

Wind Erosion and Intensive Prehistoric Agriculture: A Case Study from the Kalaupapa Field System, Moloka'i Island, Hawai'i

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Wind erosion is a major problem for modern farmers, a key variable affecting nutrient levels in ecosystems, and a potentially major force impacting archaeological site formation; however, it has received scant consideration in geoarchaeological studies of agricultural development compared with more easily quantifiable environmental costs, such as vegetation change or fluvial erosion. In this study, soil nutrient analysis is used in the Kalaupapa field system, Moloka'i Island, Hawai'i, to detect an increase in wind erosion attributable to intensive agriculture following the burning of endemic forest. This practice began on a small scale in the 13th century A.D., expanded around cal A.D. 1450–1550, and continued until the near total abandonment of the fields after European contact in the 18th century. Nutrients that naturally occur in high amounts in coastal windward areas due to the long-term, cumulative effect of sea spray were especially impacted. However, thanks to the unique landform of the Kalaupapa Peninsula, nutrient depletion in windward areas was offset by downwind enrichment and likely contributed to the long-term sustainability of the system as a whole. Future research on tropical and arid agriculture should consider the cumulative environmental cost of increased eolian erosion attributable to anthropogenic landscape modification. © 2007 Wiley Periodicals, Inc.

INTRODUCTION

Although recent studies cite wind erosion as a major problem for modern farmers (Sterk, 2003), a key variable effecting nutrient levels in ecosystems (Chadwick et al., 1999; Kurtz et al., 2001; Reynolds et al., 2001; Riksen and De Graaff, 2001; Okin et al., 2004), and a potentially major force impacting archaeological site formation (Rick, 2002), it has received scant consideration in geoarchaeological studies of agricultural development compared with more easily quantifiable environmental costs, such as vegetation change or fluvial erosion (Redman, 1999). Here we analyze the spatial distribution of soil nutrients to document increased wind erosion associated with the transformation of a forested landscape into an intensively cultivated field system on Kalaupapa Peninsula, Moloka'i Island, Hawai'i. We find that although efforts to control erosion

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using artificial windbreaks could not stop nutrient depletion in areas directly exposed to northeastern trade winds, the subsequent enrichment of downwind soils may have helped to mitigate the impact of short-fallow intensive agriculture.

We begin our study by evaluating soil conditions prior to prehistoric agricultural intensification in the study area with the use of control samples from under field walls to determine what impact, if any, wind erosion has had on the distribution of nutrients before intensification. By examining a suite of elements, we detected a remarkable amount of nutrient input in coastal areas attributable to sea spray and little evidence of eolian erosion. Next, control samples are compared with matching post-intensive agriculture soil samples from the center of plots in an effort to track shifts in nutrient levels over time. These results show significant correlation with distance from the windward coast due to high nutrient depletion in windward areas and nutrient enrichment in downwind, leeward areas. Finally, we examine post-intensive agriculture soils in detail to quantify changes attributable to increased wind erosion.

ARCHAEOLOGICAL RESEARCH AND ENVIRONMENTAL CONTEXT

Environment

The Kalaupapa field system is a 9 km² landscape of contiguous rain-fed plots defined by low walls built, in part, to shelter sweet potatoes (*Ipomoea batatas*) and other cultigens from trade winds across the Kalaupapa Peninsula, Hawai'i (Ladefoged, 1990, 1993; Kirch, 2002; McCoy, 2005a, 2005b) (Figures 1 and 2). The peninsula itself is home to a unique series of soils derived from 330-ky old basalt flows from Kauhakō Crater (Clague et al., 1982; Macdonald et al., 1983:343–352; Coombs et al., 1990). The peninsula averages 900 to 1300 mm of annual rainfall, and constant northeast trade winds create distinct windward and leeward sections separated by a central ridge that rises to the crater's summit (123 meters above sea level [masl]). Within the study area, local elevation is closely correlated with rainfall, and thus we find similar rainfall gradients on the peninsula's leeward and windward coasts (Juvik and Juvik, 1988:56). Kalaupapa Series soils have been described as a "very rocky, silty clay loam" with an average soil temperature of 23°C and a typical profile consisting of topsoil (0–13 cmbs) and subsoil ending at bedrock 30 cm below surface (Foote et al., 1972:56). Our research confirms that these soils rarely deviate from this description (McCoy et al., 2004).

Although the environmental factors that helped define the boundaries of the better-known Kohala field system, Hawai'i Island (Ladefoged et al., 1996; Vitousek et al., 2004), have been the topic of a great deal of research, the conditions that set the smaller Kalaupapa field system's boundaries are more straightforward (Figure 1). The northern and eastern limits of the fields—visible in air photographs—parallel the local coastal sea spray (halophytic) zone (Canfield, 1990). High winds and the potential for aerosol salts to diminish crop growth apparently discouraged farming in the area immediately along the windward coast. The western boundary of the fields is slightly more difficult to define due to modern disturbances, especially the footprint of the modern Kalaupapa Settlement in the southwest section of the peninsula. However, current evidence suggests that the field system probably extended right across the peninsula, because preserved fields can be found within 75 m of the western coastline

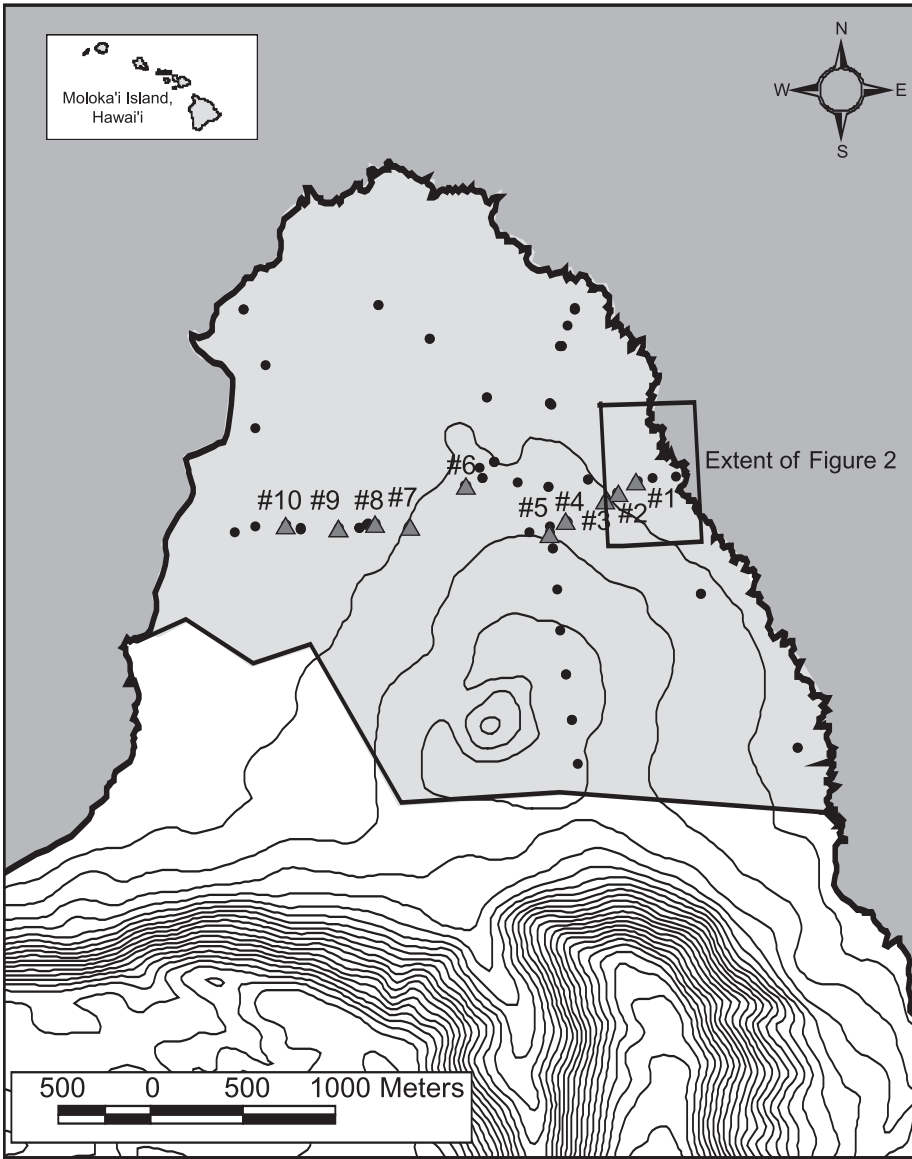


Figure 1. The Kalaupapa field system, Kalaupapa Peninsula, Moloka'i Island, Hawaii'i. Shaded area indicates the approximate extent of the fields based on archaeological survey and air photograph interpretation. Points represent soil sample locations, and triangles show the locations of paired wall and plot soil samples on the Kalaupapa East Transect. One-hundred-foot elevation contours show the contrast between the low, flat landform of the peninsula and adjacent cliffs and valleys.



Figure 2. Air photograph of windward coast, Kalaupapa Peninsula. Although the Kalaupapa Field System is defunct today, densely packed windbreak field walls are visible from the air, because modern intrusive plants take advantage of the shelter they provide from northeast trade winds. Courtesy of the National Park Service, KALA #12996, IR3-6. Approximate extent of photograph is 775×500 m.

(McCoy, 2006). Finally, the southern boundary of the field system—disturbed by historic period road construction and covered with dense vegetation—was probably indistinguishable from an adjacent zone of agricultural terraces described elsewhere (McCoy, 2002; Somers, 1985). Thus, in practical terms, the southern edge of the fields is defined by the geographic extent of Kalaupapa Series soils, because these soils likely presented farmers similar opportunities and constraints.

Adjacent to the peninsula is a much wetter ecological zone with colluvial soils distributed in valley bottoms and along the base of cliffs (Foote et al., 1972). Although only the large Waikolu Valley has perennial flow today, nearby valleys have substantial intermittent streams that may have had more regular flow in the past. The area's patchwork of colluvial soils is similar to locations on Kaua'i Island, where soil scientists have found evidence of natural nutrient rejuvenation attributed to the exposure of fresh weathering surfaces of redeposited stones, making these landscapes more fertile than one would expect based on their age (Vitousek et al., 2003). Archaeological evidence confirms that native Hawaiians took advantage of this wetland area adjacent to the field system for intensive agriculture (Somers, 1985).

Prehistoric and Historic Agricultural Land Use

Recent research has outlined the history of agricultural development in the region through radiocarbon dating (Kirch, 2002; Kirch et al., 2003; McCoy, 2002, 2003, 2004, 2005b). The earliest evidence of people in the study area dates to cal A.D. 800–1000. However, the first signs of burning on the peninsula that are possibly attributable to horticulture date to the 13th century A.D. The earliest evidence of widespread agriculture, dated to cal A.D. 1450–1550, is marked by a shift in vegetation and the incorporation of charcoal in agricultural soils across the landscape (Figure 3). There is also a considerable time gap between initial agricultural development and the first evidence of permanent occupation on the peninsula after cal A.D. 1650. Overall, it appears that the field system was a secondary zone of settlement and agricultural development, with the wetter valley and colluvial areas the preferred zone (McCoy, 2005b). Interestingly, there is no difference between the timing of land use of the leeward and windward portions of the peninsula (McCoy, 2005b, 2006).

The Kalaupapa field system was abandoned soon after European contact at the end of the 18th century, when settlement shifted to small house sites along the coast and roadways. The introduction of cattle in 1830 precipitated the construction of large, architecturally distinct walls to protect fields and yards from roving animals (Greene, 1985). In a short-lived resurrection, portions of the fields were reactivated and intensified to supply potatoes and other products to California's Gold Rush markets (Ladefoged, 1993). In a Hawaiian language newspaper article published on March 4th, 1857, M.L. Napihelua described the richness of the fields almost ten years after their reactivation (cited in Handy and Handy, 1972:518):

Kalaupapa is a good land because the crops planted are successful and the gain is large... Many sweet potatoes are being planted now, four or five patches to each man. Most of the crops are water-melons, and some small and big beans and onions. Be on the watch, you traders, for Kalaupapa is the best in all the islands for good prices and fast work. All the California ships come to Kalaupapa.

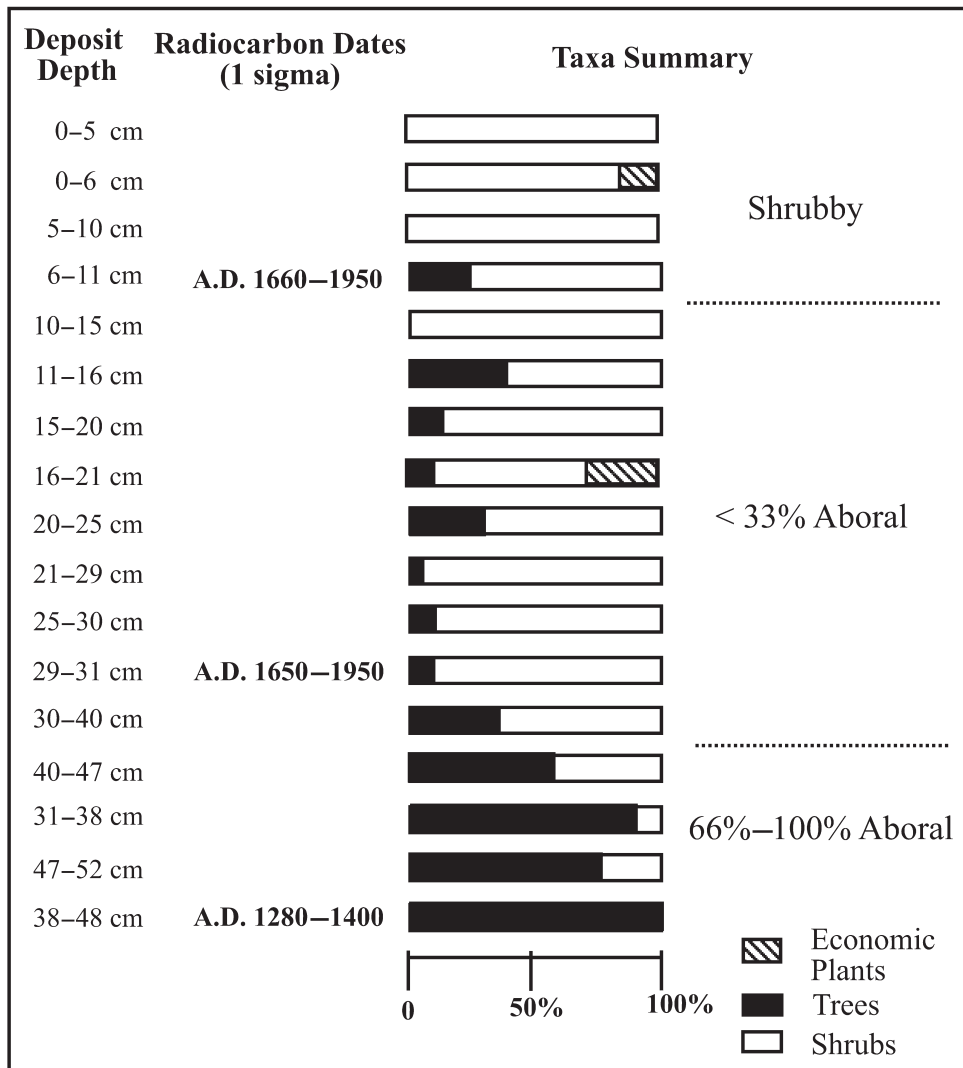


Figure 3. Charcoal identified by plant taxa from Kaupikiawa Rockshelter, Kalaupapa Peninsula (adapted from Kirch et al., 2003). The shift in the composition of burned vegetation is a proxy for the transition from a stable endemic forest to an anthropogenic landscape of economic plants and secondary growth shrubs. Direct radiocarbon dates on recovered charcoal suggest the process began as early as the 13th century A.D., marking the beginning of 400–500 years of washed-in charcoal and sediment accumulation that “indirectly reflects human activity on the northern end of the Kalaupapa Peninsula, particularly burning of the native dryland forest, possibly associated with horticultural activities” (Kirch et al., 2003:24). (Radiocarbon dates from lowest layers to highest: Beta-155366, Ly VIB, *Antidesma* sp. charcoal, 650 ± 640; Beta-155365, Ly IV/V, *Chenopodium* sp. charcoal 220 ± 40; Beta-155364, Ly IIA, *Sida* sp. charcoal, 200 ± 40.)

However, this renewal was cut short in 1866 by the creation of a leprosarium. With the exception of house gardens and short-lived, small farmsteads, agriculture essentially ceased. Today, the last remnants of cattle and other grazing animals have been removed from the peninsula, and the area is overgrown with exotic shrubs.

Several lines of evidence suggest that historic-era cattle ranching and farming had remarkably little impact on the environment. First, two local newspaper accounts suggest much of the area was in stable grasslands during the historic period. In 1857, the author of the article cited above claims that Kalaupapa crops “are not eaten by caterpillars and cut worms” or the local “cattle, horses, donkeys, and mules,” because “there is much grass” (cited in Handy and Handy, 1972:518). In another newspaper account almost thirty years later, R.J. Creighton (1886) gives a similar description of the landscape as “heavily grassed with Bermuda or manienie grass,” so rich that it had the capacity to “easily carry 10,000 sheep” if necessary. Second, economic and historical forces limited the opportunity for farming and ranching in Kalaupapa. Historic records indicate that the 18th-century boom in Hawaiian exports quickly subsided once California growers began to produce crops at levels that could meet local demands (Kuykendall, 1947; Ladefoged, 1993). In addition, due to the legal restrictions of the leprosy settlement—established just 36 years after the first cattle were brought to the isolated peninsula and only 17 years after the California gold rush—export of all goods from the region ceased. Overall, it appears that historic-era cattle ranching and farming were rarely ever practiced above a subsistence scale, and through the analysis of air photographs, we can now place these historic features on specific sections of the landscape.

Agronomic Infrastructure

In the absence of either permanent or intermittent streams, the rain-fed fields of the Kalaupapa Peninsula reflect adaptations to different landforms and microclimates, resulting in two major types of plots: long, narrow linear plots and irregular plots constructed in swales between boulder outcrops. Linear plots—defined by low field walls generally one or two courses of stone 50 cm tall—are packed densely together in locations exposed to the northeast trade winds (Figure 2). Field surveys have allowed linear plots to be classified in three size categories—two varieties of wide plots averaging 16 m (range 12.0–18.1 m) and 8 m (range 6.0–12.0 m) and narrow plots with a mean width of 3 m (range 0.5–6.0 m) (McCoy, 2006:105; see also Kirch, 2002; McCoy, 2002; Manning and Neller, in press). Most plots are narrow, accounting for 87.4% of the 492 plots mapped over 1.94 km of survey transects (McCoy, 2006). The wide plots are primarily found on the eastern edge of the fields and on the southern half of the peninsula, and the widest variety is extremely rare, accounting for only 1% of plots measured.

The form, size, and distribution of Kalaupapa’s wide linear plots suggest that they may be unmodified remnants of an early phase in the field system’s life history. The average size of wide plots is roughly two and four times that of narrow plots—exactly what one would expect if the field system had undergone an intensification process in which plots were subdivided twice. Indeed, if average size has tended to make stepwise moves—leaping from around 16 m, to 8 m, to 4 m with each phase of subdivision—this may account for the “gap” in the overall histogram of plot widths

(i.e., no plots with widths between 11.3 and 13.8 m were recorded) (McCoy, 2006:Figure 5.10).

The second major type of fields, irregular plots, are equally as densely packed on the landscape but conform to local landform. Indeed, where conditions allow, irregular fields mimic the dimensions of linear plots. On the steep western slopes of Kauhakō Crater, irregular plots sometimes take on a terrace-like form. In other cases, plots are built in small clearings on boulder outcrops themselves. Unfortunately, the potential for relative chronology building in these types of fields is lower than for linear fields. Nonetheless, there is no reason to believe irregular fields were more than an adaptation to local substrate conditions, with a similar history as the rest of the field system.

High stone walls, commonly referred to as boundary or cattle walls, are readily visible in air photos (McCoy, 2006:Figure 5.11) and are found in two contexts: (1) enclosing fields carved out of the overall field system (Ladefoged, 1990:182) and (2) separating portions of the peninsula from one another over remarkably large areas. In some cases, enclosed fields clearly represent historic gardens where it was necessary to keep roving animals away from crops (Ladefoged, 1990, 1993). At a historic homestead excavated by Goodwin (1994)—easily the best studied of the local enclosed fields—linear plots within the enclosure are generally shorter and narrower than adjacent open fields. Air photos and survey show enclosed fields tend to be found more frequently on the western half of the peninsula.

METHODS

To track a variety of soil properties that might be impacted by agriculture or erosion, we followed a methodology that has proven useful in recent research on the relationship between soil nutrients and agricultural development in the Hawaiian Islands (Kirch et al., 2004; Vitousek et al., 2004). Soil samples ($n = 122$) were collected from across the landscape, then analyzed for total phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and sodium (Na) by x-ray fluorescence (ALS Chemex, Sparks, NV); exchangeable base cations (K, Ca, Mg, and Na); cation exchange capacity (CEC); resin-extractable phosphorus (P); and total carbon (C) and nitrogen (N). Results are reported here on a mass basis as wt %, and all values refer to total element concentration unless labeled otherwise.

The majority of these samples were taken in locations within two perpendicular transects (Figure 1). On the 2 km long east transect—oriented roughly parallel to the dominant wind pattern—soil was collected from under walls and in the center of agricultural plots at ten locations. Samples from under walls are assumed to correspond to a period before the most intensive phase of cultivation undertaken in that particular field, and those from the center of plots, the post-intensive-cultivation soil. Hereafter, these will be referred to as wall and plot samples, respectively. We should note that field crews avoided taking samples from fields that had clear evidence of historic period use, because judging the relative age of individual field walls is difficult. Therefore, our control wall samples may represent soil that has undergone some cultivation. Thus, these are conservatively considered as pre-intensive agriculture because they must at least pre-date the last stage of wall construction.

It is also important to note that unlike in other field systems in the Hawaiian Islands, archaeological survey suggests that little soil modification was undertaken in wall construction (McCoy, 2002). In some areas, especially along the north transect, access to field walls was impossible due to thick vegetation, and matching samples were not taken. Nonetheless, a total of 31 samples were obtained from under walls and 38 from within plots.

To account for local patterns of wind strength and direction, a total of 25 field examinations of permanently wind-deformed vegetation were made primarily on Christmas berry (*Schinus terebinthifolius*) ($n = 21$) with a few additional observations on Java Plum (*Syzygium cumini*) ($n = 3$) and lantana (*Lantana camara*) ($n = 1$) (Figure 4). The direction of deformation matches the expected range of northeast trade winds between 33.5 (NE) to 68.5 (ENE) degrees from true north (Juvik and Juvik, 1988). Relative levels of vegetation deformation were ranked on an ordinal scale from 0 to 5 (Noguchi, 1979). These observations were used to create a wind map using Geographic Information Systems software (Environmental Systems Research Institute). Although not as dramatic as the island-scale windward-leeward dichotomy, there is a clear transition between northeastern lands directly exposed to trade winds (Noguchi's Grade 5) and those immediately in the lee of the Kauhakō Crater and its main lava tube (Noguchi's Grade 3). This transition is located on the eastern transect at roughly 1500 m from the windward coast. In a narrow section along the western leeward coast—not extensively tested in our soil study or archaeological surveys due to modern disturbance—winds once again increase as the sheltering effect of the crater ridge begins to dissipate.

Three zones were defined through wind pattern analysis: windward, central, and leeward zones (Figure 4). Whereas the boundary between the windward and central zones is arbitrarily set at 500 m from the windward coastline within the area directly exposed to trade winds, the boundary between the central and leeward zones is defined by the natural transition in wind strength described above. Overall, because the northeast trade winds are a byproduct of the Hadley Cell circulation—a pattern caused by rising warm air at the equator and subsiding air at 30 degrees north latitude—these zones are likely to have been stable over a long period of time.

RESULTS

The results of soil analysis designed to test the impact of wind erosion are presented below in three parts. The first section describes the state of the landscape prior to the last stage of prehistoric agricultural development. Paleoenvironmental research suggests that prior to human modification, the landscape was forested, and our analysis indicates that in this environment, wind erosion was not a major problem. In the second section, pre- and post-intensive agriculture conditions are compared using matching samples along a 2 km transect roughly parallel to the dominant winds. Through linear regression, we find a consistent relationship between changes in nutrient levels and distance to the windward coast that suggests a marked increase in wind erosion. In the final section, the overall condition of post-intensive agriculture soils is assessed to quantify changes attributable to increased wind erosion.

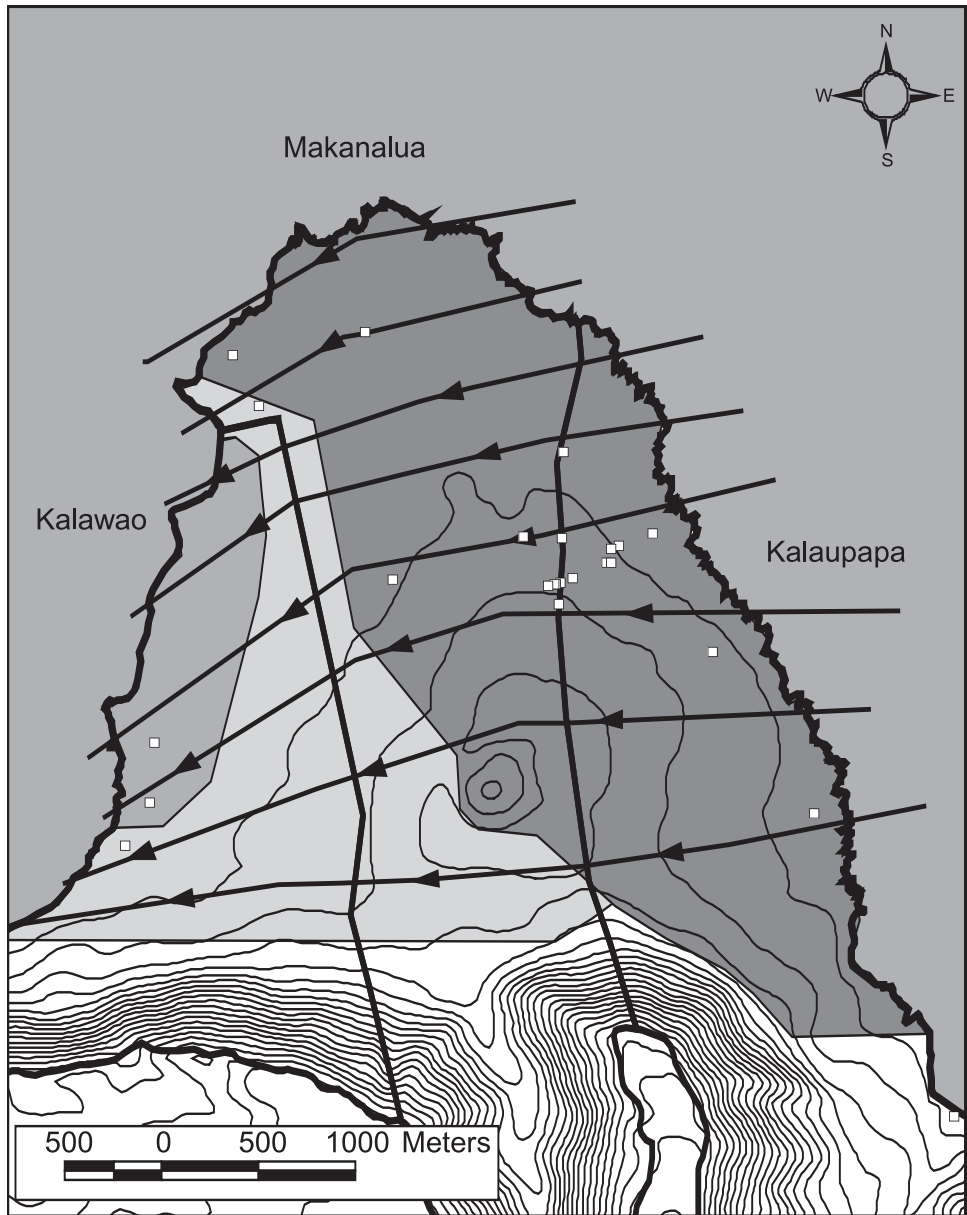


Figure 4. Micro-climatic zones on the Kalaupapa Peninsula, Moloka'i Island, Hawai'i. Arrows and shading show direction of trade winds and relative wind strength derived from observations on permanently wind-deformed vegetation. Bold lines mark community territory boundaries and one hundred foot elevation contours are shown.

Pre-Intensive Agriculture Vegetation and Soil Properties

A recent reconstruction of the Kalaupapa Peninsula's endemic vegetation based on charcoal from early anthropogenic burning indicates that the area was at one time dominated by endemic tree species such as *Diospyros* (*'ōlapa*), *Acacia* (*koa*), and *cf. Flueggea* (*mēhamehame*). This is distinctly unlike the treeless landscape seen today (Kirch et al., 2003). It seems likely that given the limited sources of natural fires in the Hawaiian Islands, fires seldom disturbed this endemic forest (Juvik and Juvik, 1988). Therefore, our first analysis was designed to test whether wind erosion was a problem in what appears to have been a stable, if declining, forest environment before intensive agriculture.

If wind erosion was a problem prior to the intensification of agriculture, we would expect soil nutrients in the control samples to be distributed unevenly after exposure to trade winds. However, the ratio of windward to leeward samples along the east transect indicated a remarkably even distribution of P, N, C, base saturation, and cation exchange capacity (Figure 5). Nonetheless, Na, Mg, Ca, and K deviate from a 1:1 ratio, showing unusually high amounts along the northeast coast and in the leeward zone. Because these four elements are abundant in seawater,

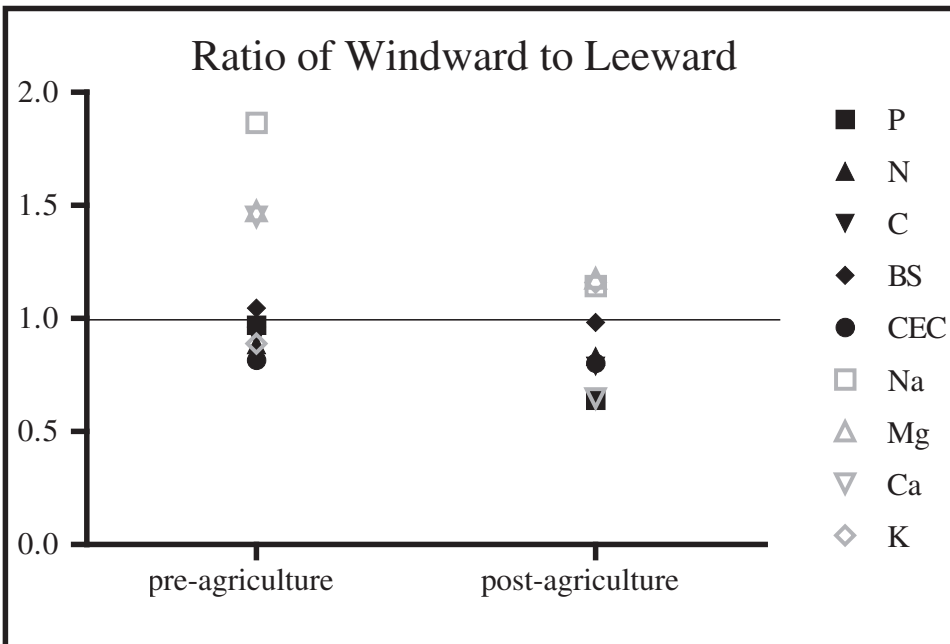


Figure 5. Ratio of windward to leeward soil nutrients in pre-agriculture control samples and post-agriculture samples. Prior to agriculture, most measures show an even distribution of nutrients, with the notable exceptions of elements common in seawater (shown in gray): Na, Mg, Ca, and K. These elements are elevated in the windward control samples due to the long-term inputs from sea spray. In the wall samples, there is a general shift away from an even distribution to greater levels in the leeward. This is attributed to increased eolian erosion redepositing soils.

which averages around 10.77 g/kg Na, 1.29 g/kg Mg, 0.412 g/kg Ca, and 0.399 g/kg K at 35% salinity, we interpret these results as indicating that wind erosion was not a problem prior to intensive agriculture, and landscape stability allowed sea spray to make significant contributions to soil nutrients (Berner and Berner, 1996:313). Indeed, this is consistent with previous research on the effects of sea spray on soil nutrients in similar environments (Gustafsson and Franzén, 1996; Whipkey et al., 2000).

Finally, to confirm that increased inputs from sea spray account for the unusually high amounts of elements in windward locations, a second ratio was calculated using wall samples from across the landscape (Figure 6). This ratio (the proportion of exchangeable to total Na) clearly shows an increased proportion of exchangeable Na within 500 m of the windward coast prior to intensive agriculture. This final line of evidence confirms that sea spray is probably responsible for higher amounts of some elements in windward locations.

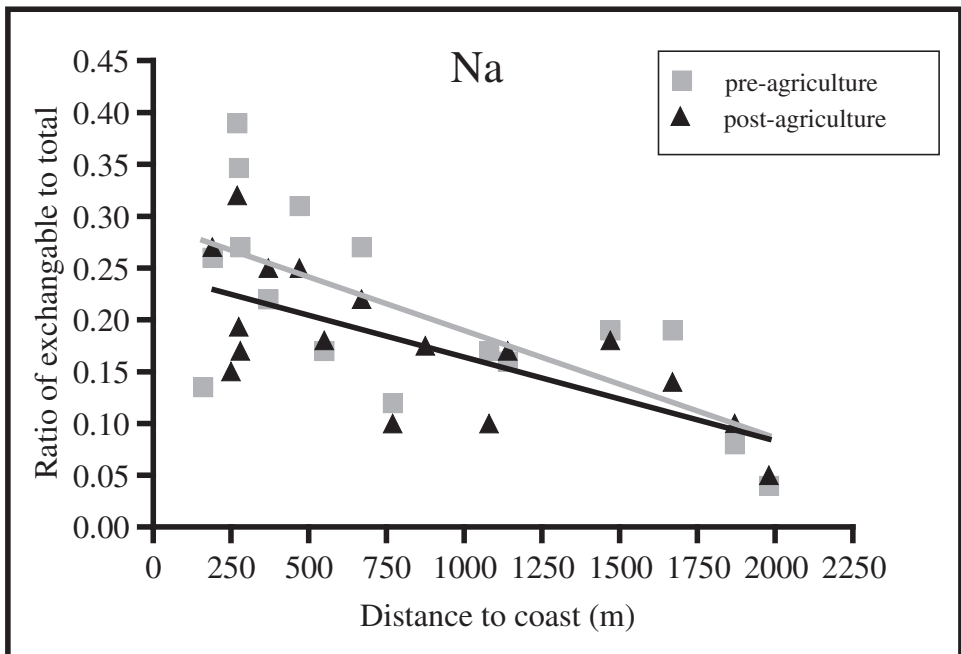


Figure 6. Ratio of exchangeable-to-total sodium on Kalaupapa Peninsula, Hawai'i. Samples from under field walls ($n = 21$) show increased proportions of exchangeable sodium within 500 meters from the windward coast due to natural inputs from sea spray; $y = -0.0001x + 0.293$; $r^2 = 0.46$; $p = 0.0038$. 95% confidence intervals of linear regression shown. Pre-agriculture (gray) is compared with post-agriculture (black). Pre-agriculture: $n = 21$; $y = -0.0001x + 0.293$; $r^2 = 0.46$; $p = 0.0038$. Post-agriculture: $n = 21$; $y = -8E - 05x + 0.245$; $r^2 = 0.49$; $p = 0.0019$. For all analysis, multiple samples from the same location and context were averaged, and location 10 on the Kalaupapa East Transect was removed as an outlier (see Table I).

Soil Nutrients and Distance to the Windward Coast

To determine whether wind erosion was a problem after the advent of intensive agriculture, we compared nutrient levels in paired wall and plot samples to wind strength. The amount of nutrients in wall samples was subtracted from the amount in matching plot samples at ten locations to estimate gain or loss in soil nutrients over the period of intensification (Table I). This was repeated for measurements of base saturation (BS) and cation exchange capacity (CEC).

Using linear regression we found that five nutrients (Na, Mg, Ca, C, and P) and BS showed significant positive correlation with distance to the windward coast (Figure 7). Because these correlations can arise in several ways, we examined measured changes at different locations. Three nutrients (Na, Mg, Ca) show evidence of both decreased levels close to the windward coast and increased or stable levels downwind. Carbon, phosphorus, and BS showed correlation primarily due to increased leeward levels. Surprisingly, there is no evidence for depletion of windward soils without leeward enrichment—the expected pattern if wind erosion without downwind replacement

Table I. Measured nutrients in control wall and plot samples on East Kalaupapa Transect.

| Location | Zone | Sample no. | Distance to coast (m) | P | K | Mg | Ca | N | C | Na | BS | CEC |
|---------------------|----------|------------|-----------------------|------|-----|-----|-----|-----|------|-----|----|-----|
| Wall Samples | | | | | | | | | | | | |
| 1 | windward | 3 | 270 | 0.36 | 0.8 | 4.4 | 1.4 | 0.5 | 5.1 | 0.3 | 41 | 53 |
| 2 | windward | 6 | 370 | 0.25 | 1.1 | 2.6 | 0.8 | 0.4 | 3.6 | 0.3 | 36 | 57 |
| 3 | windward | 7 | 470 | 0.33 | 0.9 | 2.6 | 0.7 | 0.4 | 4.4 | 0.3 | 41 | 54 |
| 4 | central | 9 | 670 | 0.22 | 1.1 | 2.2 | 0.7 | 0.4 | 4.5 | 0.2 | 44 | 54 |
| 5 | central | 11 | 770 | 0.28 | 1.0 | 2.4 | 0.9 | 0.7 | 6.7 | 0.3 | 43 | 56 |
| 6 | central | 14 | 1140 | 0.38 | 0.9 | 2.0 | 0.8 | 0.6 | 5.3 | 0.1 | 35 | 50 |
| 7 | central | 29 | 1470 | 0.36 | 1.1 | 1.9 | 0.6 | 0.6 | 5.2 | 0.1 | 43 | 51 |
| 8 | leeward | 31 | 1670 | 0.15 | 1.5 | 1.8 | 0.4 | 0.2 | 2.1 | 0.2 | 42 | 49 |
| 9 | leeward | 37 | 1870 | 0.44 | 0.7 | 2.9 | 2.0 | 0.5 | 5.5 | 0.3 | 43 | 53 |
| 10 | leeward | 42 | 2170 | 0.29 | 1.2 | 1.7 | 1.0 | 0.6 | 5.8 | 0.2 | 30 | 66 |
| Plot Samples | | | | | | | | | | | | |
| 1 | windward | 4 | 270 | 0.31 | 0.9 | 3.2 | 1.0 | 0.6 | 6.1 | 0.2 | 38 | 63 |
| 2 | windward | 5 | 370 | 0.29 | 1.2 | 2.0 | 0.5 | 0.4 | 3.9 | 0.2 | 32 | 51 |
| 3 | windward | 8 | 470 | 0.25 | 1.2 | 2.0 | 0.5 | 0.4 | 4.0 | 0.2 | 39 | 48 |
| 4 | central | 10 | 670 | 0.24 | 1.1 | 2.2 | 0.7 | 0.5 | 5.5 | 0.2 | 33 | 76 |
| 5 | central | 12 | 770 | 0.35 | 1.0 | 2.8 | 0.9 | 0.6 | 6.1 | 0.2 | 46 | 52 |
| 6 | central | 15 | 1140 | 0.37 | 1.1 | 1.8 | 0.6 | 0.5 | 4.9 | 0.1 | 32 | 47 |
| 7 | central | 28 | 1470 | 0.37 | 1.2 | 1.9 | 0.7 | 0.6 | 5.8 | 0.1 | 46 | 55 |
| 8 | leeward | 30 | 1670 | 0.27 | 1.2 | 2.4 | 0.9 | 0.5 | 4.3 | 0.2 | 35 | 65 |
| 9 | leeward | 34 | 1870 | 0.59 | 0.7 | 2.7 | 2.4 | 0.8 | 8.3 | 0.3 | 51 | 61 |
| 10 | leeward | 41 | 2170 | 0.31 | 0.6 | 2.1 | 1.4 | 0.8 | 10.1 | 0.2 | 50 | 69 |

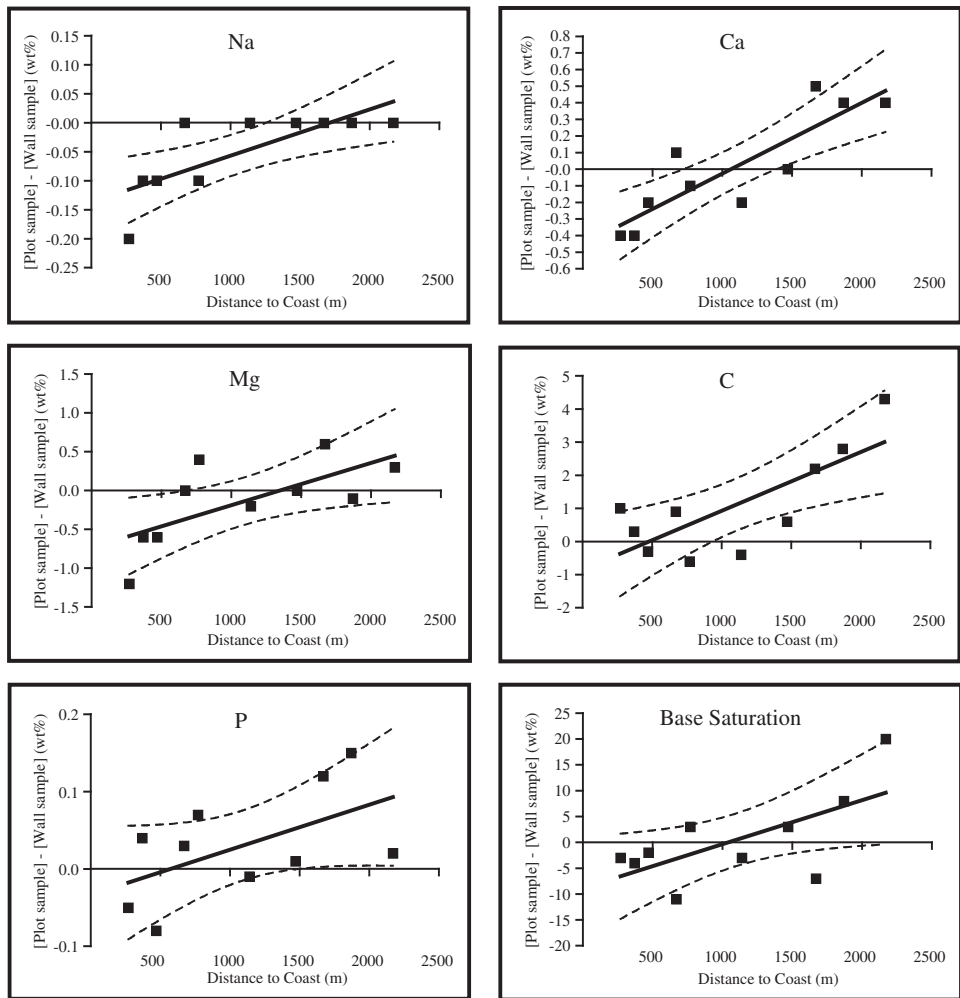


Figure 7. Soil nutrient depletion and enrichment on the Kalaupapa east transect. Note the general trend of depletion near the windward coast (left) and stability downwind in the leeward zone (right). Sodium (upper left) $y = 8E - 05x - 0.1368$; $r^2 = 0.5832$; $p = 0.0101$; Calcium (upper right) $y = 0.0004x - 0.4537$; $r^2 = 0.7568$; $p = 0.0011$. Magnesium (center left) $y = 0.0005x - 0.7321$; $r^2 = 0.4649$; $p = 0.0299$. Carbon (center right) $y = 0.0018x - 0.852$; $r^2 = 0.5805$; $p = 0.0104$. Potassium (lower left) $y = 9E - 05x - 0.0554$; $r^2 = 0.5028$; $p = 0.0942$. Base Saturation (lower right) $y = 0.0085x - 8.858$; $r^2 = 0.4333$; $p = 0.0385$. 95% confidence intervals of linear regression shown.

were a major problem. Finally, we found an anomalous negative correlation for K with distance to coast that we could not explain with current evidence; however, inputs from mulching remain a possibility (Hartshorn et al., 2006:11095).

Correlation between nutrients and distance to the coast was not overwhelmingly strong (a sign that wind erosion is not the only factor that affected nutrient distribution), yet the results show good spatial grouping of depletion in the windward

zone, relatively little change in the large central area, and enrichment in the leeward zone. Overall, the patterns described above are best explained as the result of an unprecedented increase in wind erosion after land clearing for agriculture.

Post-Intensive Agriculture Nutrient Depletion and Enrichment

Due to increased wind erosion, the windward to leeward ratio of nutrients changes following agricultural intensification (Figure 5). Eight out of nine measures show a directional difference consistent with windward depletion and/or leeward enrichment. Here we consider the magnitude of these changes in terms of the windward, central, and leeward zones (Figure 8).

Although change in nutrients in the windward area averages around 12% depletion, it appears to have especially impacted nutrients found naturally in high amounts due to sea spray (Na, Mg, and Ca). The measured reductions of these elements

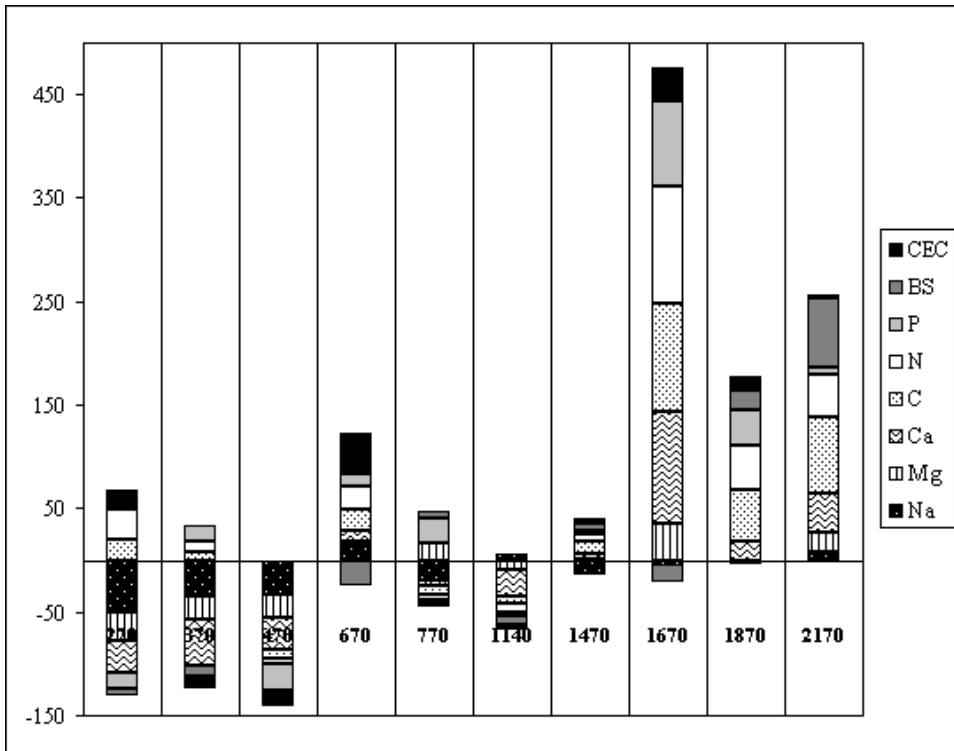


Figure 8. Relative magnitude of soil nutrient depletion and enrichment on Kalaupapa east transect. Values shown are percentages of nutrient change calculated independently for each element as: [plot sample wt %] - [wall sample wt%] / [wall sample wt%]. Locations 1 to 10 are shown left to right with corresponding distance to coast. Note the general windward depletion in locations 1-3, relatively little central area change in locations 4-7, and remarkable leeward enrichment in locations 8-10. The unexpectedly high enrichment of the latter samples is attributed to concentrated re-deposition of eroded soils.

are dramatic, ranging from 51–22% of the original amount in the soil. Other nutrients show more variable changes. For example phosphorus—essential for plant growth—shows a loss of around 24% in one case, but a 16% enrichment in another. If we compare the ratio of exchangeable to total Na in pre-agriculture and post-agriculture samples from across the peninsula, we observe a slight overall decrease in the proportion of exchangeable Na within 500 m of the windward coast (Figure 6).

Central area depletion and enrichment are mixed, but overall much less dramatic, averaging only a 2% increase (Figure 8). Nutrient levels at location 4, just outside the windward zone, represent the extremes, ranging up to a 40% increase and 25% depletion. Overall, given the intensity of agricultural development across the peninsula, it is remarkable to find such small differences in central samples.

Marked enrichment in the leeward area, averaging around 37%, doubled the amount of nutrients in soils in some cases (Figure 8). Unlike the windward area, there is almost no evidence of depletion. In fact, given the extraordinary scale of nutrient increases, it is possible that nutrients became concentrated in the air prior to re-deposition.

Taken together, it appears wind erosion and intensive agriculture strongly depleted windward areas but did not diminish the natural productivity of Kalaupapa Series soils over most of the area. Unfortunately, these results cannot be converted in a straightforward manner into actual yields due to the high local variation in nutrient levels, rainfall, and other factors not specifically addressed in this study. Nonetheless, a recent study of a leeward environment on Maui Island shows similar depletions in nutrients attributed to intensive agriculture (Ca –49%, Mg –28%, Na –75%, and P –32%); yet the authors found that “prehistoric yields were sufficient to meet local demand over very long time frames, but the associated acceleration of nutrient losses could have compromised subsequent yields” (Hartshorn et al., 2006:11092). In the final section, we isolate landform as the major reason erosion and intensive agriculture did not diminish soil fertility across the entire area and suggest directions for future research. However, first we discuss some other factors potentially impacting soil nutrient levels and wind erosion.

OTHER FACTORS IMPACTING SOIL NUTRIENTS AND WIND EROSION

There are a number of variables outside of nutrient inputs from sea spray, anthropogenic burning, and intensive agriculture that could potentially impact soil nutrients, vegetation change, and wind erosion. Here we highlight three—seabird nesting, introduced rats, and natural processes and perturbations. Seabirds are well known to play an important role in soil nutrient cycling in coastal ecosystems and may account for the higher ratios of some nutrients in windward wall samples (for example, see Mitzutani et al., 1986). Indeed, seabirds have evolved to take advantage of high-wind environments like the windward coast of Kalaupapa Peninsula (Furness and Bryant, 1996; Gilchrist et al., 1998; Weimerskirch et al., 2000); many of these birds were extirpated from Pacific islands following human colonization (Kirch, 1985, 1996, 2000, 2005; James et al., 1987; Dye and Steadman, 1990; Moniz, 1997). Nonetheless, we cannot completely eliminate windward coastal seabird rookeries as a vector for increased soil nutrients. Given that nutrient input from bird guano has

been specifically associated with higher levels of phosphorus and nitrogen (Mitzutani et al., 1986)—both of which show no significant difference in their geographic distribution in pre-intensive agriculture—we believe sea spray is a better explanation for the pattern observed.

Recent research on O'ahu Island has implicated the arrival of the Polynesian rat (*Rattus exulans*) as a primary cause of *early period* large-scale disturbance of native ecosystems (ca. A.D. 800–1000) through their consumption of palm seeds and bird predation (Athens et al., 2002). On the Kalaupapa Peninsula, we have what appears to be a similar *later period* phenomenon. Figure 3 shows a record of charcoal within deposits that began accumulating after A.D. 1300 (Kirch et al., 2003). A similar pattern can be seen on the southern coast of Moloka'i in a deep wetland core (Denham et al., 1999). Pollen analysis of sediments from this core shows a clear transition from an endemic dry-mesic forest (Zone A; 500–160 cmbs) where *Pritchardia* was the dominant species, to a decline in trees and shrubs, a rise in indicators of forest disturbance (e.g., *Cibotium*), and the “initial occurrence and subsequent rise in the frequency of charcoal particles” (Zone B; 160–165 cm below surface [cmbs]) (Denham et al., 1999:42). This change is estimated to have occurred over 450–650 years between A.D. 800–1000 and perhaps in A.D. 1450 (Layer III, 40–46 cmbs; Beta-94996; cal A.D. 1320–1660, 2 σ) (Denham et al., 1999). The relatively late and rapid decline of the peninsula's forest, which current evidence suggests could have occurred in as little as 150–350 years between A.D. 1300 and 1450–1650, is indeed remarkable. We interpret this rapid change as being primarily caused by burning associated with swidden agriculture and possibly the late introduction of the rat to this isolated section of the island. Unfortunately, we currently lack direct evidence of the timing of the rat's introduction to the study area. However, rat introduction would have certainly increased the rate of vegetation change and perhaps suppressed forest recovery after anthropogenic burning.

There are several natural processes and perturbations important to understanding Pacific island ecology (Kirch, 2000:50–53). On the longest time scale, the accumulation of dust carried by high altitude winds from continental Asia has been documented as a vector of soil nutrient inputs in the Hawaiian Islands and across the Pacific (see Vitousek, 2006, for a recent review). Although we have not directly tested for these inputs, it seems unlikely that the pre-intensive agriculture pattern of high windward nutrients is due to Asian dust, because their composition more closely matches that of seawater. On a shorter time scale, the El Niño-Southern Oscillation (ENSO) phenomenon—currently documented to have impacted the Pacific basin for at least 5000 years (Enfield, 1992)—has a local manifestation of lessened trade winds and increased southern storm intensity (Juvik and Juvik, 1988:51). Thus, drought conditions associated with the higher frequency of ENSO years around A.D. 1300 (Nunn, 2000), like the introduction of the rat, may have played a secondary role in the directional change in the local ecosystem but is unlikely to be the sole explanation.

Lastly, the low elevation of the peninsula makes it vulnerable to tsunamis. Indeed, on the opposite shore of Moloka'i, Moore, Bryan, and Ludwig (1994) have found inland evidence of a massive wave in the distant past. In the recent past, an eyewitness

account of a 1946 tsunami that reached the Kalaupapa Peninsula describes dramatic, but spatially limited, destruction of houses on the northern tip of the peninsula (Ladefoged 1990:8). However, the excellent condition of surface architecture mapped by archaeological surveys and lack of geomorphologic evidence of ancient tsunami suggest these perturbations had essentially no impact on the development of the Kalaupapa field system.

CONCLUSIONS

Burning of endemic forest and intensive agriculture led to an increase in wind erosion in the Kalaupapa field system that can be detected by comparing soil nutrients in control samples taken under agricultural field walls to samples from the center of plots (Figure 9). The erosion of soils from the area within 500 m of the windward coast is especially recognizable in nutrients that naturally occur in high amounts in coastal areas due to the long-term effects of sea spray. Downwind enrichment may have worked serendipitously to mitigate the impacts of dryland intensive agriculture on soil, allowing for later historic reuse of the area.

Given the apparent inability of artificial windbreaks to completely stop erosion, the peninsula's unique landform likely played an important role in preventing widespread

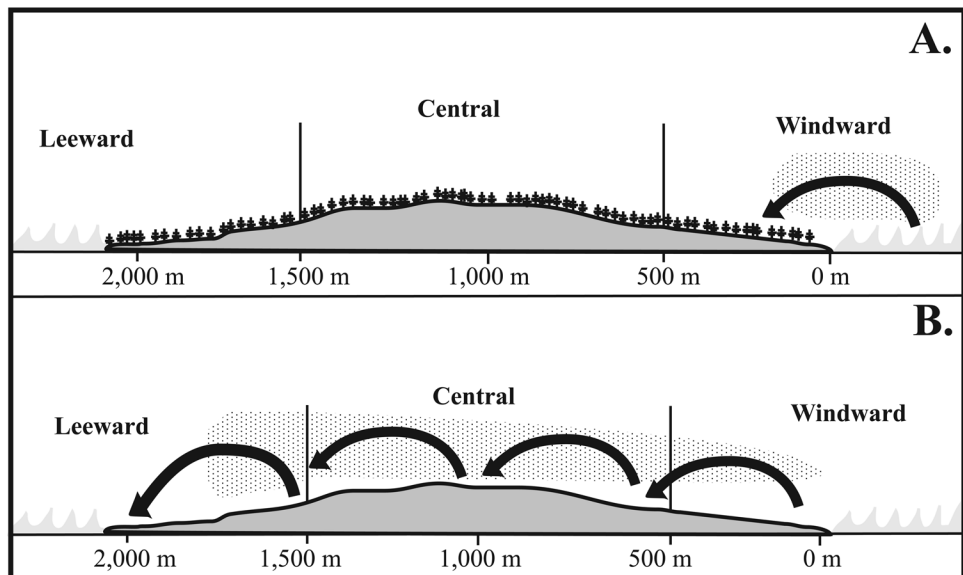


Figure 9. Kalaupapa Peninsula soil nutrient ecosystem before and after intensive agriculture: (A) Before intensive agriculture, a stable forest effectively countered wind erosion and sea spray introduced additional nutrients to windward soils; (B) After intensive agriculture, native trees are replaced with economic plants, secondary growth shrubs, and a series of artificial windbreaks, eolian erosion redistributed soils across the landscape removing them from windward areas and depositing them in leeward areas. Distance from windward coast shown.

nutrient depletion by wind erosion after the intensification of agriculture. Specifically, the Kalaupapa Peninsula has a high central area that forces trade winds upslope, as well as a leeward zone naturally sheltered from the wind (Figure 9). In contrast, in the larger Kohala field system where Vitousek et al. (2004) have demonstrated geographically extensive nutrient depletion after the advent of agriculture, trade winds originate at the crest of Kohala Mountains and travel downslope across an undissected landscape. Thus, despite its similarities with other field systems, the long-term trajectory of agricultural development and nutrient cycling in the study area was uniquely influenced by the landscape upon which the Kalaupapa field system was built.

Overall, through a detailed examination of landform, microclimatic conditions, and soil nutrients, this case study shows that the impact of wind erosion is detectable across large agricultural systems. Future research on tropical and arid agriculture should seek to quantify changes in soil nutrients caused by wind erosion during harvest and fallow periods, and how these chronic losses impacted the sustainability of intensive agriculture.

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REFERENCES

- Athens, J.S., Tuggle, H.D., Ward, J.V., & Welch, D.R. (2002). Avifaunal extinctions, vegetation change, and Polynesian impacts in prehistoric Hawai'i. *Archaeology in Oceania*, 37, 57–78.
- Berner, E.K., & Berner, R.A. (1996). *Global environment: Water, air, and geochemical cycles*. Upper Saddle River, NJ: Prentice Hall.
- Canfield, J.E. (1990). Description and map of the plant communities of the northeast coastal spray zone of Kalaupapa National Historical Park. Honolulu, HI: Cooperative National Park Resources Studies Unit, Hawaii.
- Chadwick, O.A., Derry, L.A., Vitousek, P.M., Huebert, B.J., & Hedin, L.O. (1999). Changing sources of nutrients during four million years of ecosystem development. *Nature*, 397, 491–497.
- Clague, D.A., Dao-gong, C., Murnane, R., Beeson, M.H., Lanphere, A., Dalrymple, G.B., Friesen, W., & Holcomb, R.T. (1982) Age and petrology of Kalaupapa Basalt, Molokai, Hawaii. *Pacific Science*, 36, 411–420.
- Coombs, C.R., Hawke, B.R., & Wilson, L. (1990). Terrestrial analogs to lunar sinuous rilles: Kauhako crater and channel, Kalaupapa, Molokai, and other Hawaiian lava conduit systems. *Proceedings of the Lunar Plant Scientific Conference*, 20, 195–206.
- Creighton, R.J. (1886). Molokai, description of the leper colony on this island. Honolulu, P.C. Advertiser.
- Denham, T., Eblé, F.J., Winsborough, B., & Ward, J.V. (1999). Palaeoenvironmental and Archaeological Investigations at 'Ohiāpilo Pond, Leeward Coast of Molokai. *Hawaiian Archaeology*, 7, 35–60.
- Dye, T.S., & Steadman, D.W. (1990). Polynesian ancestors and their animal world. *American Scientist*, 78, 207–215.

- Enfield, D.B. (1992) Historical and prehistorical overview of El Niño/Southern Oscillation. In H.F. Diaz & V. Markgraf (Eds.), *El Niño: Historical and paleoclimatic aspects of the Southern Oscillation*. Cambridge: Cambridge University Press.
- Foote, D.E., Hill, E.L., Nakamura, S., & Stephens, F. (1972). Soil survey of the islands of Kauai, Oahu, Maui, Molokai, and Lanai, State of Hawaii. U.S. Department of Agriculture. Washington, D.C.: U.S. Government Printing Office.
- Furness, R.W., & Bryant, D.M. (1996). Effect of wind on field metabolic rates of breeding Northern Fulmars. *Ecology*, 77, 1181–1188.
- Gilchrist, H.G., Gaston, A.J., & Smith, J.N.M. (1998). Wind and prey nest sites as foraging constraints on an avian predator, the Glaucous Gull. *Ecology*, 79, 2403–2414.
- Greene, L.W. (1985). Exile in paradise: The isolation of Hawai'i's leprosy victims and development of Kalaupapa Settlement, 1865 to present. Branch of Planning Alaska/Pacific Northwest/Western Team. Denver: U.S. Department of the Interior, National Park Service.
- Goodwin, C.M. (1994). A Kalaupapa sweet potato farm: Report on archaeological data recovery operations, Kalaupapa Airport Improvement Project, Kalaupapa, Molokai, Hawai'i. Honolulu, International Archaeological Research Institute, Inc.
- Gustafsson, M.E.R., & Franzén, L.G. (1996). Dry deposition and concentration of marine aerosols in a coastal area, SW Sweden. *Atmospheric Environment*, 30, 977–989.
- Handy, E.S.C., & Handy, E.G. (1972). *Native planters in old Hawaii: Their life, lore, and environment*. Honolulu, HI: Bishop Museum Press.
- Hartshorn, A.S., Chadwick, O.A., Vitousek, P.M., & Kirch, P.V. (2006). Prehistoric agricultural depletion of soil nutrients in Hawaii. *Proceedings of the National Academy of Sciences, USA*, 103, 11092–11097.
- James, H., Stafford, T.W., Steadman, D.W., Olson, S.L., Martin, P.S., Jull, A.J.T., & McCoy, P.C. (1987). Radiocarbon dates on bones of extinct birds from Hawaii. *Proceedings of the National Academy of Sciences, U.S.*, 84, 2350–2354.
- Juvik, S.O., & Juvik, J.O. (1988). *Atlas of Hawaii*. Honolulu, HI: University of Hawaii Press.
- Kirch, P.V. (1985). *Feathered gods and fishhooks: An introduction to Hawaiian archaeology and prehistory*. Honolulu, HI: University of Hawaii Press.
- Kirch, P.V. (1996). Late Holocene human-induced modifications to a central Polynesian island ecosystem. *Proceedings of the National Academy of Sciences, USA*, 93, 5296–5300.
- Kirch, P.V. (2000). *On the road of the winds: An archaeological history of the Pacific islands before European contact*. Berkeley, CA: University of California Press.
- Kirch, P.V. (2002). From the “Cliffs of Keolewa” to the “Sea of Papaloa”: An archaeological reconnaissance of portions of the Kalaupapa National Historical Park, Moloka'i, Hawaiian Islands. Berkeley, CA: Archaeological Research Facility, University of California, Berkeley.
- Kirch, P.V. (2005). Perspectives on Diamond's collapse: How societies choose to fail or succeed. *Current Anthropology*, 46, S91–S99, Supplement 5.
- Kirch, P.V., Hartshorn, A.S., Chadwick, O.A., Vitousek, P.M., Sherrod, D.R., Coil, J., Holm, L., & Sharp, W.D. (2004). Environment, agriculture, and settlement patterns in a marginal Polynesian landscape. *Proceedings of the National Academy of Sciences, USA*, 1, 9936–9941.
- Kirch, P.V., O'Day, S., Coil, J., Morgenstein, M., Kawelu, K., & Millerstrom, M. (2003). The Kaupikiawa Rockshelter, Kalaupapa Peninsula, Moloka'i: New investigations and reinterpretation of its significance for Hawaiian prehistory. *People and Culture in Oceania*, 19, 1–27.
- Kurtz, A.C., Derry, L.A., & Chadwick, O.A. (2001). Accretion of Asian dust to Hawaiian soils: Isotopic, elemental, and mineral mass balances. *Geochimica et Cosmochimica*, 65, 1971–1983.
- Kuykendall, R.S. (1947). *The Hawaiian Kingdom 1778–1854: Foundation and transformation*. Honolulu, HI: University of Hawaii Press.
- Ladefoged, T.N. (1990). A dryland agricultural system at Kalaupapa, Moloka'i: Archaeological inventory survey, Airport Improvement Project. Honolulu, HI: International Archaeological Research Institute.
- Ladefoged, T.N. (1993). Hawaiian dryland agricultural intensification and the Pacific economy. *Pacific Studies*, 16, 119–131.

- Ladefoged, T.N., Graves, M.W., & Jennings, R.P. (1996). Dryland agricultural expansion and intensification in Kohala, Hawai'i Island. *Antiquity*, 70, 861–880.
- Macdonald, G.A., Abbott, A.T., & Peterson, F.L. (1983). *Volcanoes in the sea: The geology of Hawaii* (2nd ed.). Honolulu, HI: University of Hawaii Press.
- Manning, E., & Neller, E. (in preparation). Chapters 2–6. In M.D. McCoy (Ed.), *Kalaupapa archaeology: A collection of five surveys in the Kalaupapa National Historical Park*. Honolulu, Research Corporation of the University of Hawai'i and National Park Service, U.S. Department of the Interior.
- McCoy, M.D. (2002). Report on Kalaupapa Peninsula Archaeological Project 2002. Unpublished manuscript.
- McCoy, M.D. (2003). Report on Kalaupapa Peninsula Archaeological Project 2003. Unpublished manuscript.
- McCoy, M.D. (2004). Report on Kalaupapa Peninsula Archaeological Project 2004. Unpublished manuscript.
- McCoy, M.D. (2005a). The lands of Hina: An archaeological overview and assessment of Kalaupapa National Historical Park, Moloka'i Island. Technical Report 135. Honolulu, HI: Pacific Cooperative Studies Unit of the University of Hawai'i and National Park Service, U.S. Department of the Interior.
- McCoy, M.D. (2005b). The development of the Kalaupapa field system, Moloka'i Island, Hawai'i. *Journal of the Polynesian Society*, 116, 339–358.
- McCoy, M.D. (2006). Landscape, social memory, and society: An ethnohistoric-archaeological study of three Hawaiian communities. Unpublished PhD dissertation, University of California, Berkeley.
- McCoy, M.D., Hartshorn, A.S., & Chadwick, O.A. (2004). The origins of the Kalaupapa field system: A Geographic Information Systems-based study of the Kalaupapa Peninsula, Moloka'i Island, Hawai'i. 17th Annual Society for Hawaiian Archaeology Meeting, Kailua-Kona, HI.
- Mitzutani, H., Hasegawa, H., & Wada, E. (1986). High nitrogen isotope ratio for soils of seabird rookeries. *Biogeochemistry*, 2, 221–247.
- Moniz, J. (1997). The role of seabirds in Hawaiian subsistence: Implications for interpreting avian extinction and extirpation. *Polynesia Asian Perspectives*, 36, 27–50.
- Moore, J.G., Bryan, W.B., & Ludwig, K.R. (1994). Chaotic deposition by a giant wave, Molokai, Hawaii. *Geological Society of America Bulletin*, 106, 962–967.
- Nunn, P.D. (2000). Environmental catastrophe in the Pacific Islands about A.D. 1300. *Geoarchaeology*, 15, 715–740.
- Noguchi, Y. (1979). Deformation of trees in Hawaii and its relation to wind. *Journal of Ecology*, 67, 611–628.
- Okin, G.S., Mahowald, N., Chadwick, O.A., & Artaxo, P. (2004). Impact of desert dust on the biogeochemistry of phosphorus in terrestrial ecosystems. *Global Biogeochemical Cycles*, 18, 1–9.
- Redman, C.L. (1999). *Human impacts on ancient environments*. Tucson, AZ: University of Arizona Press.
- Reynolds, R., Belnap, J., Reheis, M., Lamothe, P., & Luiszer, F. (2001). Aeolian dust in Colorado Plateau soils: Nutrient inputs and recent change in source, *Proceedings of the National Academy of Sciences, USA*, 98, 7123–7127.
- Rick, T. (2002). Eolian processes, ground cover, and the archaeology of coastal dunes: A taphonomic case study from San Miguel Island, California, USA. *Geoarchaeology: An International Journal*, 17, 811–833.
- Riksen, M.J.P.M., & De Graaff, J. (2001). On-site and off-site effects of wind erosion on European light soils. *Land Degradation and Development*, 12, 1–11.
- Somers, G.F. (1985). *Kalaupapa, more than a leprosy settlement: Archaeology at Kalaupapa National Historical Park*. Tucson, AZ: National Park Service.
- Sterk, G. (2003). Causes, consequences and control of wind erosion in Sahelian Africa: A review. *Land Degradation and Development*, 14, 95–108.
- Vitousek, P. (2006). Ecosystem science and human-environment interactions in the Hawaiian archipelago. *Journal of Ecology*, 94, 510–521.
- Vitousek, P.M., Chadwick, O.A., Matson, P., Allison, S., Derry, L., Kettley, L., Luers, A., Mecking, E., Monastera, V., & Porder, S. (2003). Erosion and the rejuvenation of weathering-derived nutrient supply in an old tropical landscape. *Ecosystems*, 6, 762–772.

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- Vitousek, P.M., Ladefoged, T.N., Kirch, P.V., Hartshorn, A.S., Graves, M.W., Hotchkiss, S.C., Tuljapurkar, S., & Chadwick, O.A. (2004). Soils, agriculture, and society in precontact Hawai'i. *Science*, 304, 1665–1669.
- Weimerskirch, H., Guionnet, T., Martin, J., Shaffer, S.A., & Costa, D.P. (2000). Fast and fuel efficient? Optimal use of wind by flying albatrosses. *Proceedings of the Royal Society of London Bulletin*, 267, 1869–1874.
- Whipkey, C.E., Capo, R.C., Chadwick, O.A., & Stewart, B.W. (2000). The importance of sea spray to the cation budget of a coastal Hawaiian soil: A strontium isotope approach. *Chemical Geology*, 168, 37–48.

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