Microclimatic Effects of Kō (Sugarcane, *Saccharum officinarum*) Row Planting in the Leeward Kohala Field System, Hawai'i Island[1]

Michael W. Burnett,[2,7,8] *Duncan Coleman,*[2] *Gabriel Saiz,*[2] *Kiara Bacasen,*[3] *Marina Luccioni,*[4] *Kēhaulani Marshall,*[5] *and Peter M. Vitousek*[6]

Abstract: The Leeward Kohala Field System (LKFS) on Hawai'i Island once featured over 60 km^2 of productive, rain-fed croplands. For several centuries, its occupants cultivated 'uala (*Ipomoea batatas*, sweet potato) as a staple crop between kuaiwi (earthen or rock walls) planted with kō (*Saccharum officinarum*, sugarcane). These raised kō rows could have influenced 'uala growth through an array of microclimatic processes, including wind abatement, shading, and the redistribution of moisture. While such effects are frequently mentioned in the literature, efforts to directly quantify them and relate them to 'uala production have been lacking. We measured wind speeds, precipitation rates, solar illuminance, soil moisture, and 'uala yields along a transect through three kō rows within the LKFS. Kō rows proved effective windbreaks, reducing near-surface wind speeds by up to 90% and for distances of up to 10 m. The rows also concentrated wind-blown moisture at their upwind edges while creating rain shadows 5–6 m in length. 'Uala yields peaked at 3.8–6.0 kg m^{-2} near the center of inter-row space, probably because 'uala were energy-limited during the wet study period and grew slowly when shaded by the kō. A zone of low turbulence leeward of each kō row also appeared to benefit 'uala growth. Additional measurements are needed to investigate the landscape-level hydrologic effects of kō row planting. Our findings will help guide ongoing efforts to expand agricultural and educational activities in the LKFS.

Keywords: sugarcane, sweet potato, traditional agriculture, windbreaks, row planting, microclimates, traditional ecological knowledge, land stewardship

Hawaiians were unique within pre-contact Polynesia for their reliance on—and mastery of—dryland agriculture (Lincoln and Vitousek 2017). After beginning to farm in fertile lowlands and river valleys, Hawaiians expanded their agricultural operations into increasingly marginal environments as their population swelled into the hundreds of thousands (Dye 2011; Swanson 2019). Eventually, this agricultural development included large rain-fed systems that were less consistent than irrigated pondfields and gardens, but which could be built over vast areas of fertile soil on the younger Hawaiian volcanos (Ladefoged et al. 2009; Vitousek et al. 2014).

The conversion of nearly all of Hawaii's arable drylands into productive agricultural systems evinces a remarkable tradition of innovation and experimentation (Ladefoged

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[2]Earth Systems Program, Stanford University, Stanford, CA 94305, USA.
[3]Department of Civil and Environmental Engineering, Stanford University, Stanford, CA 94305, USA.
[4]Department of Biology, Stanford University, Stanford, CA 94305, USA.
[5]Ulu Mau Puanui, Kamuela, HI 96743, USA.
[6]Department of Earth System Science, Stanford University, Stanford, CA 94305, USA.
[7]Present address: Department of Ecology, Evolution, and Marine Biology, University of California Santa Barbara, Santa Barbara, CA 93106, USA; The Nature Conservancy, Kamuela, HI 96743, USA.
[8]Corresponding author (email: mburnett@ucsb.edu).

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et al. 2011). The high, windy slopes of geologically young Hawai'i Island differed significantly from the eroded islands and weathered soils on which Polynesians had refined their agricultural techniques for generations (McCoy and Graves 2010). Rain-fed food production in these challenging new environments necessitated centuries of innovation by indigenous Hawaiians, but much of this knowledge was lost when the labor-intensive dryland fields were abandoned in the aftermath of European contact (Kirch 2010; Dye 2011; Marshall et al. 2017).

While indigenous Hawaiian agricultural knowledge will never be fully recovered, researchers and land stewards have sought to restore productivity to Hawaii's dryland field systems by combining archaeology, ethnography, and field experimentation to revitalize traditions of agricultural innovation (Kagawa and Vitousek 2012; Marshall et al. 2017; Sirabis et al. 2022).

Much of this work has taken place in the Leeward Kohala Field System (LKFS) on the island of Hawai'i, one of the largest and best documented Hawaiian rain-fed agricultural systems (Ladefoged et al. 1996; Ladefoged and Graves 2011). Large-scale agricultural development in the LKFS began in the 13^{th} or 14^{th} century A.D. (Ladefoged and Graves 2008; Dye 2011) and eventually expanded to cover over 60 km^2 before its abandonment (Ladefoged et al. 2011).

Although these fields have long lay abandoned, their remnants are still visible in the extensive latticework of raised earth and stone walls (kuaiwi) constructed approximately along the slope's contours (Ladefoged et al. 2003, 2011, Ladefoged and Graves 2011). These kuaiwi, now covered by exotic pasture grasses, provide a prehistoric foundation upon which planting trials can uncover how indigenous Hawaiians operated the field system and how their methods might be adapted to the present day (Marshall et al. 2017).

Ethnohistorical accounts of the LKFS note that its kuaiwi were densely planted with kō (*Saccharum officinarum*, sugarcane) while the less rocky areas between the kuaiwi were planted with 'uala (*Ipomoea batatas*, sweet potato) and, to a lesser extent, dryland kalo (*Colocasia esculenta*, taro), uhi (*Dioscorea* spp., yam), 'ulu (*Artocarpus altilis*, breadfruit), and mai'a (*Musa* spp., banana/plantain) (Lincoln et al. 2017; Marshall et al. 2017). The apparent intensification of kuaiwi construction in the LKFS's most fertile areas (Ladefoged et al. 2011) despite the minor role of kō as a food crop suggests raised kō plantings may have somehow supported the cultivation of other crops (Lincoln et al. 2017). Several agricultural functions have been proposed for the kō rows, including providing nutrient-rich mulch for other crops (Lincoln and Vitousek 2016; Lincoln et al. 2017) and producing feed for pigs (Dye 2014).

Additionally, the raised kō rows appear to create significant microclimatic effects in the LKFS, where strong winds and rain nearly always come from the upslope (northeasterly) direction. McCoy and Graves (2010) describe the kuaiwi of the LKFS as an agricultural innovation meant to reduce soil erosion and damage to plants by the strong trade winds typical of North Kohala. Ladefoged et al. (2003) suggest that they are sufficient in size and number to have significantly reduced evaporation over large areas, potentially conserving moisture, while McCoy and Hartshorn (2007) found that kuaiwi in the rain-fed Kalaupapa Field System on Moloka'i help slow the loss of soil nutrients to the strong trade winds.

These effects would be magnified by the establishment of kō atop the kuaiwi; in fact, Marshall et al. (2017) reported that dense kō rows planted in the LKFS were such effective windbreaks that 'uala planted in their immediate lee dried out and died, prompting them to thin the rows for greater airflow.

Others have theorized that kuaiwi and kō in the LKFS functioned as moisture catchers, intercepting raindrops from the region's strong trade winds (Handy et al. 1972; Ladefoged and Graves 2011; Lincoln and Vitousek 2017; Lincoln et al. 2017; Marshall et al. 2017). These processes would mostly amount to a redistribution of moisture, probably toward the windward side of the kuaiwi during wet periods.

Lincoln et al. (2017) found that kuaiwi planted with kō strongly influenced local soil moisture patterns, with the windward sides of kuaiwi featuring 150–300% as much moisture as the leeward sides over a wide range of rainfall levels. They also noted that the interception and subsequent dripping of mist from kō leaves could provide a net gain of water during dry periods with no vertical rainfall.

In sum, these notable physical features of the LKFS generate an array of microclimatic effects (slowed winds, redistributed moisture, and shading) that could profoundly influence crops grown between the kuaiwi. Despite this potential, to our knowledge there have been no experimental studies of the fine-scale effects of raised kō rows on moisture inputs, wind speeds, sunlight, and, most importantly, ʻuala yields.

We examined these climatic variables and their cumulative impacts on ʻuala growth in an experimental māla (garden) using a transect running through multiple kō rows. Our findings will help illuminate the remarkable agricultural practices of indigenous Hawaiians while informing ongoing efforts to restore productivity to dryland cropping systems like the LKFS.

MATERIALS AND METHODS

Study Site

Puanui is one of at least 33 ahupuaʻa (Hawaiian land divisions) that span the LKFS (Ladefoged and Graves 2006) and is today home to three experimental māla in which traditional Hawaiian dryland agricultural methods are tested in field trials (Kagawa and Vitousek 2012; Marshall et al. 2017). The present study took place in the highest and wettest māla (Figure 1; 20.152° N, 155.819° W), located at 730 m elevation and typically receiving about 1,660 mm/yr of rainfall (Giambelluca et al. 2013), although many recent years have been drier (Marshall et al. 2017).

A weather station inside the māla recorded 389.2 mm of rainfall during the 109-day study period for precipitation, although consistently high wind speeds (mean of 9.9 mph or 4.4 m s^{-1} with mean gusts of 15.9 mph or 7.1 m s^{-1} during the same period) probably led to underestimations of total precipitation by the elevated tipping-bucket gauge (Pollock et al. 2018). Mean air temperature for the same period was 20.6°C and mean relative humidity was 91.4%. This location represents the wet upper region of the LKFS, above which high rainfall levels have depleted soil nutrients and decreased crop productivity (Vitousek and Chadwick 2013). Rainfall totaled 1,648.0 mm over this study's 219-day ʻuala growing period, indicating wetter-than-average conditions.

The māla is planted with ~1 m thick rows of kō that reach ~3 m in height and lean downwind, with their longest leaves hanging about 2 m leeward of the stems. The kauiwi here have been degraded and obscured by large amounts of rainfall and grazing relative to downslope areas, but the mature kō rows planted with the same approximate spacing nonetheless provide an extremely effective windbreak (Marshall et al. 2017). The areas between rows were covered by kikuyu grass (*Cenchrus clandestinus*) that was regularly mowed to simulate an open cropping space.

Field Measurements

We measured precipitation, soil moisture, solar illuminance, and wind speed along a 24 m transect perpendicular to the kō rows and parallel to the dominant trade winds (Figure 2). The transect crossed two kō rows and stopped just windward of a third. The farthest upslope row abutted the māla's wire fence, beyond which lay open pasture. Precipitation was measured along the full 24 m transect while the other variables were measured along a 14 m subset between two of the rows (Figure 3*F*).

Precipitation data were acquired at 18 points along the transect using 2.8 m long, 4 cm wide steel troughs set perpendicular to the transect and angled 15° into enclosed plastic collection buckets (Figure 2). Buckets were weighed to 5 g precision every 2–7 days from August 18 through December 5, 2018, to determine the amount of water collected at each point. Weights of collected water were

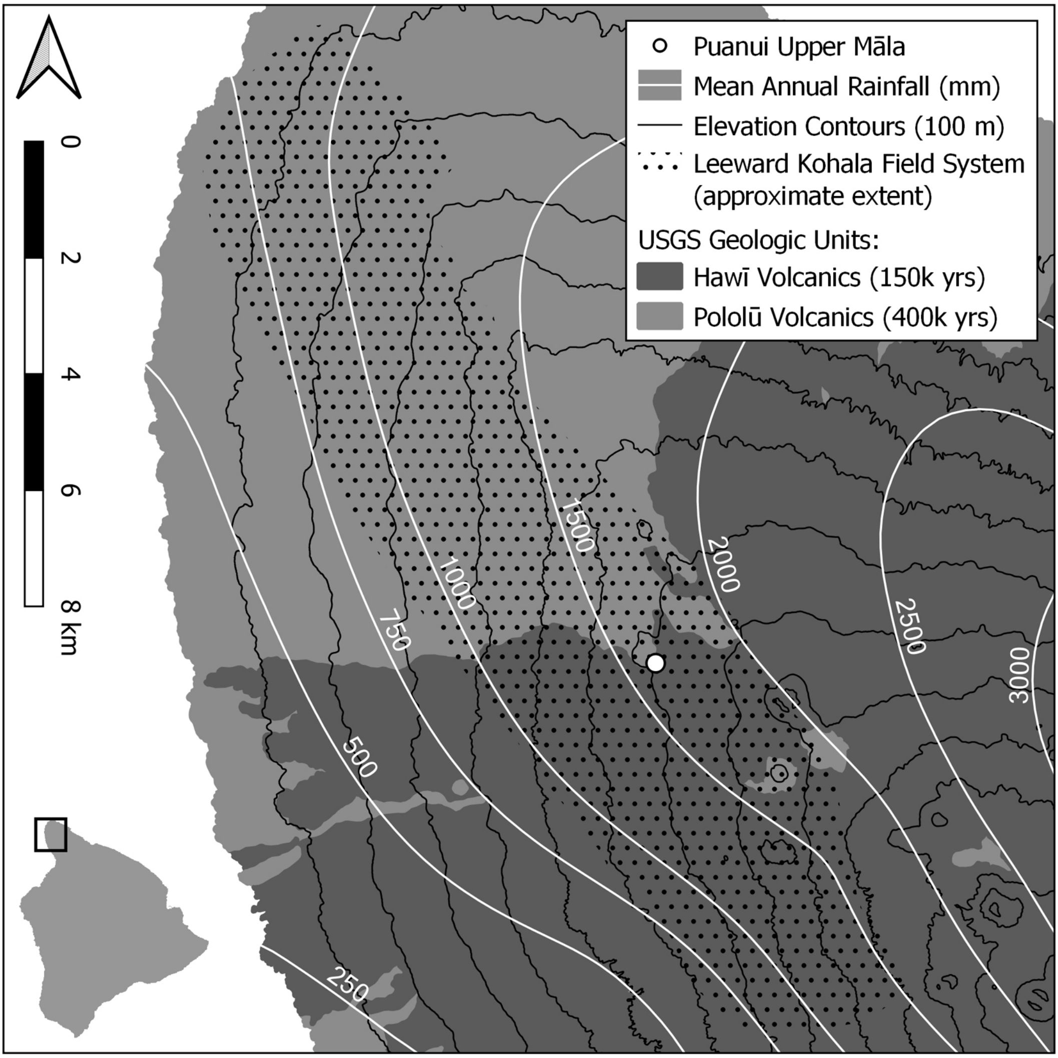

FIGURE 1. The study site on Kohala, Hawai‘i Island. Thin dark lines are elevation contours, white lines are mean annual rainfall isohyets (Giambelluca et al. 2013), and black dots demark the approximate maximal extent of the LKFS (Ladefoged et al. 2011). The dark gray shading shows ~150,000 year-old Hawī lava flows, and lighter shading shows ~400,000 year-old Pololū volcanics (Sherrod et al. 2007).

converted to precipitation rates using the horizontal catch area of the steel troughs (0.108 m^2) and the time elapsed between measurements. Some measurement periods were discarded due to precipitation collectors breaking or overflowing; only the 18 periods (representing 82 days) in which all buckets could be measured are reported in this study.

To investigate the effects of kō rows on precipitation patterns during different weather conditions, each measurement period was classified using mean wind speeds and rainfall rates recorded by the māla weather station. Winds, which were consistently northeasterly, were divided into weak (<5 mph), moderate (5–10 mph), and strong

FIGURE 2. Precipitation collectors and ʻuala plots along the transect in October 2018.

(>10 mph) periods (5 mph = 2.2 m s^{-1}). Rainfall was divided into dry (<1 mm/day), moderate (1–5 mm/day), and wet (>5 mm/day) periods. Precipitation measurement periods are summarized in Table 1.

Six total 10 cm soil samples were taken from each of the ʻuala plots, dried, and weighed at four timepoints from December 1 to 5. These six measurements are presented as means with standard errors.

Solar illuminance (lux or lumens m^{-2}) was measured at each of the ʻuala plots using photometric light sensors (MX2202, Onset Computer Corporation, Bourne, MA) from December 7 to 10. On each day, three upward-facing sensors were staked beside three ʻuala plots and another in an unobstructed area outside the transect to act as a control. After 24 hours, the three sensors on the transect were relocated to new plots until all eleven plots had been measured for one diurnal cycle. Illuminance from the ʻuala plots is reported as the mean proportion of the control illuminance for all 1-minute sampling intervals. Mean illuminance measured by the control logger varied by <10% between days.

Wind speed was measured on a day with robust northeasterly trade winds (December 9, 2018) using 5 s sampling intervals over 3-minute sampling periods for each plot. A handheld anemometer mounted on a rotating weathervane (5500L, Kestrel Instruments, Boothwyn, PA) was positioned 30 cm above the soil surface to reflect the horizontal wind speeds experienced by crops; 3 m wind speeds logged every 5 min at the māla weather station averaged 27.2 mph (12.2 m s^{-1}) over the entire 2-hour measurement period and showed little variation (standard deviation of 0.5 mph, no significant linear trend).

ʻUala Planting and Yield Measurements

ʻUala mounds were dug and planted on September 30, 2018, in 15 one-square-meter plots representing 11 distances along the transect (Figures 2 and 3*F*). The farthest upwind plot was located immediately windward of the middle kō row, and another plot was placed in a cleared spot inside the row. The farthest downwind plot was located immediately upwind of the third kō row.

TABLE 1

Number of Precipitation Measurement Periods (And Total Measurement Days) for Each Rainfall and Wind Class

	Rainfall Class			
Wind Class	Dry	Moderate	Wet	Totals
Weak trades	1 (8)	1 (11)	–	2 (19)
Moderate trades	4 (17)	2 (8)	–	6 (25)
Strong trades	4 (18)	4 (13)	2 (7)	10 (38)
Totals	9 (43)	7 (32)	2 (7)	18 (82)

Three replicate plots were planted at two distances along the transect, one under partial shade from the kō and one under open sky.

Soil in the plots was mixed thoroughly to ~30 cm and mounded before four 30–40 cm ʻuala cuttings of the Lanikeha variety were buried in the sides of the mounds (Marshall et al. 2017; Sirabis et al. 2022). ʻUala tubers were harvested and immediately weighed on May 9, 2019.

RESULTS

We observed that kō rows created pronounced microclimatic effects from the strong trade winds that blow across the LKFS. The most drastic effect was an up to 90% decrease in ground-level wind speeds for over 5 m behind each row of kō; wind speeds had still not fully recovered after 10 m (Figure 3*C*).

Shading was also significant in and around the rows, with ʻuala planted inside and just leeward of the kō stems receiving only 22–24% of unobstructed illuminance on average (Figure 3*B*). ʻUala planted immediately windward of the kō saw a 48% reduction in solar illuminance while those planted beneath the overhanging kō leaves experienced a 32% reduction. Illuminance fraction increased with increasing distance from the rows, peaking at 95% ~7.5 m leeward of one row's stalks and ~4.5 m windward of the next row's.

Mean precipitation rates varied between 1.6 and 5.8 mm/day along the transect (Figure 3*E*). In general, the kō rows created leeward rain shadows 5–6 m long, but also concentrated moisture where wind-blown droplets splashed against their windward faces (Figure 4*A*). The wettest location detected on the transect was the windward edge of the leading (most upslope) row of kō in the māla, while the windward edges of the next two rows were only 57% and 61% as wet. This result indicates wider spacing between kō rows could create greater concentrations of moisture in the narrow areas that catch splashes from the kō stalks, although precipitation rates appeared relatively stable between 3 and 4 mm/day for the 7 m ahead of the final row.

Soil moisture data suggest the rain shadow effect is large enough to affect plant growth, with the top 10 cm of soil containing only 37–50% water by mass in the rain shadow compared to 56–67% beyond it (Figure 3*D*). Soil moisture levels recovered and stabilized at approximately the same distance as precipitation rates, confirming the measured precipitation patterns.

Precipitation patterns around the kō rows were more pronounced in wetter, windier periods. This trend is evident after generalizing all measurement points to a single theoretical kō row (Figure 4): precipitation rates fell below 1 mm/day across the transect during dry periods but were slightly elevated ahead and inside of the kō during windier dry periods (Figure 4*C*). The entire transect was wetter during periods with moderate vertical rainfall, but precipitation rates were drastically higher outside of the rain shadows when trade winds were also strong (Figure 4*D*).

The wettest periods showed the most variation in precipitation rates across the kō transect (Figure 4*E*). This trend was dominated by the leading kō row, which appears (based on the soil moisture measurements) to have produced more splashed droplets that

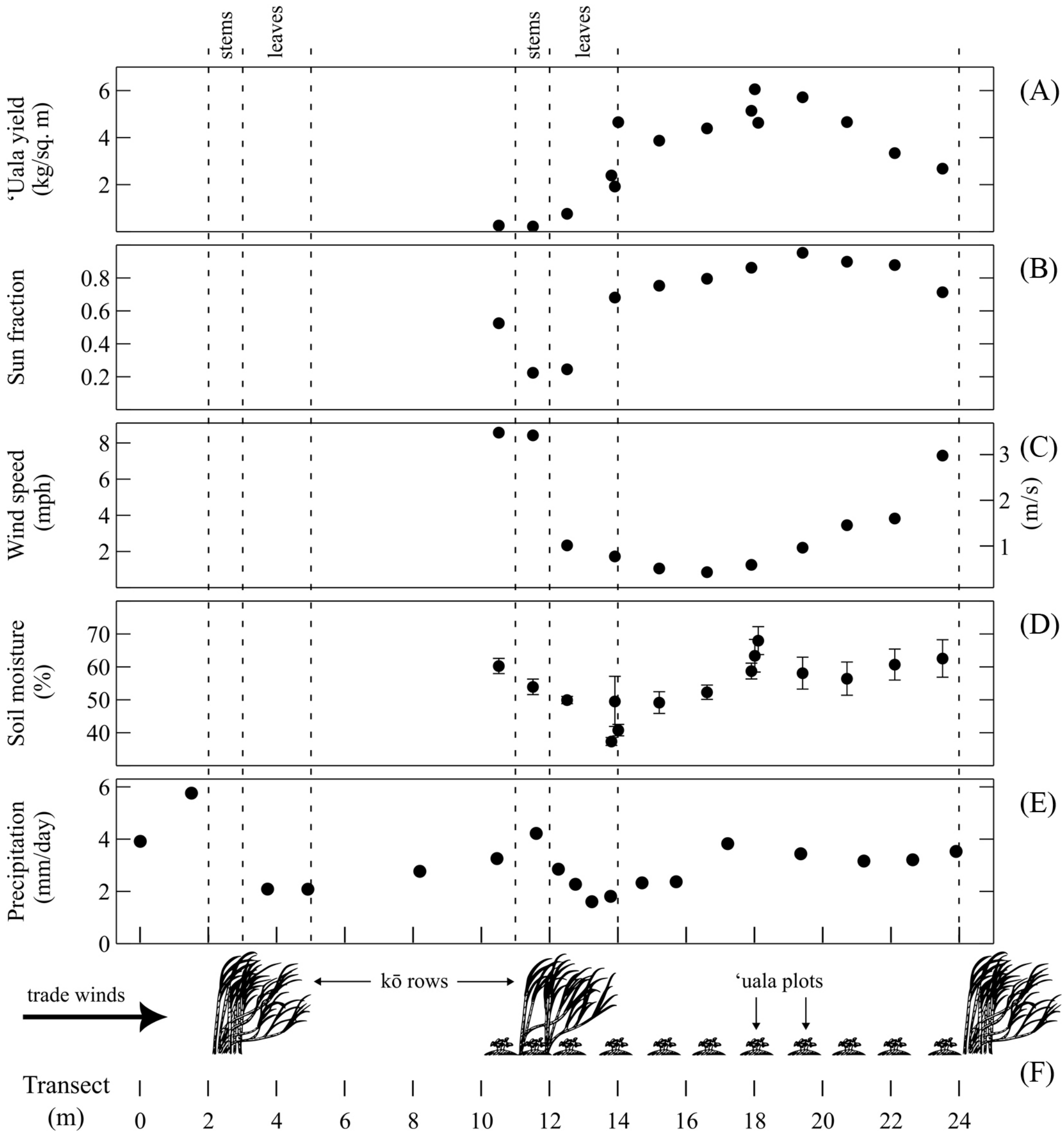

FIGURE 3. Yield and microclimate patterns across the transect: (*A*) 'uala tuber yield per m^2, (*B*) mean proportion of illuminance measured relative to an unobstructed sensor over 24 hours, (*C*) mean 30 cm horizontal wind speed over 3 minutes, (*D*) percent soil moisture by mass, with error bars representing standard errors from six 10 cm samples taken per point, and (*E*) precipitation rate. Panel (*F*) shows a cross-sectional view of the transect's kō rows and 'uala plots.

landed in collector troughs than the rows behind it.

'Uala yields ranged between 0.2 and 6.0 kg m^{-2} and peaked about midway between the kō rows (Figure 3*A*). This location corresponds to maximal sun exposure, low wind speeds, and consistent moisture availability past the rain shadow. While moisture remained high for the ~7 m upwind of the next row, increased shading and/or wind

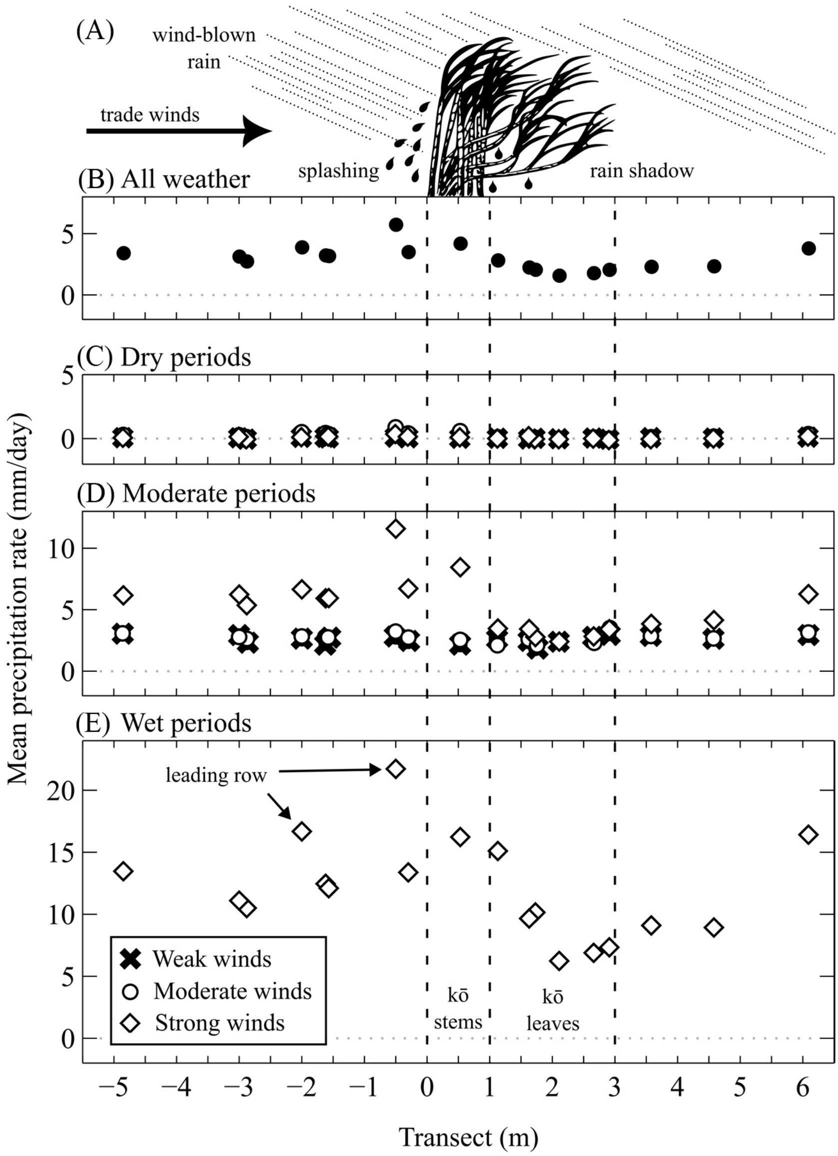

FIGURE 4. Precipitation patterns around a generalized kō row: (*A*) interactions between a kō row and wind-blown rain, (*B*) precipitation rates averaged across all measurement periods, and (*C–E*) precipitation rates averaged across dry, moderate, and wet periods and plotted separately for different wind strengths. The horizontal axis represents distance relative to the windward edge of a kō row. All vertical scales are the same.

appeared to progressively hamper ʻuala growth in this region.

ʻUala grown directly beneath the kō produced very little tuber biomass (0.2–0.7 kg m^{-2}), while mounds dug immediately upwind of the rows produced mixed results (0.2–2.7 kg m^{-2}). We encountered evidence of rodent damage to tubers during harvesting, but with no obvious pattern with respect to the kō transect.

DISCUSSION

Kō Rows as Windbreaks

Kuaiwi planted with kō are frequently regarded as windbreaks designed to shield crops from the strong winds of leeward Kohala and other arable drylands in Hawai'i (Ladefoged et al. 2003; McCoy and Hartshorn 2007; McCoy and Graves 2010; Marshall et al. 2017). Our results confirm that even thinned meter-wide kō rows without raised kuaiwi platforms can serve as extremely effective windbreaks. Wind speeds were significantly (50–90%) depressed for over 10 m behind a kō row during strong trade winds and may have continued in this fashion for even longer distances if rows were planted at wider intervals (Figure 3*C*).

The abrupt shift to higher precipitation rates and soil moisture levels 5–7 m leeward of the kō stems (the approximate end of the rain shadow) could reflect enhanced moisture deposition by turbulent airflow in the windbreak's wake (Ladefoged et al. 2003). Porous windbreaks such as row crops produce "quiet zones" in their lees throughout which levels of turbulence and wind are relatively low and isolated from the air flowing above the windbreaks (McNaughton 1988). At the end of this quiet zone, larger turbulent flows that were diverted by the windbreak reach the ground.

Experiments on porous, regularly spaced windbreaks have measured the lengths of these quiet zones as ~1.8 times the height of the windbreaks (Judd et al. 1996; Cleugh 1998). Applying this approximation to Puanui, a 3 m tall kō row would produce a quiet zone extending ~5.4 m leeward of the row. This rough estimate corresponds to the distance at which precipitation rates and soil moisture both increased and stabilized until the next windbreak (Figures 3*E* and 4*E*). While horizontal wind speeds remained relatively low at this transect distance, turbulence was not measured by the anemometer and can only be inferred from the moisture data.

As this study examined kō rows without prominent kuaiwi features, the combined aerodynamic effects of a porous kō row atop a nonporous earthen mound remain unclear. The size of the quiet zone would probably be increased as a consequence of the greater windbreak height, but the effects of added turbulence from the kuaiwi require additional study (Cleugh 1998).

Local Redistribution of Moisture by Kō Rows

Many have theorized that kuaiwi and kō rows redistribute wind-blown rains and capture mist (Handy et al. 1972; Ladefoged and Graves 2011; Lincoln and Vitousek 2017; Lincoln et al. 2017; Marshall et al. 2017). We found strong evidence for the former, with precipitation rates peaking immediately windward of the kō and dropping substantially for 5–6 m in its wake (Figure 4*B*).

We interpret the 5–6 m dry area as a rain shadow that corresponds to the aforementioned quiet zone (McNaughton 1988). Some of the precipitation that would otherwise arrive in this rain shadow ends up inside of the kō row and much of it is splashed off the row's windward face, perhaps up to 2 m away when the winds are strong (Figure 4).

The rows accumulated moisture on their windward sides even during dry periods, provided winds were sufficiently strong (Figure 4*C*). Strong trade winds produced similar distributions of precipitation in both moderately rainy and very wet periods, although the distributions were scaled to different magnitudes (Figure 4*D*,*E*). Windward splashing was especially prevalent on the leading kō row (Figure 3*E*) where winds blew unobstructed over a long distance, suggesting the proportion of water splashing off each row may increase with lower row density. With a longer run-up before encountering a kō row, trade winds would probably attain greater speeds, lower turbulence, and greater amounts of wind-blown rain, culminating in more pronounced splashing effects.

Landscape-Scale Hydrologic Effects

In addition to the clear microclimatic effects summarized in Figure 3, the immense size of the LKFS suggests that kuaiwi construction and kō row planting could have produced landscape-scale hydrologic effects. These effects cannot be examined in depth with our dataset, but we review some possible mechanisms and unknown factors below.

Ladefoged et al. (2003) hypothesized that the added surface roughness of kuaiwi would reduce evaporation by slowing the flow of air over land and vegetation surfaces. We found that wind speeds were indeed depressed over a large distance behind the kō rows, indicating this mechanism of evaporation reduction is plausible in the LKFS.

However, the actual evaporative dynamics of crops and soil behind a porous windbreak are complex and depend on a variety of environmental and physiological factors. Windbreaks have been demonstrated to increase evaporation in some cases, particularly when water is not abundant (Cleugh 1998). Thus it is difficult to predict whether windbreaks in the LKFS generally decrease or increase evaporation rates, especially given the wide range of climates (1,000–1,900 mm/yr of rainfall) spanned by the kuaiwi there (Marshall et al. 2017).

Lincoln et al. (2017) observed that kō rows in Puanui intercepted ground-level clouds that may otherwise have failed to accumulate on the land surface, noting that the long kō leaves deposited much of this moisture as droplets in the immediate lee of the kuaiwi. Rather than a simple redistribution of moisture around the windbreak, this form of cloud interception represents a net input of water into the terrestrial system that would not have occurred in the absence of the plant canopy—a process that has been found hydrologically relevant elsewhere on leeward Kohala (Burnett 2020) and throughout the Hawaiian Islands (DeLay and Giambelluca 2010; Tseng 2021).

We were unable to detect cloud interception in our dataset due to the coarse temporal resolution employed—without directly sampling a cloud event during which no rain fell, our precipitation trends were dominated by wind-blown rains. The only two measurement periods during which the rain gauge recorded no rainfall failed to produce any detectable precipitation in our collectors. In plant canopies with many small-diameter stems, high proportions of intercepted cloud water may also travel to the ground via stemflow (Takahashi et al. 2011), which was not measured in this study.

Several other relevant aspects of this system's plant water dynamics remain unknown: for instance, kō's large stature and dense foliage may provide so much aboveground water storage capacity that interception losses (precipitation evaporated from vegetation surfaces before it can reach the ground) are increased relative to shorter crops or the pasture grasses that today dominate the LKFS. The water lost to transpiration from the large kō leaves would also need to be considered in order to estimate the cumulative hydrologic impacts of kō rows.

Lessons for Kō and ʻUala Cultivation in Leeward Kohala

The microclimate and ʻuala yield data from this experiment can help inform future agricultural activities within the LKFS and elsewhere in Hawaiʻi.

Perhaps our most important finding is a clear pattern of tuber production between the kō rows (Figure 3*B*): yields were largest just beyond the rain shadow where sunlight was maximized, winds remained relatively calm, and the nonturbulent quiet zone gave way to a region of increased moisture deposition. ʻUala planted here also featured more aboveground biomass and faster leaf growth rates compared to plots closer to the kō.

In this māla (with kuaiwi about 8–12 m apart), planting the ʻuala at least 3 m away from the kō stalks produced the best outcomes. Areas with differently spaced kuaiwi would probably feature different optimal zones for ʻuala cultivation. The yields in this transect's optimum zone (3.8–6.0 kg m^{-2}) compared favorably to those reported by Kagawa and Vitousek (2012) (1.8–4.0 kg m^{-2}) and Marshall et al. (2017) (0.4–1.6 kg m^{-2}) even without the use of rock or litter mulches that have proven highly effective at Puanui (Sirabis et al. 2022). The high yields we achieved can probably be attributed to higher-than-average rainfall during the growth period.

Generalizing the results of this study across the LKFS and beyond will require careful consideration of local growing contexts. The māla studied here stands in a relatively wet portion of the ancient field system, and environmental conditions differ greatly even a hundred meters down the slope. The wet winter of 2018–2019 meant that our ʻuala were probably limited less by water than by sunlight, which would explain the coincidence of high yields with high illuminance, but water certainly limits growth at other times in this system.

This study's lack of replication across time or space must also be noted when interpreting its results: most variables were measured in a single growing season across a single inter-row space, and replication at specific transect points was minimal if present at all. While the patterns visible in the microclimate and yield data appear relatively unnoisy, other transects may produce different patterns due to variables for which this study does not account (e.g. slope, kō thickness, kō height, row spacing).

Low wind speeds may have determined the location of the most productive ʻuala along this transect, as yields began to decline at points where illuminance and moisture levels remained high (20–22 m; Figure 3). Wind speeds at these points were still depressed relative to the front of the windbreak but were steadily climbing. Wind could have caused mechanical damage to ʻuala leaves, especially if airflows became more turbulent beyond the quiet zone (Cleugh 1998).

The climatic factors explored here (wind, water, and sunlight) and their relationships to Puanui's windbreaks can all be reevaluated and reprioritized for future plantings. For instance, ʻuala planted lower in the LKFS will probably be limited by water and may benefit from partial shading as well as wind mitigation. Planting the ʻuala along the windward edge of kuaiwi may result in critical water gains in locations where trade wind-driven rains reach far enough down the slope.

Alternatively, ʻuala at lower elevations could be planted downwind of kuaiwi during wet winters to take advantage of windbreak and shade effects while relying on southwesterly Kona rainstorms for moisture (Kagawa and Vitousek 2012). If wind abatement is desired but rain shadows prove problematic for ʻuala, creating gaps in kō rows or adding more space between rows could help mitigate moisture deficits between rows. The optimal balances of these microclimatic effects for a given time and location can only be determined by trial, error, and careful observation.

The environment of the LKFS has changed immensely over the past two centuries: the landscape is today dominated by exotic pasture grasses, and the rich fields that were once home to thousands of people are roamed mostly by exotic ungulates. Some evidence suggests this leeward area may have been wetter when it was built during the Little Ice Age (1400–1850 A.D.) than it is today (Pau et al. 2012; Diaz et al. 2016), and model simulations suggest the region may become rainier, hotter, and more humid in the future (Xue et al. 2020), though there can be little certainty in predicting a climate as dynamic as Kohala's. This ever-changing environment will require navigation by innovative land stewards who can combine local, traditional, and scientific knowledge to manage productive landscapes.

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Literature Cited

Burnett, M. W. 2020. Cloud water interception by a montane tropical forest in Leeward Kohala, Hawai'i (MS). Stanford University, Stanford, CA.

Cleugh, H. A. 1998. Effects of windbreaks on airflow, microclimates and crop yields. Agrofor. Syst. 41:55–84.

DeLay, J. K., and T. W. Giambelluca. 2010. History of fog and cloud water interception research in Hawai'i. Pages 332–341 *in* L. A. Bruijnzeel, F. N. Scatena, and L. S. Hamilton, eds. Tropical montane cloud forests: Science for conservation and management. Cambridge University Press, Cambridge, UK.

Diaz, H. F., E. R. Wahl, E. Zorita, T. W. Giambelluca, and J. K. Eischeid. 2016. A five-century reconstruction of Hawaiian Islands winter rainfall. J. Clim. 29(15): 5661–5674.

Dye, T. S. 2011. The tempo of change in the Leeward Kohala Field System, Hawai'i Island. Rapa Nui J. 25(2):21–30.

———. 2014. Wealth in old Hawai'i: good-year economics and the rise of pristine states. Archaeol. Oceania 49(2):59–72.

Giambelluca, T. W., Q. Chen, A. G. Frazier, J. P. Price, Y.-L. Chen, P.-S. Chu, J. K. Eischeid, and D. M. Delparte. 2013. Online rainfall atlas of Hawai'i. Bull. Am. Meteorol. Soc. 94(3):313–316.

Handy, E. S. C., E. G. Handy, and M. K. Pukui. 1972. Native planters in old Hawaii: Their life, lore, and environment. Bishop Museum Bulletin. Bishop Museum Press, Honolulu, HI.

Judd, M. J., M. R. Raupach, and J. J. Finnigan. 1996. A wind tunnel study of turbulent flow around single and multiple windbreaks, Part I: Velocity fields. Bound.-Layer Meteorol. 80:127–165.

Kagawa, A. K., and P. M. Vitousek. 2012. The Ahupua'a of Puanui: a resource for understanding Hawaiian rain-fed agriculture. Pac. Sci. 66(2):161–172.

Kirch, P. V. 2010. How chiefs became kings: Divine kingship and the rise of archaic states in ancient Hawai'i. University of California Press, Berkeley, CA.

Ladefoged, T. N., and M. W. Graves. 2006. The formation of Hawaiian territories. Pages 259–283 *in* I. Lilley, ed. Archaeology of Oceania: Australia and the Pacific Islands. Blackwell Publishing, Malden, MA.

———. 2008. Variable development of dryland agriculture in Hawai'i: a fine-grained chronology from the Kohala field system, Hawai'i Island. Curr. Anthropol. 49(5): 771–802.

———. 2011. The Leeward Kohala Field System. Pages 89–110 *in* P. V. Kirch, ed. Roots of conflict: Soils, agriculture, and sociopolitical complexity in ancient Hawai'i. School for Advanced Research Press, Santa Fe, NM.

Ladefoged, T. N., M. W. Graves, and R. P. Jennings. 1996. Dryland agricultural expansion and intensification in Kohala, Hawai'i Island. Antiquity 70(270):861–880.

Ladefoged, T. N., M. W. Graves, and M. D. McCoy. 2003. Archaeological evidence for agricultural development in Kohala, Island of Hawai'i. J. Archaeol. Sci. 30(7):923–940.

Ladefoged, T. N., P. V. Kirch, S. M. Gon, O. A. Chadwick, A. S. Hartshorn, and P. M. Vitousek. 2009. Opportunities and constraints for intensive agriculture in the Hawaiian archipelago prior to European contact. J. Archaeol. Sci. 36(10):2374–2383.

Ladefoged, T. N., M. D. McCoy, G. P. Asner, P. V. Kirch, C. O. Puleston, O. A. Chadwick, and P. M. Vitousek. 2011. Agricultural potential and actualized development in Hawai'i: an airborne LiDAR survey of the Leeward Kohala Field System (Hawai'i Island). J. Archaeol. Sci. 38(12): 3605–3619.

Lincoln, N. K., and P. Vitousek. 2016. Nitrogen fixation during decomposition of sugarcane (*Saccharum officinarum*) is an important contribution to nutrient supply in traditional dryland agricultural systems of Hawai'i. Int. J. Agric. Sustain. 14(2): 214–230.

———. 2017. Indigenous Polynesian agriculture in Hawai'i. Oxford research encyclopedia of environmental science. Oxford University Press, Oxford, UK.

Lincoln, N. K., A. Kagawa-Viviani, K. Marshall, and P. M. Vitousek. 2017. Observations of sugarcane and knowledge specificity in traditional Hawaiian cropping systems. Pages 273–282 *in* R. Murphy, ed. Sugarcane: Production systems, uses and economic importance. Nova Science Publishers, Hauppauge, NY.

Marshall, K., C. Koseff, A. L. Roberts, A. Lindsey, A. K. Kagawa-Viviani, N. K. Lincoln, and P. M. Vitousek. 2017. Restoring people and productivity to Puanui: challenges and opportunities in the restoration of an intensive rain-fed Hawaiian field system. Ecol. Soc. 22(2):23.

McCoy, M. D., and M. W. Graves. 2010. The role of agricultural innovation on Pacific Islands: a case study from Hawai'i Island. World Archaeol. 42(1):90–107.

McCoy, M. D., and A. S. Hartshorn. 2007. Wind erosion and intensive prehistoric agriculture: a case study from the Kalaupapa field system, Moloka'i Island, Hawai'i. Geoarchaeology 22(5):511–532.

McNaughton, K. G. 1988. Effects of windbreaks on turbulent transport and microclimate. Agric. Ecosyst. Environ. 22/23: 17–39.

Pau, S., G. M. MacDonald, and T. W. Gillespie. 2012. A dynamic history of climate change and human impact on the environment from Keālia Pond, Maui, Hawaiian Islands. Ann. Assoc. Am. Geogr. 102(4):748–762.

Pollock, M. D., G. O'Donnell, P. Quinn, M. Dutton, A. Black, M. E. Wilkinson, M. Colli, M. Stagnaro, L. G. Lanza, E. Lewis, C. G. Kilsby, and P. E. O'Connell. 2018. Quantifying and mitigating wind-induced undercatch in rainfall measurements. Water Resour. Res. 54(6):3863–3875.

Sherrod, D. R., J. M. Sinton, S. E. Watkins, and K. M. Brunt. 2007. Geologic map of the State of Hawai'i. USGS Open File Report 2007–1089. US Geological Survey, Reston, VA.

Sirabis, W., M. Kantar, T. Radovich, and N. Lincoln. 2022. Nitrogen dynamics and sweet potato production under indigenous soil moisture conservation practices in the Leeward Kohala Field System, Hawai'i Island. Soil Syst. 6:16.

Swanson, D. 2019. A new estimate of the Hawaiian population for 1778, the year of first European contact. Hūlili 11(2): 203–222.

Takahashi, M., T. W. Giambelluca, R. G. Mudd, J. K. DeLay, M. A. Nullet, and G. P. Asner. 2011. Rainfall partitioning and cloud water interception in native forest and invaded forest in Hawai'i Volcanoes National Park. Hydrol. Process. 25(3): 448–464.

Tseng, H. 2021. Cloud Water Interception in Hawai'i (PhD). University of Hawai'i at Mānoa, Honolulu, HI.

Vitousek, P. M., and O. A. Chadwick. 2013. Pedogenic thresholds and soil process domains in basalt-derived soils. Ecosystems 16(8):1379–1395.

Vitousek, P. M., O. A. Chadwick, S. C. Hotchkiss, T. N. Ladefoged, and C. M. Stevenson. 2014. Farming the rock: a biogeochemical perspective on intensive agriculture in Polynesia. J. Pac. Archaeol. 5 (2):51–61.

Xue, L., Y. Wang, A. J. Newman, K. Ikeda, R. M. Rasmussen, T. W. Giambelluca, R. J. Longman, et al. 2020. How will rainfall change over Hawai'i in the future? High-resolution regional climate simulation of the Hawaiian Islands. Bull. Atmos. Sci. Tech. 1:459–490.