al., 1988).

We therefore conclude that USLE overestimated annual soil losses resulting from water erosion for our sites. We suspect that unfitting LS factor values for hillslopes comprised of Hawaii's unique volcanic ash soils is a major problem with USLE. Runoff and subsequent erosion from a field with a given slope length and gradient is not as great in these volcanic ash parent materials as in soils found in the U.S. midwestern states where USLE was developed. High infiltration rates and large total water storage capacity allows the Hydrandepts and Dystrandepts along the Hamakua

Coast to "absorb" a much larger proportion of water received from a rainstorm and this, in turn, results in less runoff. The revised USLE (RUSLE) has modified the slope length and gradient relationships considerably and the new LS factors for our sites would be appreciably lower (30-50%). Consequently, annual soil loss estimates for our sites would be greatly reduced if calculated through RUSLE. However, much research is still needed on the other equation factors for proper application to Hawaii's unique climate and cropping systems.

Shallow profile depth and low organic C content at the Laupahoehoe 3 site suggest a significant reduction in soil depth has occurred since the area was converted to cropland. Significant quantities of soil are removed from fields during the harvesting operation. Hirai and Associates, Inc. (1982) reported that the Hilo Coast Processing plant produced 1100-1200 tons of sediment in cane-wash through their daily operations. Therefore, it is reasonable to assume that removal of soil from the field during harvest and redistribution of surface soil from steeper slopes to other portions of the landscape during tillage operations are large contributing factors to soil depth reductions along the Hamakua Coast.

The soils derived from Pahala ash along the Hamakua Coast are indeed remarkably resilient to runoff and erosion because of their favorable physical properties. Yet these soils are a finite resource that should be used judiciously to insure their continued productivity. Hillslopes with gradients exceeding 15% are generally considered to have a high erosion potential if cultivated. The sites we investigated with slope gradients exceeding 25% do appear to be severely eroded. Fields on these steeper slopes should be seeded to perennial vegetation such as pasture that would provide permanent ground cover.

We believe the use of empirical equations such as the USLE or RUSLE for obtaining estimates of annual soil losses from steep slopes along the Hamakua Coast must be reassessed. Areas in native vegetation should be evaluated throughout the Hamakua Coast in order to establish relative soil depths prior to cultivation. These sites could then serve as benchmarks against which models used to predict cultivation-induced erosion could be validated. Future government support for the sugar industry in Hawaii may become influenced by the sugar producers' demonstrated land stewardship. Therefore, accurate methods to assess erosion on all land resources used for sugar production should be developed. Removal of sediment from fields during harvesting operations contributes to soil depth reduction and should also be considered in assessments of annual soil loss from fields used for sugarcane production.

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Table 1. Elevation and precipitation at ten sites selected for study along the sugarcane growing region of the Hamakua Coast.

| Site | Elevation (m) | Annual Precipitation (mm) |
|---|---|---|
| Papaikou 1 (lower) | 120 | 3,685 |
| Papaikou 2 (mid) | 242 | 4,500 |
| Papaikou 3 (upper) | 382 | 5,250 |
| Laupahoehoe 1 (lower) | 170 | 3,750 |
| Laupahoehoe 2 (mid) | 261 | 4,475 |
| Laupahoehoe 3 (upper) | 582 | 5,175 |
| Paauillo | 242 | 2,800 |
| Kukuihaele 1 (lower) | 46 | 1,725 |
| Kukuihaele 2 (mid) | 388 | 2,425 |
| Kukuihaele 3 (upper) | 685 | 2,300 |

Table 2. USLE factors used in soil loss estimates on steep cultivated fields along the Hamakua Coast.

|  | Factor |  |  |  |  |
|---|---|---|---|---|---|
| SITE | R* | K** | LS** | C** | P** |
| Papaikou 1 | 772 | 0.05 | 7.49 | 0.15 | 1.00 |
| Papaikou 2 | 940 | 0.05 | 3.33 | 0.15 | 0.90 |
| Papaikou 3 | 1093 | 0.05 | 7.62 | 0.14 | 0.90 |
| Laupahoehoe 1 | 787 | 0.10 | 9.46 | 0.15 | 1.00 |
| Laupahoehoe 2 | 935 | 0.05 | 7.33 | 0.15 | 0.95 |
| Laupahoehoe 3 | 1078 | 0.05 | 12.50 | 0.14 | 1.00 |
| Paauilo | 593 | 0.10 | 6.74 | 0.15 | 0.95 |
| Kukuihaele 1 | 374 | 0.10 | 15.09 | 0.16 | 1.00 |
| Kukuihaele 2 | 517 | 0.10 | 4.12 | 0.16 | 1.00 |
| Kukuihaele 3 | 491 | 0.05 | 6.89 | 0.14 | 1.00 |

* R-Factor values calculated by the regression equation of Lo (1982) expressing the relationship between average annual $EI_{30}$ index and average annual rainfall amount.

** Values recommended by USDA Soil Conservation Service (1985).

Table 3. Landscape, soil characteristics and classification of soil mapping units at the ten study sites along the Hamakua Coast.

| SITE | Slope Gradient (%) | Slope Length | Bedrock Depth | Pahala Ash Thickness | Nature of Bedrock or Contact with Pahala Ash | Soil Series* & Classification |
|---|---|---|---|---|---|---|
| | | | (meters) | | | |
| Papaikou 1 | 26 | 43 | 1.60 | 0.89 | Aa Basalt | Hilo silty clay loam<br>*(thixotropic, isohyperthermic Typic Hydrandept)* |
| Papaikou 2 | 17 | 34 | 3.19 | 2.00 | Clay Lens | Kaiwiki silty clay loam<br>*(thixotropic, isothermic Typic Hydrandept)* |
| Papaikou 3 | 27 | 39 | 2.99 | 1.27 | Clay Lens | Kaiwiki silty clay loam<br>*(thixotropic, isothermic Typic Hydrandept)* |
| Laupahoehoe 1 | 29 | 48 | 1.25 | 1.25 | Aa Basalt | Ookala silty clay loam<br>*(thixotropic, isohyperthermic Hydric Dystrandept)* |
| Laupahoehoe 2 | 23 | 62 | 0.81 | 0.38 | Aa Basalt | Honokaa silty clay loam<br>*(thixotropic, isothermic Typic Hydrandept)* |
| Laupahoehoe 3 | 32 | 61 | 0.92 | 0.17 | Clay Lens | Kaiwiki silty clay loam<br>*(thixotropic, isothermic Typic Hydrandept)* |
| Paauilo | 21 | 71 | 1.68 | 1.68 | Pahoehoe Basalt | Kukaiau silty clay loam<br>*(thixotropic, isothermic Hydric Dystandept)* |
| Kukuihaele 1 | 30 | 109 | 1.65 | 1.24 | Aa Basalt** | Paauhau silty clay loam<br>*(thixotropic, isohyperthermic Hydric Dystrandept)* |
| Kukuihaele 2 | 18 | 44 | 1.56 | 0.85 | Aa Basalt** | Kukaiau silty clay loam<br>*(thixotropic, isothermic Hydric Dystandept)* |
| Kukuihaele 3 | 27 | 32 | 0.90 | 0.56 | Aa Basalt | Honokaa silty clay loam<br>*(thixotropic, isothermic Typic Hydrandept)* |

* USDA Soil Conservation Service, Soil Survey of the Island of Hawaii, 1973.

** Weathered aa - older basalt flows associated with the Kohala Dome.

Table 4. Soil organic C content and total pore space in the upper 1 meter of soil at the 10 study sites.

| Site | Organic C ($kg\ m^{-3}$) | Pore Space ($m^3\ m^{-3}$) |
|---|---|---|
| Papaikou 1* | 18.0 | 0.76 |
| Papaikou 2* | 24.4 | 0.85 |
| Papaikou 3* | 13.5 | 0.85 |
| Laupahoehoe 1* | 16.5 | 0.85 |
| Laupahoehoe 2* | 12.6 | 0.65 |
| Laupahoehoe 3* | 7.2 | 0.67 |
| Paauilo* | 17.9 | 0.84 |
| Kukuihaele 1* | 31.4 | 0.73 |
| Kukuihaele 2* | 21.2 | 0.85 |
| Kukuihaele 3** | 33.5 | 0.82 |

* Approximately 43 yr of cultivation.
** 15 yr of cultivation.

Table 5. Quantity of Pahala ash parent material and soil loss estimates calculated by the Universal Soil Loss Equation.

| SITE | Pahala Ash Thickness (cm) | Soil Quantity ($Mg\ ha^{-1}$) | Annual Soil Loss Rate ($Mg\ ha^{-1}\ yr^{-1}$) | Time for Complete Removal (yr) | Profile Reduction Rate ($cm\ yr^{-1}$) | Profile Reduction Since Mechanization (cm) |
|---|---|---|---|---|---|---|
| Papaikou 1 | 89 ± 11 | 5,406 ± 687 | 120 | 45 ± 6 | 2.0 | 86* |
| Papaikou 2 | 200 ± 9 | 7,612 ± 335 | 50 | 152 ± 7 | 1.3 | 56* |
| Papaikou 3 | 127 ± 9 | 4,609 ± 332 | 119 | 39 ± 3 | 3.3 | 142* |
| Laupahoehoe 1 | 125 ± 13 | 4,836 ± 508 | 254 | 19 ± 2 | 6.6 | 284* |
| Laupahoehoe 2 | 38 ± 8 | 3,116 ± 673 | 111 | 28 ± 6 | 1.4 | 60* |
| Laupahoehoe 3 | 17 ± 8 | 1,139 ± 548 | 214 | 5 ± 2 | 3.2 | 138* |
| Paauilo | 168 ± 11 | 8,082 ± 509 | 128 | 63 ± 4 | 2.7 | 116* |
| Kukuihaele 1 | 124 ± 13 | 8,748 ± 962 | 202 | 43 ± 5 | 2.9 | 125* |
| Kukuihaele 2 | 85 ± 18 | 3,610 ± 762 | 77 | 47 ± 10 | 1.8 | 77* |
| Kukuihaele 3 | 56 ± 9 | 4,283 ± 685 | 54 | 79 ± 13 | 0.7 | 11** |

* Based on 43 yr cultivation.
** Based on 15 yr cultivation.

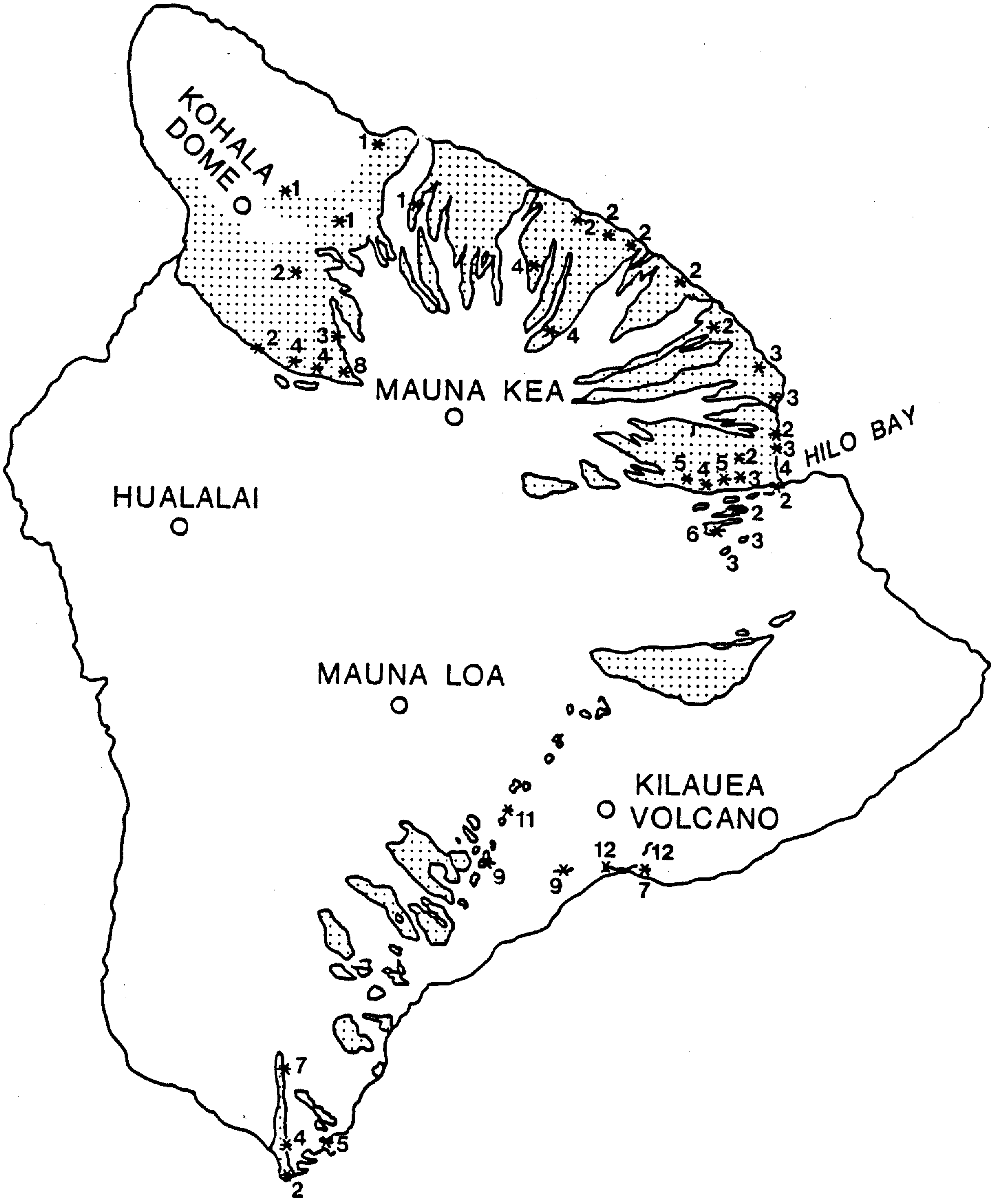

Figure 1. Distribution (shaded area) and depths (m) of Pahala ash deposits, Island of Hawaii as reported by Sterns and MacDonald (1946). Note the general decrease in ash depths upon progressively moving northwest along the Hamakua Coast; thickest ash deposits (5-6 meters) occurred in the Hilo Bay area and the shallowest ash depths (1-2 meters) occurred within the Kohala Dome area.

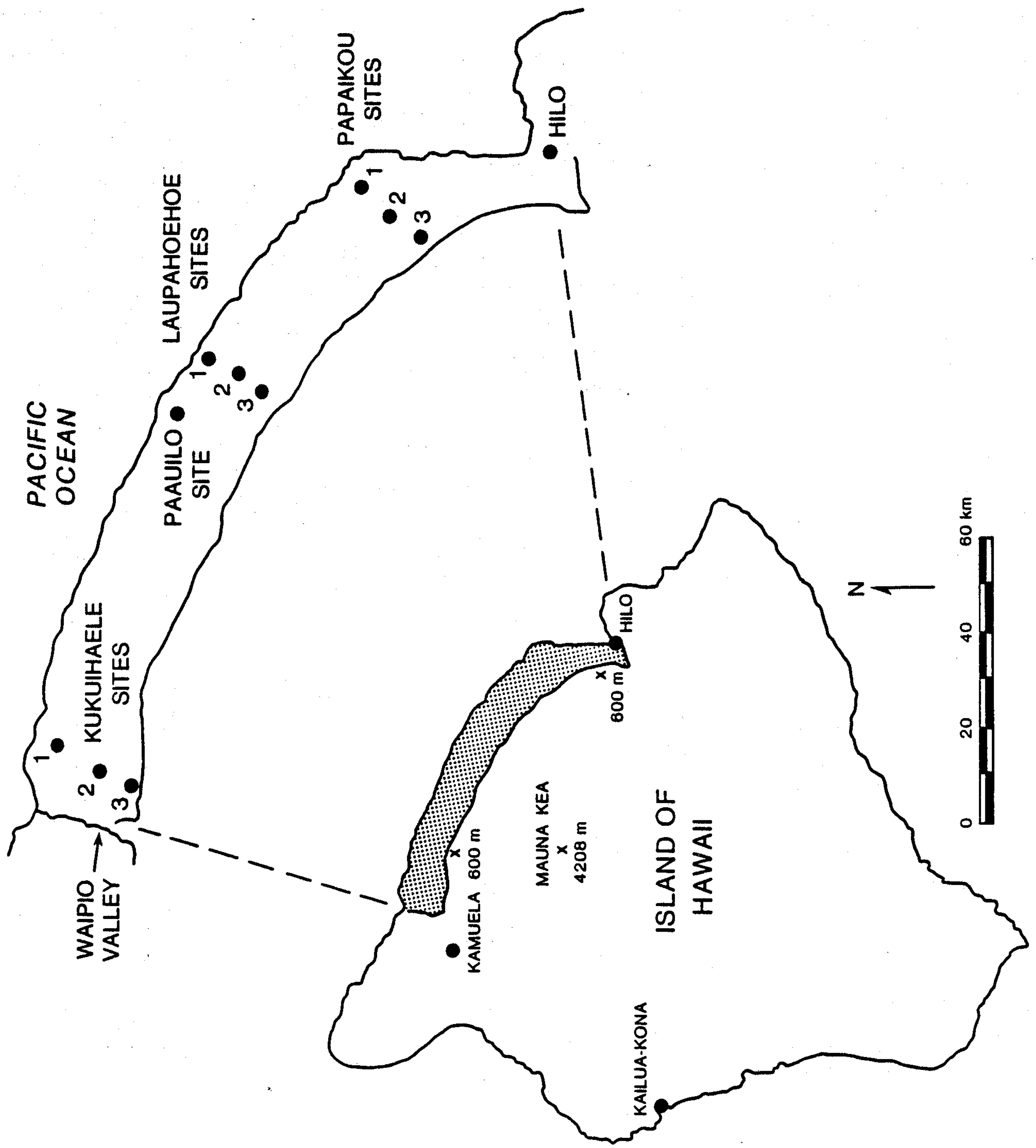

Figure 2. Location of 10 steeply sloping fields selected for study along the Hamakua Coast, Island of Hawaii. The sites represent the lower (1), mid (2), and upper (3) elevations of sugarcane production within the various zones of the Coast.

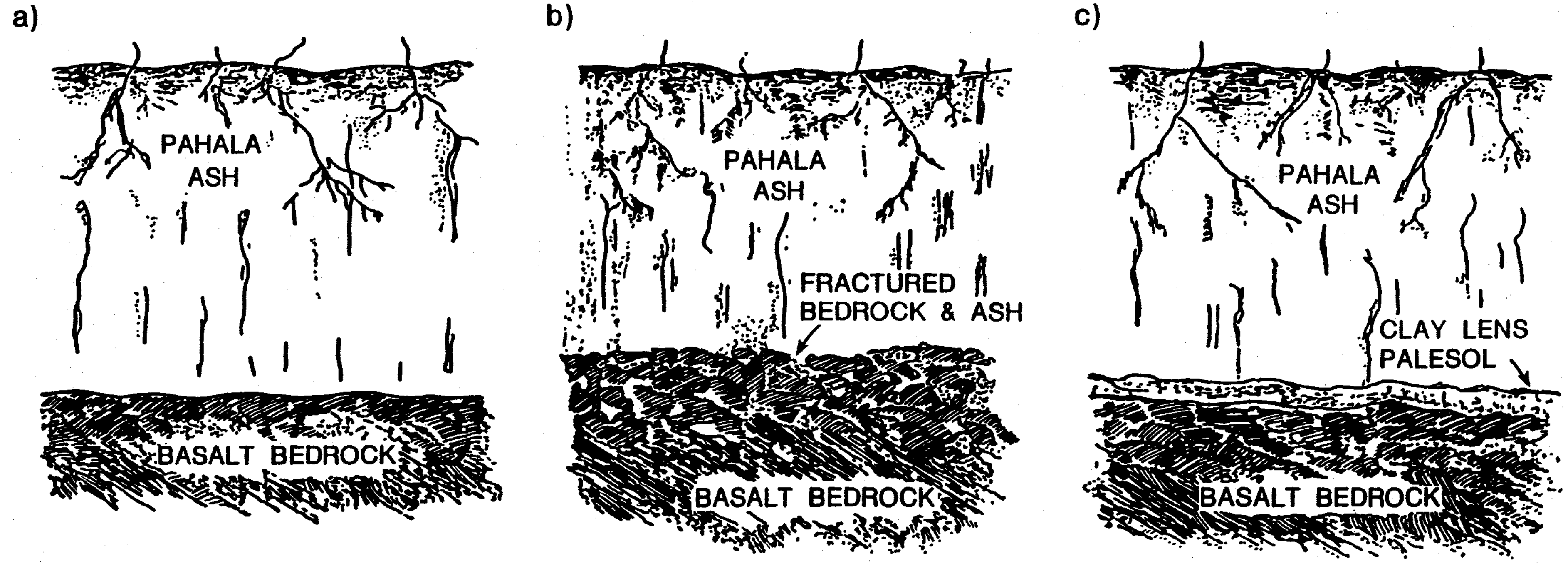

Figure 3. Nature of the volcanic ash/basalt bedrock contact in soils occurring along the Hamakua coast: a) abrupt contact between Pahala ash and slightly weathered aa or pahoehoe basalt flow, b) gradual transition between Pahala ash and consolidated bedrock due to presence of partially weathered basalt zone (common in older lava flows associated with the Kohala Dome), c) occurrence of a clay lens paleosol between the Pahala ash and underlying consolidated or partially weathered bedrock.