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Agricultural potential and actualized development in Hawai'i: an airborne LiDAR survey of the leeward Kohala field system (Hawai'i Island)

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A B S T R A C T

Archaeological investigations of Hawaiian agriculture have relied on relatively coarse-grained data to investigate archipelago-wide processes, or on fine-grained data to examine patterning within localized zones of agricultural production. These trade-offs between spatial coverage and data resolution have inhibited understanding of both spatial patterns and temporal trends. Our analysis of 173 km^2 of high-resolution airborne Light Detection and Ranging (LiDAR) data for leeward Kohala, Hawai'i Island identifies spatial and temporal patterning in regional agricultural development. Differential densities of alignments suggest variable levels of agricultural intensity. Agricultural processes of expansion, segmentation, and intensification can also be discriminated, with distinct zones of the field system having undergone different mixes of development. Areas within the field system with moderate to high levels of both average production and variability in production (determined using a climate-driven productivity model) were utilized relatively early in a highly intensified manner; these areas often underwent processes of segmentation and intensification. Less productive areas were developed later and exhibit evidence of expansion with lower amounts of segmentation and intensification, at set levels of intensity. The spatial and temporal variability in agricultural activities was influenced by the diverse environmental conditions across the landscape as well as variation in cultivars and cultivation techniques. Combining the high-resolution LiDAR data from a large area with potential productivity modeling allows for a more fine-grained understanding of agricultural development in this region of the Hawaiian archipelago.

The trajectory of socio-political evolution in pre-contact Hawai'i was influenced by spatial and temporal variability in agricultural productivity. Researchers investigating the linkages between agriculture and socio-political evolution have focused their work on this topic at a variety of scales, from inter-island archipelago-wide analyses, to regional studies, to observations in small localized landscapes. While research at each of these scales provides insight, there are trade-offs between relatively coarse data from large areas and more precise data from smaller regions.

At the archipelago scale, broad distinctions have been made between the irrigation-dominated agro-ecosystems characteristic of the older Hawaiian Islands, and rain-fed or dry-land intensive field systems covering large tracts on the leeward sides of the younger islands (Kirch, 1985, 1994, 2011; Ladefoged et al., 2009; Vitousek et al., 2004). Recent Geographic Information System (GIS)-based modeling has identified the areas suitable for intensified irrigated and rain-fed production in windward and leeward zones (Ladefoged et al., 2009, 2011). The limitations of agricultural intensification in each of these areas have been noted, with leeward production reaching the inflection point on the intensification

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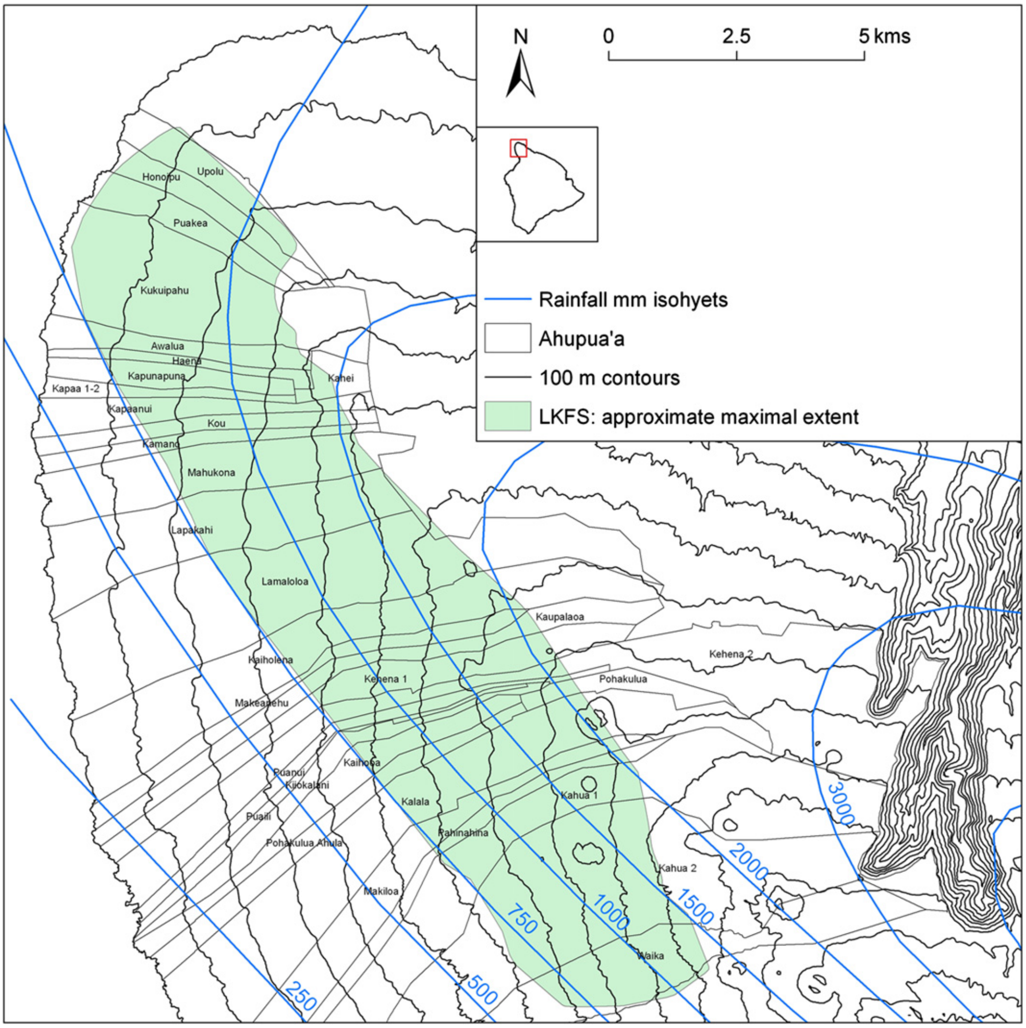

Fig. 1. The maximal distribution of the LKFS with rainfall isohyets, 100 m contours, and ahupua'a boundaries. (For interpretation of the references to color in this figure legend, the reader is referred to the online version of this article.)

curve earlier than production in windward zones (Kirch, 1994, 2010). In some instances this differential may have prompted leeward populations to consider alternative strategies for controlling resources, including conquest warfare (Kirch, 2010). In a more spatially constrained analysis, Graves et al. (2011) considered inter-island variation in productive zones on Maui and Hawai'i Island, and incorporated analyses of recorded oral traditions and genealogies to track temporal trends in island-wide political integration and warfare associated with smaller independent polities. Graves et al. (2011) were able to assess changes in the political systems, but could only relate these to non-temporal measures of potential agricultural productivity. Indeed, this is a characteristic of all archipelago-scale studies, which have been successful in documenting socio-political transformations and assessing gross spatial variation in zones of production, but unable to estimate temporal change in agricultural production over large areas.

At the other end of the spatial scale, many studies have documented changing levels of agricultural productivity within confined study areas. For example, Spriggs and Kirch (1992) used a combination of ethnohistorical records, archaeological survey and excavation data to model production and surplus in the late pre-contact to early post-contact irrigation systems of the Anahulu Valley, O'ahu. Additionally, McElroy (2007) estimated temporal trends in irrigated agriculture in a 105 ha study area of Wailau Valley (Moloka'i); Allen (1987, 1992) has investigated temporal developments of irrigation systems in ca. 31 ha of Kāne'ohe *ahupua'a* (O'ahu); researchers in leeward Kohala documented temporal trends in dryland production in ca. 88 ha (McCoy, 2000; Ladefoged et al., 2003) and ca. 19 ha (Field et al., 2011) of the rain-fed field system; and McCoy and Graves (2010) noted temporal trends in the development of tableland irrigation in the small Waiapuka gulch in windward Kohala. These and other studies utilized fine-grained mapping and excavation of archaeological features in limited areas to discern relatively precise temporal changes in production. The authors often extrapolated their results to larger regions to consider the implications of changing production levels, but data were usually confined to a relatively small spatial area.

Bridging the divide between localized studies and the generalized archipelago analyses are a number of studies that have attempted to monitor temporal and spatial patterning in production over regional areas. A recent LiDAR analysis has quantified the development of productive areas in windward Kohala (McCoy et al., 2011a). Other studies have focused on zones of rain-fed production (e.g. McCoy (2005, 2006), McCoy and Hartshorn (2007) in Kalaupapa (Moloka'i); Kirch and colleagues (Coil and Kirch, 2005; Kirch et al., 2005; Kirch, 2010) in Kahikinui (Maui); Reith and Morrison (2010) and the earlier work of Clark and colleagues (Clark, 1987; Clark and Kirch, 1983) in Waimea (Hawai'i Island); and Ladefoged and Graves (2000, 2008) and colleagues in leeward Kohala). In these studies, radiocarbon and to a limited extent Thorium 230 dating, along with the seriation of architectural features, have been used to be construct chronologies of production change. While data from these relatively large areas have been informative, they do not provide sufficient detail to firmly establish regional spatial and temporal trends.

In this paper we address the problem of scale by using high-resolution airborne Light Detection and Ranging (LiDAR) data processed through a GIS model to assess the palimpsest left behind by centuries of farming over large areas of leeward Kohala. Previous studies in leeward Kohala have been conducted with limited detail at a regional scale (air photo, historic maps, predictive model), or with substantial detail at a micro-scale (field GPS survey data), but have been unable to combine detail with broad geographic range in the way that ariborne LiDAR survey provides. We integrate the results of the LiDAR analysis with a new productivity model for the area to interpret spatial and temporal trends in the development of regional agricultural production.

1. Agricultural practices in leeward Kohala

Archaeological evidence of traditional Hawaiian agriculture is visible over ca. 63 km^2 of the leeward side of the Kohala peninsula (Fig. 1). Within much of this area, archaeological features deriving from agricultural, residential, and ritual activities are distributed continuously across the landscape. However, in the northern zone the archaeological landscape has been highly disturbed by historic land-use activities (principally plantation cultivation of sugarcane and pineapple, mainly between AD 1860 and 1970) leaving behind discontinuous patches of well-preserved features. Furthermore, in the far southern zone of Kahua 2 and Waika *ahupua'a*, the archaeological features were originally constructed in a more discontinuous manner, with large areas lacking infrastructural improvements. In these relatively vacant areas there are few signs of historic disturbance, indicating that the discontinuous nature of the field system in this far southern area is not the result of post-depositional processes.

Within the leeward Kohala field system (LKFS), a range of agricultural features have been identified (see Ladefoged and Graves, 2008 for a review). They primarily consist of linear agricultural alignments (often referred to as "walls" in previous publications) orientated perpendicular to the slope and the predominant NE tradewinds. These linear features served a number of functions, including decreasing wind velocity and acting as windbreaks for protecting cultigens (see Ladefoged et al., 2003). Current grass cover suggests that the alignments also had a micro-orographic effect, with the upwind side (within 2–3 m of the centerline of the alignment) intercepting more precipitation than the downwind side. This effect was probably enhanced by planting sugarcane (*Saccharum officinarum*) on the alignments, a practice noted in the ethnohistoric literature (Menzies, 1920) and recently tested in LKFS experimental gardens (Vitousek n.d.).

The construction style of alignments in the LKFS varies according to the amount of soil development and availability of surface rock. In the higher rainfall zones where soils are thicker and contain fewer rocks the alignments are predominantly earthen embankments ranging in width from 1 to 2 m, and in height from 20 cm to as much as 90 cm. In the drier rockier zones the alignments are constructed as stacked stone walls ranging in height from 20 to 75 cm. In both areas alignment length ranges from ca. 10 m to upwards of 450 m. A series of trails dissect the agricultural alignments and extend parallel to the slope of the terrain. These trails are often curb-lined with rocks and include sections of causeways and cleared areas. Some of the larger trails are associated with the boundaries of traditional community territories (*ahupua'a*) recorded in the mid-nineteenth century (see Ladefoged and Graves, 2007). The orthogonal intersection of the trails and agricultural alignments form rectangular plots that were intensively cultivated with sweet potato (*Ipomoea batatas*) and dryland taro (*Colocasia esculenta*), with secondary crops of yam (*Dioscorea* spp.) and paper mulberry (*Broussonetia papyrifera*) for barkcloth. Additional

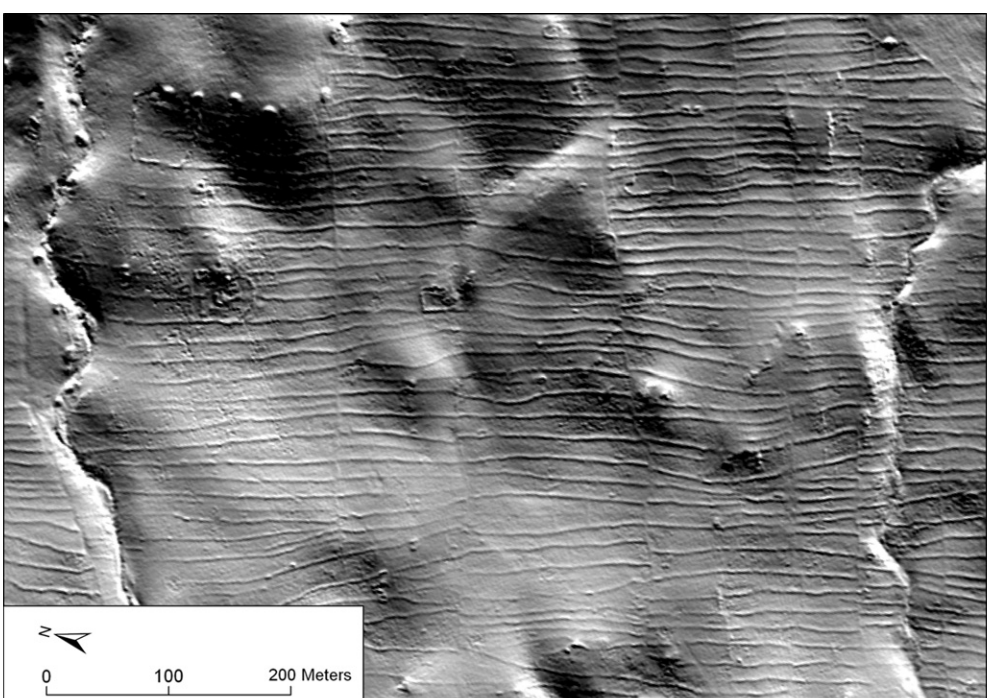

Fig. 2. Hillshading of a portion of the LiDAR data.

plantings of sugarcane (*S. officinarum*) and other cultigens occurred on the alignments.

The spatial distribution and density of the agricultural alignments in the LKFS is the result of a number of critical environmental variables and their parameters (see Ladefoged and Graves, 2000; Vitousek et al., 2004; Ladefoged et al., 2009). The construction of the agricultural alignments was a response to the nearly constant and sometimes extremely strong tradewinds that blow down the slope of the Kohala ridge, today averaging over 30 km/h at a height of 9 m above the ground surface at Kahua Ranch (Ladefoged et al., 2003: 927). The downslope edge of the LKFS is defined by rainfall, with a sharp boundary of the field system matching the current 750 mm annual isohyet. The relationship between the isohyets and the distribution of archaeological remains likely results from the relationship between crop production and seasonal rainfall levels, which is more important for crop production than is total annual rainfall. Several studies of the LKFS have established the relationship between soil nutrients and the age of the geologic substrate, temperature, and rainfall (Chadwick and Chorover, 2001; Chadwick et al., 2003, 2007; Vitousek et al., 2004; Vitousek, 2004). These studies suggest that the older a geologic substrate, the less rainfall can be sustained before nutrients are leached below critical levels necessary for supporting intensive agriculture. In the LKFS, the upper rainfall limit is approximately 1750 mm on the ~400,000-year-old Pololu geologic substrate and 2000 mm on the younger ~150,000-year-old Hawi geologic substrate.

Agricultural development within the LKFS involved several processes. It is likely that during a pioneering phase of development the area was farmed using a slash and burn fallowing regime with little infrastructural improvement (see Yen, 1973). At some stage, perhaps as early as the fifteenth century in the northern portions of the field system, and as late as the sixteenth or seventeenth centuries in the southern section, earthen and rock agricultural alignments and trails began to be constructed (Ladefoged and Graves, 2008). The initial gridwork of agricultural plots resulting from this process represents what we term **expansion** of initial infrastructural improvements and agricultural development. If the construction of infrastructural improvements took place in areas that had never been previously incorporated in a slash and burn fallowing regime, then this would have been expansion in the strictest sense of the word. However, if the first construction and expansion of agricultural alignments did take place in areas that were already under a less intensive cultivation regime, this would have been an early form of intensification through the addition of permanent infrastructure. For this study, we do not distinguish between expansion in the strict sense and expansion as a form of intensification since this issue is one better resolved through a combination of careful excavations and paleoethnobotany.

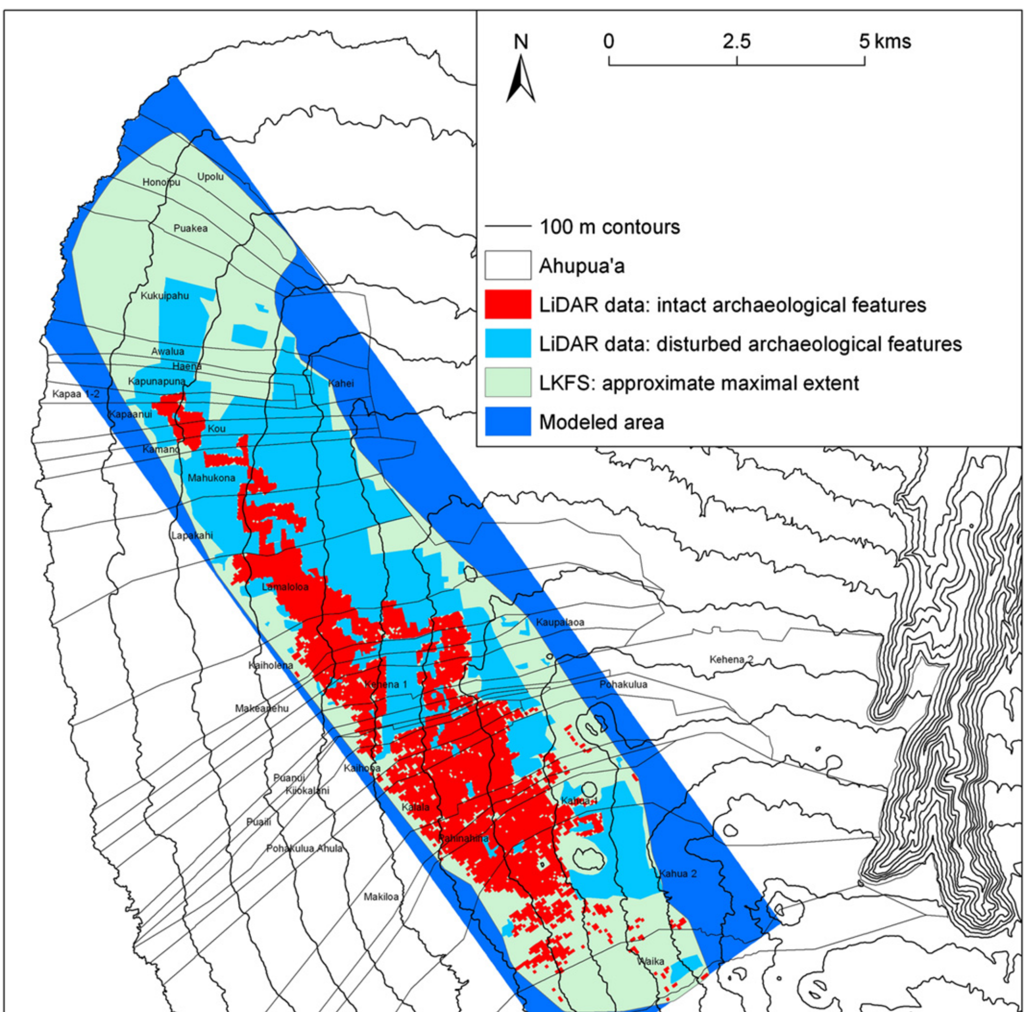

Fig. 3. The distribution of different categories of LiDAR data and the area of the NPP model. (For interpretation of the references to color in this figure legend, the reader is referred to the online version of this article.)

A second phase in the process of agricultural development involved the **segmentation** of an already existing set of field plots through the construction of new trails that intersected the existing agricultural alignments. During segmentation, alignments extending between trails are intersected by additional trails. In this case it is impossible to determine the absolute length of time between the construction of the first alignments and the intersecting trails, but in relative time the alignments were constructed prior to the trail which later intersected them. Whether such segmentation enhanced production, and therefore represents agricultural intensification in the usual sense of increased yields per unit area with increased labor inputs, is uncertain. It is possible that segmentation of plots was primarily the outcome of social processes of family bifurcation or of subdivision of chiefly controlled territories (see Field et al., 2011). Minimally, the additional labor of trail construction expended within a set area of land probably increased agricultural productivity by lowering transport costs and/or increasing managerial efficiency.

We use the term **infrastructural intensification** (or just **intensification**) to refer to the process whereby additional agricultural alignments were constructed in an area already defined by a gridwork of alignments and trails. This process would have significantly increased production per unit of land by concentrating moisture levels along alignments and by providing cultivars with physical protection from the wind. These three processes of agricultural development (expansion, segmentation, and intensification) are distinct from measures of **agricultural intensity** (see Leach, 1999; see Kirch and Zimmerer, 2011). The intensity of agricultural features in an area can be quantified by the density of alignments or the spacing between alignments. The level of agricultural intensity at any one point in time does not directly track temporal processes of development. For example, if we find that two sections of the field system have identical densities of plots, this measure alone will not tell us how this level of intensity was reached. It may be that it came from a shared history of expansion, segmentation, and intensification; or the same intensity of farming could have been reached by different, independent trajectories.

The temporal development of specific portions of the LKFS has been studied previously. Rosendahl's (1972, 1994) initial work relied on fine-grained plane table and alidade mapping of a restricted area of 65 ha within upper Lapakahi *ahupua'a*. Rosendahl (1972) suggested that the spatial relationship between agricultural alignments and trails was an indication of temporal developments, while Kirch (1984) used Rosendahl's maps to demonstrate three relative phases of field system development in a limited survey area within Lapakahi. Ladefoged et al. (1996) analyzed the extant portions of the entire field system (ca. 63 km^2 coverage) using a map created from aerial photographs

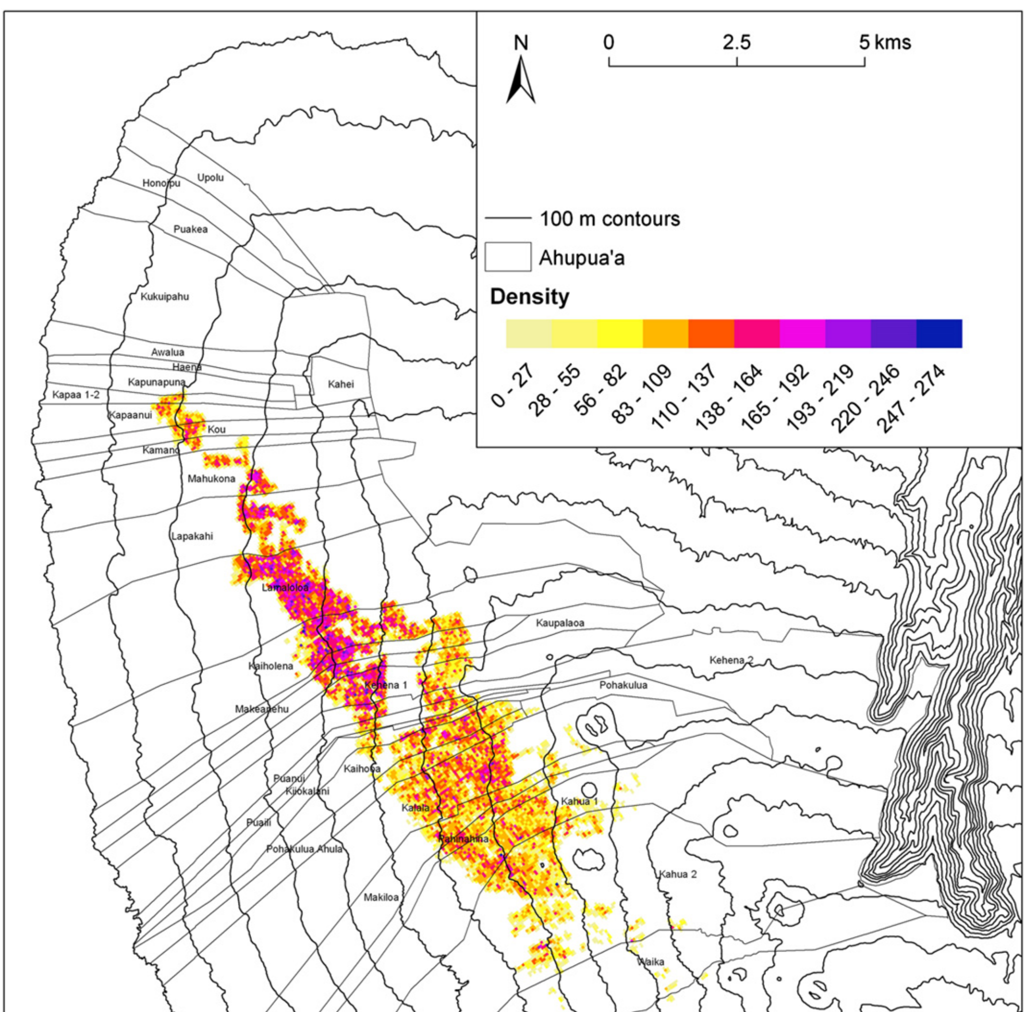

Fig. 4. The density of agricultural alignments per 0.25 ha. (For interpretation of the references to color in this figure legend, the reader is referred to the online version of this article.)

(Tomonari-Tuggle n.d.). They established spatial variability in the level of agricultural intensity by measuring the density of agricultural alignments. Using the same data set, Ladefoged and Graves (2000) employed agricultural alignment length as a proxy for the spatial relationship between alignments and trails, and proposed three phases of agricultural development throughout the entire leeward zone. However, this work was hindered by the relatively poor accuracy of the aerial photo derived map. In response, McCoy (2000) and Ladefoged et al. (2003) analyzed fine-grained GPS survey data from three sample areas covering a total of ca. 88 ha in the central and southern portion of the LKFS. Their temporal assignments were based on the assumptions that agricultural alignments abutting trails were constructed at the same time or later than that trail, and alignments intersected by trails were constructed earlier than the trail. These assumptions have since been supported by radiocarbon dates (Ladefoged and Graves, 2008) and by measures of soil nutrient depletion associated with the construction of agricultural alignments over a ca. 150 year period (Meyer et al., 2007). While providing a fine-grained temporal analysis of processes of agricultural expansion and intensification, the studies of McCoy (2000) and Ladefoged et al. (2003) were restricted in spatial extent, sampling a mere 1.3% of the 63 km^2 field system.

2. LiDAR analysis

Airborne LiDAR has proven its utility in documenting complex palimpsest landscapes in Egypt (Rowlands and Sarris, 2007), Cambodia (Angor) (Evans, 2010), Italy (Lasaponara et al., 2010), Belize (Mayan) (Chase et al., 2011), Slovenia (Kokalj et al., 2011), and most recently, windward Kohala (McCoy et al., 2011a); see McCoy and Ladefoged 2009: 276–277 for a recent review. For this study we used the Carnegie Airborne Observatory (CAO; Asner et al., 2007) to collect LiDAR data over ca. 173 km^2 of leeward Kohala in January 2009. The CAO LiDAR was operated with a laser pulse repetition frequency of 50 kHz, a maximum half-scan angle of 17° (after 2-degree cutoff), and 35–40% overlap between adjacent flight lines. Sensor to ground range was maintained at 2000 m with a standard deviation of 90 m throughout the data collection. This resulted in ±4.6% variation in laser ranging at the edge of each scan line, and ±6 cm variation in laser spot spacing. Laser spot size at ground level ranged from 1.21 to 1.33 m from nadir to the edge of each scan line (17° off-nadir).

From the LiDAR point cloud data, a physically-based model was used to estimate top-of-canopy and ground DEMs using REALM (Optech Inc., Toronto, Canada) and Terrascan/Terramatch (Terrasolid Ltd., Jyväskylä, Finland) software packages. Vertical errors in

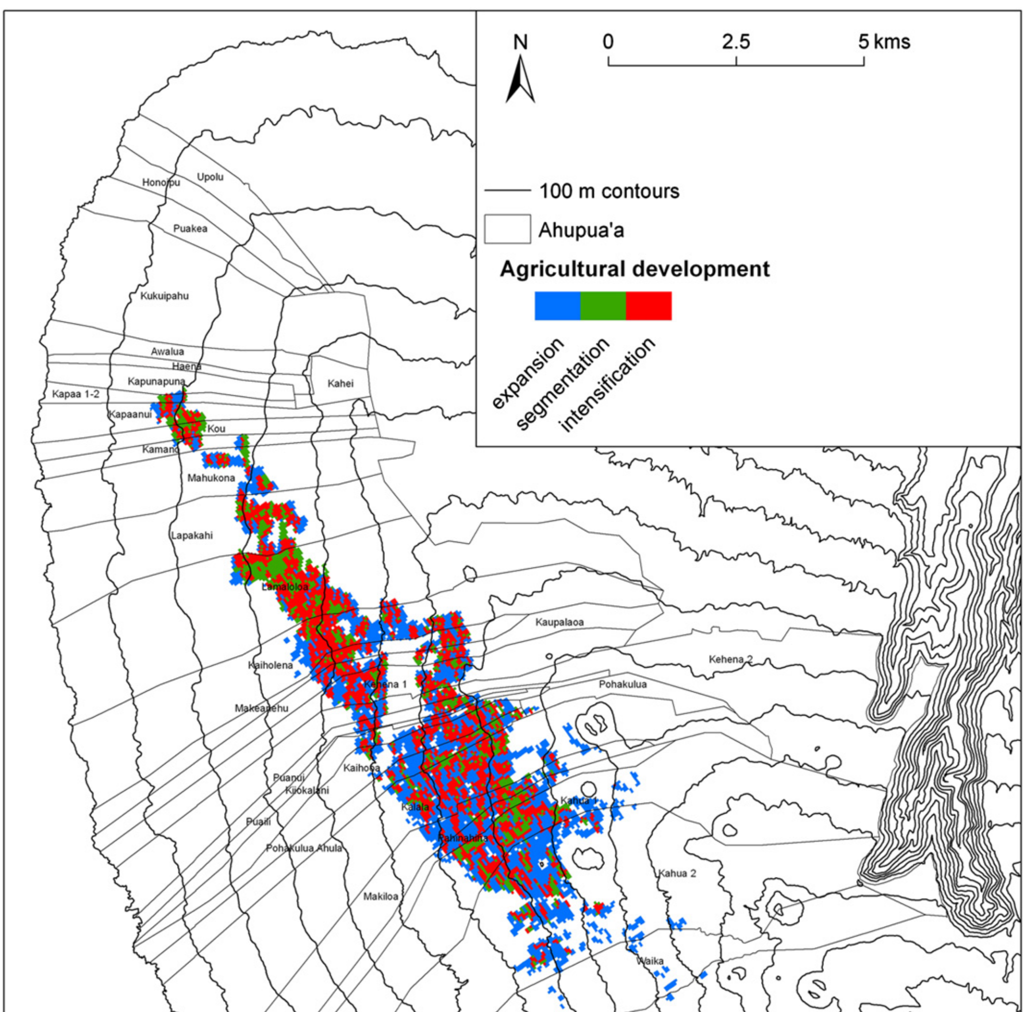

Fig. 5. The category of agricultural development in each 0.25 ha grid. (For interpretation of the references to color in this figure legend, the reader is referred to the online version of this article.)

ground heights and vegetation heights were previously estimated to be 0.12 m (s.e. = 0.14 m) and 0.7 m (s.e. = 0.2 m), respectively, in a forest study that included both sloping and flat terrain, with and without tree cover (Asner et al., 2007, 2009).

Hill-shading of the LiDAR DEM data using an azimuth of 270° and an altitude of 30° emphasizes a range of archaeological features (Fig. 2). In general, linear features are more reliably differentiated from natural rock outcrops than are features that are near regular and symmetrical polygons. While many of the thousands of residential features and tens of larger religious features in the LKFS are identifiable, the value of the LiDAR data lies in its ability to map at a fine scale the extent and nature of the agricultural alignments and trails. These features were visually identified in the hill-shading of the LiDAR DEM and their spatial distribution was manually digitized. Many of these linear features are easily defined. However, to model processes of agricultural development it is necessary to clearly determine if an agricultural alignment terminates or abuts at a trail, or alternatively, if the alignment is intersected by a trail. In the first instance the alignment is considered to post-date the trail, and in the second, the alignment is thought to have been constructed before the trail was built. We identified archaeological features in 43.5 km^2 of the ca. 63 km^2 of the core area of the LKFS (Fig. 3). In ca. 23.3 km^2 it was impossible to reliably determine the spatial relationships between the alignments and trails because that area has been impacted by modern development. While archaeological features are clearly identifiable in the data, the precise spatial relationships between features are not. In contrast, in 20.2 km^2 of the LKFS the precise relationships between agricultural alignments and trails could be determined. This area is referred to as the "leeward Kohala field system undisturbed area" (UDA) and depending on how the entire area of the LKFS is calculated, represents approximately 33% of the entire field system. In this area there are 7060 individual agricultural alignments totaling 717 km and 508 segments of trails totaling 210 km. This LiDAR data set in the UDA is more than 20-fold larger than used in the previous research of McCoy (2000) and Ladefoged et al. (2003) (33% vs. 1.3% of the entire core field system).

Analysis of the LiDAR data suggests that the level of agricultural intensity in the LKFS varies significantly over the extent of the field system. This was first noted by Ladefoged et al. (1996) using poorer resolution data, but can now be documented much more accurately using the LiDAR data. In the LiDAR data set many more alignments with greater lengths are identifiable, and the spatial distribution of these alignments differs from that identified by Ladefoged et al. (1996). Agricultural intensity was determined in the LiDAR data set by measuring the density of agricultural alignments in each cell of a 0.25 ha grid superimposed over the UDA. Density values range from 0.09 m to 273.5 m per 0.25 ha, with a mean of 88.7 m (s.d. 48.5). There is marked spatial patterning in the distribution of the density of agricultural alignments (Fig. 4). A Getis-Ord General G statistic suggests that the density values of all alignments are spatially clustered. The observed General G value of 0.000024 (Z Score: 83.686225, p-value: <0.000001) indicates clustering of high values and allows the rejection of the null hypothesis that values are randomly distributed. Density values of all alignments in the seaward (*makai*) downslope portion of the field system in the northern-central *ahupua'a* (e.g., Lamaloloa; Kaiholena; Makeanehu; Kaupalaoa; Kehena 1) are high with a mean of 119.4 m per 0.25 ha (s.d. 54.5). In marked contrast, the density of all alignments in the southern *ahupua'a* (Kālala; Makiloa; Pahinahina; Kahua 1; Kahua 2) is lower with a mean of 77.7 m per 0.25 ha (s.d. 41.6). In both the northern-central and the southern *ahupua'a*, many of the 0.25 ha cells with low values are on the edge of field plots, and the inclusion of these cells lowers the mean values, but this does not change the relative differences between the areas.

In contrast to the level of agricultural intensity, documenting the process of agricultural development requires tracking changes in infrastructural construction over time. As noted above, a number of studies have relied on the spatial relationships between agricultural alignments and trails to monitor temporal developments. Relying on data from intensive GPS-based pedestrian survey, McCoy (2000) and Ladefoged et al. (2003) were able to propose multiple phases of developments within three spatially limited study zones. However, establishing firm temporal relationships

Table 1
Ahupua'a statistics (ordered from North to South).

Ahupua'a	Expansion (ha.)	Segmentation (ha.)	Intensification (ha.)	Expansion (%)	Segmentation (%)	Intensification (%)	Average density per 0.25 ha (m)	S.D. density per 0.25 ha. (m)
Kapunapuna	0.9	0.5	0.4	47.8%	28.9%	23.3%	50.1	37.5
Kapa'a 1–2	3.7	2.7	2.7	40.6%	30.1%	29.3%	75.4	40.1
Kapa'anui	6.9	10.9	13.6	22.1%	34.7%	43.2%	80.1	39.7
Kou	1.2	9.0	9.1	6.4%	46.5%	47.1%	90.9	41.5
Kamano	6.8	4.1	4.0	45.7%	27.4%	27.0%	66.7	40.9
Mahukona	31.3	8.8	14.5	57.3%	16.0%	26.6%	90.9	51.9
Lapakahi	23.2	23.9	47.9	24.4%	25.1%	50.4%	96.3	49.7
Lamaloloa	24.3	66.4	102.3	12.6%	34.4%	53.0%	121.8	50.8
Kaiholena	79.0	18.8	78.3	44.8%	10.7%	44.5%	105.3	54.5
Makeanehu	19.3	6.3	32.2	33.3%	10.9%	55.8%	101.1	53.2
Kaupalaoa	19.5	7.5	28.6	35.0%	13.5%	51.4%	100.2	53.1
Kehena 1	48.5	13.0	51.1	43.1%	11.5%	45.4%	99.2	54.9
Kehena 2	17.6	4.3	15.5	47.0%	11.5%	41.4%	96.1	48.6
Puanui	11.2	6.0	12.8	37.2%	20.0%	42.8%	82.9	41.9
Puaili	5.8	0.4	3.2	61.9%	4.1%	34.0%	75.4	42.1
Ki'iokalani	16.4	3.9	12.6	49.8%	11.8%	38.4%	78.9	46.4
Kaihooa	50.1	9.2	41.8	49.5%	9.1%	41.4%	86.7	42.5
Pohakulua Ahula	39.0	14.6	27.1	48.4%	18.1%	33.6%	77.2	38.9
Pohakulua	1.9	0.3	0.5	71.3%	9.6%	19.2%	33.2	22.4
Kalala	114.5	30.0	102.9	46.3%	12.1%	41.6%	90.7	42.5
Makiloa	53.5	7.9	26.9	60.6%	8.9%	30.5%	76.9	38.5
Pahinahina	32.5	8.3	22.4	51.5%	13.1%	35.4%	83.3	38.8
Kahua 1	80.5	35.8	64.6	44.5%	19.8%	35.7%	79.1	40.2
Kahua 2	220.5	28.4	62.3	70.8%	9.1%	20.0%	64.1	39.0
Waika	15.7	0.0	0.0	100.0%	0.0%	0.0%	35.0	28.6

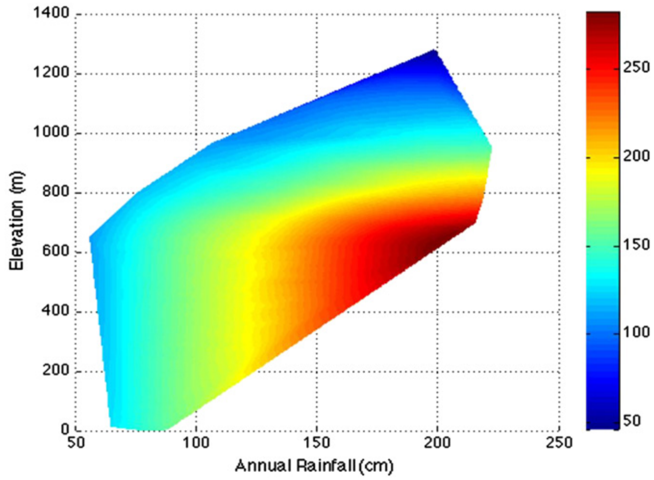

Fig. 6. The relationship between elevation, annual rainfall, and NPP values. (For interpretation of the references to color in this figure legend, the reader is referred to the online version of this article.)

between the phases within one zone to the phases in other zones was impossible because of the spatially discrete nature of each study zone. No alignments or trails linked the three zones. Furthermore, within each zone (e.g., Area A of Ladefoged et al., 2003: 931–932) it was often impossible to determine precise temporal relationships between developmental phases in various areas of the zone because construction within a zone was frequently spatially independent (also see Field et al., 2011). For example, the construction of a trail often divided an area, with subsequent alignment and trail construction occurring independently on either side of the trail. While the LiDAR data set covers a much larger area that includes spatially continuous patches of features up to 4.5 km in length, it is still impossible to link developments across the entire LKFS. Again this is because much of the construction is localized, occurring within single or adjacent *ahupua'a*. To partially overcome this limitation, we implemented an algorithm for distinguishing the agricultural developmental processes of expansion, segmentation, and intensification throughout the field system.

Expansion occurred when agricultural alignments and trails were constructed in areas that previously did not contain agricultural architectural features. Expansion can precede future segmentation or intensification, or it can be the end state of development. As the end state of development, alignments in expansion areas were never intersected by the construction of subsequent trails; rather the alignments in these areas formed a grid pattern, often with terminations at trails. While the temporal associations of all the alignments in a discrete expansion area are ambiguous, it is clear that further development in the area via the

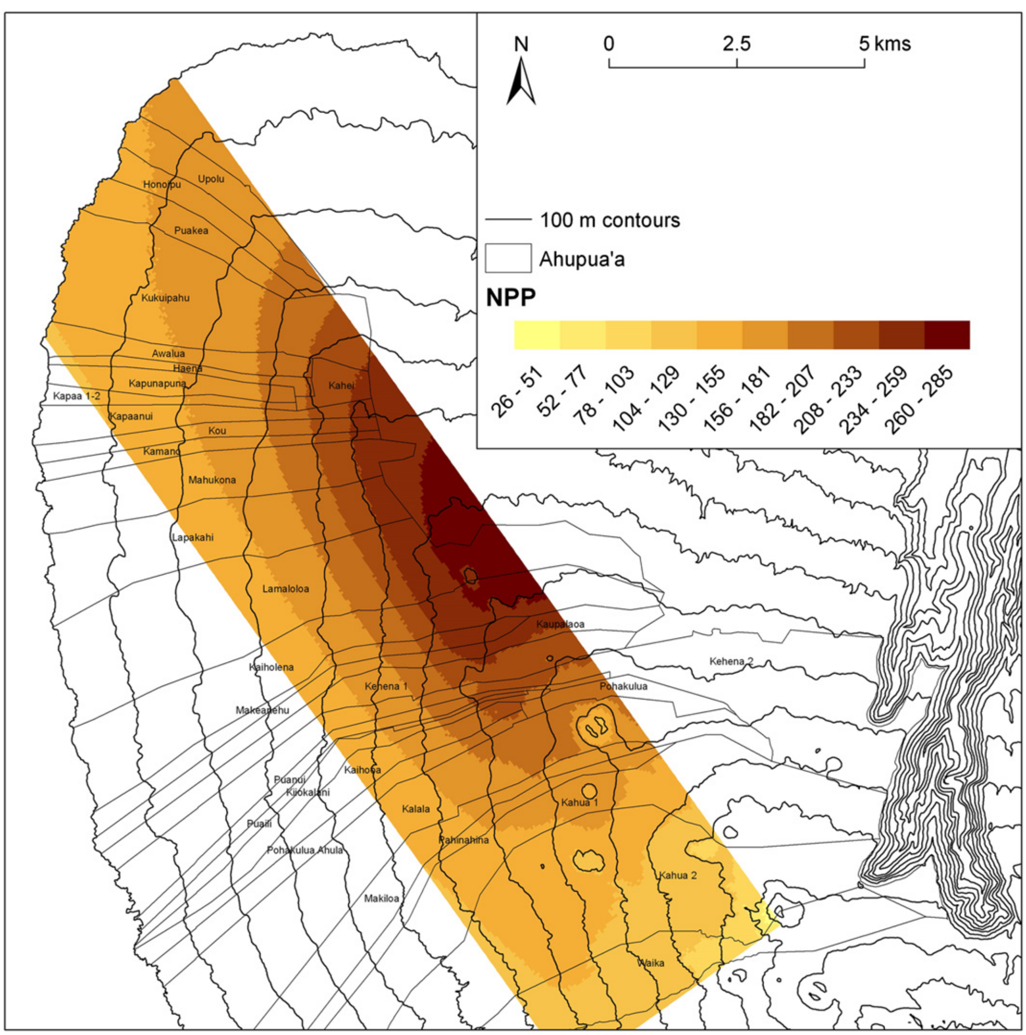

Fig. 7. NPP values for each 0.25 ha grid throughout the LKFS. (For interpretation of the references to color in this figure legend, the reader is referred to the online version of this article.)

construction of subsequent trails intersecting the alignments never occurred. In contrast to the alignments in expansion areas, alignments associated with segmentation of previously established plots were intersected by subsequent trail construction, and thus exhibit evidence of at least two phases of agricultural development. The interval of time between the two phases is unknown, and could range from quite short intervals of a few years up to periods of as long as a century or two. Areas of intensification are marked not only by intersecting alignments, but the further construction of additional alignments abutting the intersecting trails to form infilling plots. In these areas we believe that the additional infrastructural construction was associated with increasing productivity.

For our LiDAR data set, areas of expansion, segmentation, and intensification were differentiated on the basis of the relationships between alignments and trails within each 0.25 ha of the UDA. A GIS procedure established whether each of the 7060 individual alignments had been intersected. Further procedures classified each 0.25 ha grid square as either containing 1) entirely non-intersected alignments; 2) entirely intersected alignments; or 3) a mixture of non-intersected and intersected alignments. These three categories correspond to the classification of areas as expansion, segmentation, and intensification, respectively. Approximately 45.5% of the 20.2 km^2 UDA has undergone expansion alone, 15.8% segmentation, and 38.6% further intensification. The spatial distribution of each category is shown in Fig. 5. These small 0.25 ha sampling grids form larger patches associated with specific developmental processes and these have been summarized for each *ahupua'a* (Table 1). Much of the southern area of the LKFS was developed through a process of expansion, with over 44% of agricultural development in all of the southern *ahupua'a* from Ki'iokalani to Kahua 2 occurring via expansion. Several northern *ahupua'a*, including Kapunapuna, Kapa'a 1–2, Kamano and Mahukona, and the northern-central *ahupua'a* of Kaiholena, also experienced levels of expansion greater than 40%. Segmentation was a significant process in the northern *ahupua'a*, with at least 20% of agricultural development assigned to that mode in the *ahupua'a* extending from Kapunapuna to Lamaloloa (with the exception of Mahukona, where the value is ca. 16%). Segmentation was also a significant process in the southern *ahupua'a* of Kahua 1. In contrast to the southern *ahupua'a*, in the northern and north-central *ahupua'a* intensification was the dominant mode, with over 44% of agricultural development occurring via intensification in the north-central *ahupua'a* extending from Lapakahi to Kehena 1.

The relationship between the dominant mode of agricultural development and the density of alignments within a specific area provides insight into whether or not agricultural expansion occurred at similar levels of intensity as the final level of intensity

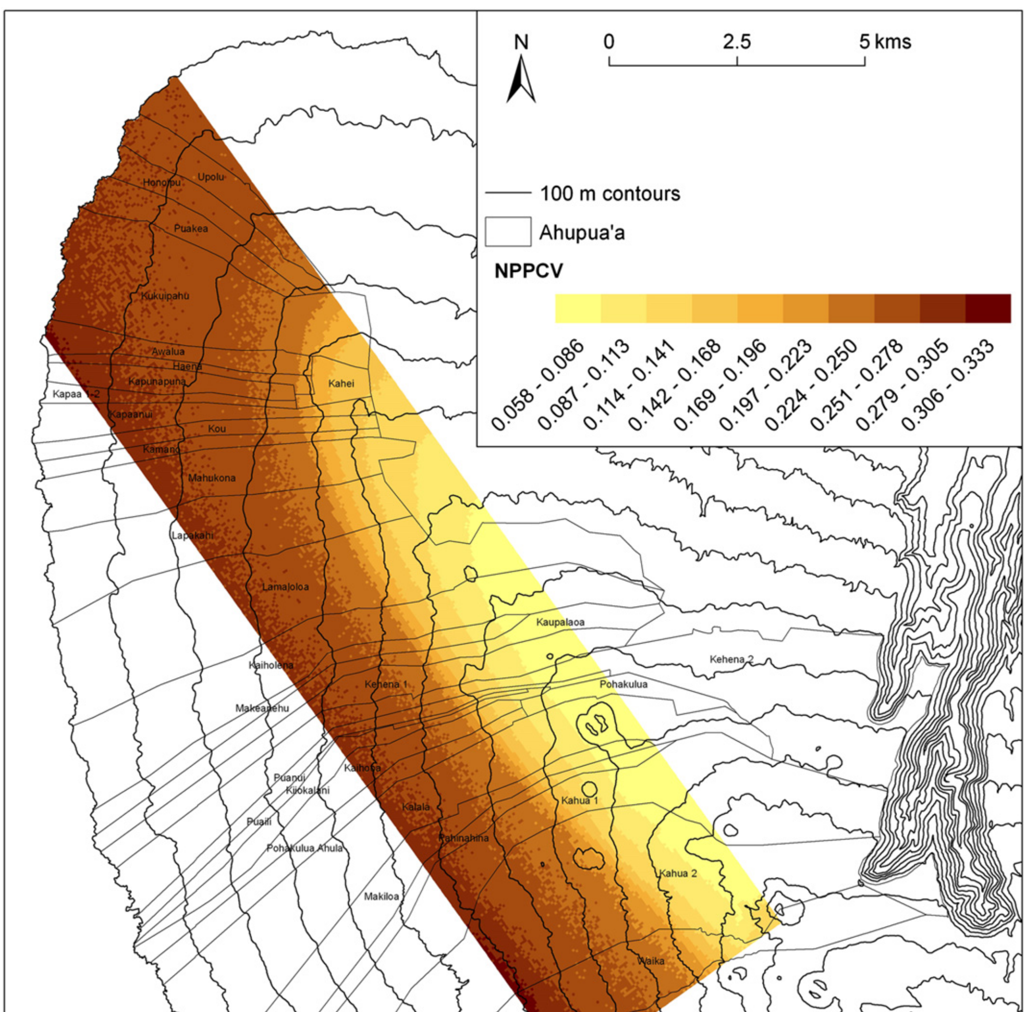

Fig. 8. NPPCV values for each 0.25 ha grid throughout the LKFS. (For interpretation of the references to color in this figure legend, the reader is referred to the online version of this article.)

achieved through the process of intensification. The weak positive correlation (Pearson Correlation 0.228; significant at 0.01 level) between the average number of alignments intersected within each 0.25 ha and the density of alignments in the same area suggests that the process of intensification did result in a higher intensity of alignment construction. However, this correlation is weak enough to suggest that agricultural expansion in some areas did achieve levels of intensity comparable to those in other areas that underwent both segmentation and intensification.

3. Potential productivity modeling

Previous studies of the Hawai'i Biocomplexity Project (e.g., Lee et al., 2006; Ladefoged et al., 2008; Lee and Tuljapurkar, 2011) have modeled the dynamics of food yield, surplus production, and human life expectancy within the LKFS by considering "variation in water and nitrogen availability due to fluctuating rainfall, as well as the resulting variability in rates of biogeochemical cycling between crop plants and the soil" (Ladefoged et al., 2008: 95). Here we rely on a model based on that used in Ladefoged et al. (2008) to generate localized estimates of potential net primary productivity (NPP), as well as the coefficient of variation in net primary productivity (NPPCV) (Puleston n.d.). We estimate NPP from the net annual carbon accumulation of an unharvested tropical grass species growing as a monocrop in the area of interest. Our model of NPP resolves nitrogen, but assumes phosphorus and other nutrients are available in sufficient quantity to avoid limitation in the unharvested grasses. The model provides an estimate of climate-driven potential productivity throughout the region. The model is based on the spatially non-linear intersection of two variables, elevation (which is used as a proxy for temperature) and rainfall (both mean and variance), and as such, produce results that differ significantly from the use of the isolated individual variables. The model was run for a 97.7 km^2 area of the Kohala peninsula at a spatial resolution of 0.25 ha. The relationships between rainfall and elevation with NPP values are shown in Fig. 6. In the graph, colors correspond to NPP values with rainfall dominating potential productivity up to an elevation threshold of ca. 800 m. The graph suggests that below this elevation, temperature is adequate and rainfall is the primary limiting variable. Above 800 m, elevation (and by proxy temperature) becomes the critical variable for potential productivity. The spatial distribution of NPP and NPPCV values are shown in Figs. 7 and 8. The figures suggest that low rainfall at lower elevations results in low potential productivity, with higher potential productivity occurring in wetter upslope zones. However, because

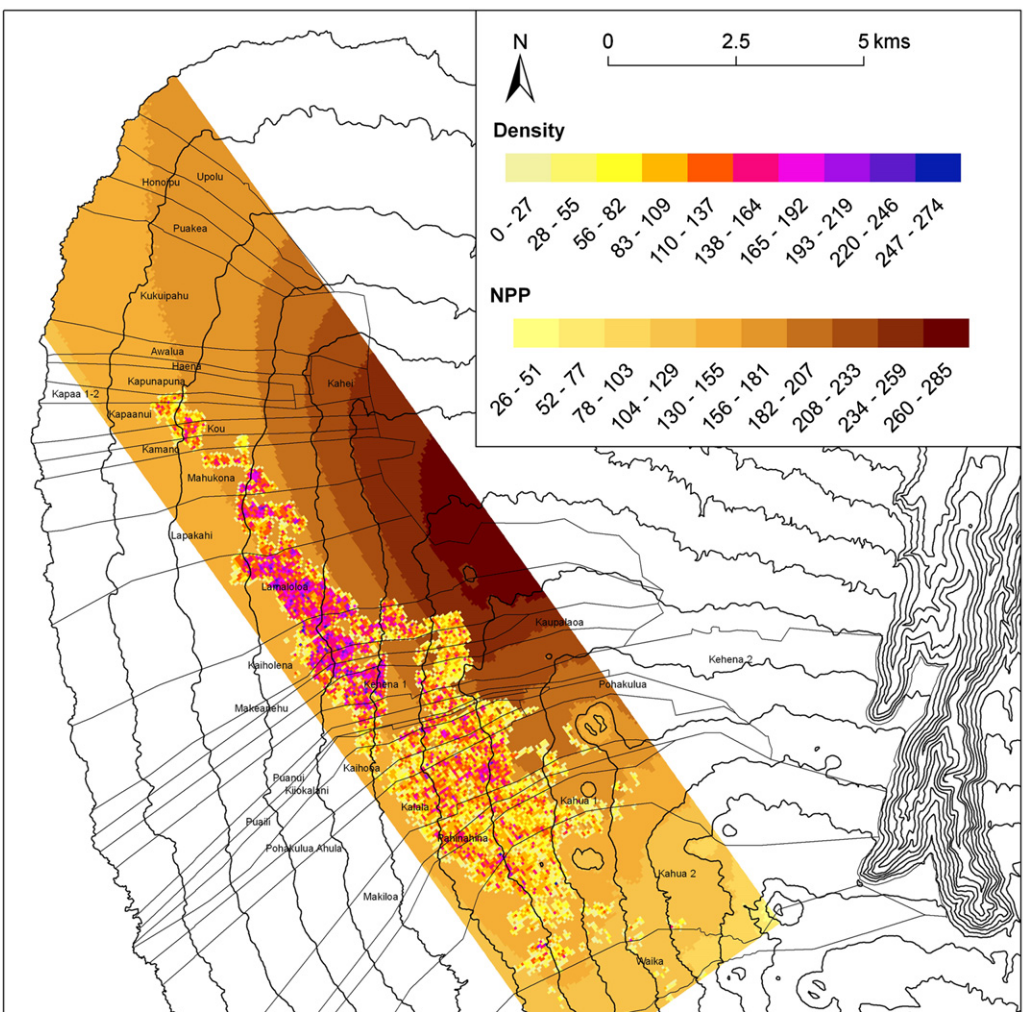

Fig. 9. The spatial distribution of density per 0.25 ha and NPP values. (For interpretation of the references to color in this figure legend, the reader is referred to the online version of this article.)

the rainfall isohyets track inland in a southerly direction, NPP values in the higher elevation southern portions of the field system are depressed due to cooler temperatures leading to decreased production. In the northern lower elevational sections of the field system, potential productivity is depressed in a westerly direction as rainfall decreases. Temporal variability in NPP, as indicated by NPPCV values, correlates closely with rainfall. Consequently NPPCV values are not overly depressed in the higher elevational southern portions of the field system in the same manner as NPP values.

4. Discussion

In an early analysis of the LKFS using aerial photography data, Ladefoged and Graves (2000) proposed that longer agricultural alignments were generally found in the northern and northern-central portions of the field system, with shorter alignments in the southern section. They interpreted this pattern as having temporal significance, with the longer walls being constructed earlier and the shorter walls in the southern section indicating late expansion in the region. Their explanation for the temporal trend focused on the distance of the field system to the coast and the location of optimal canoe landing points. They noted that the orientation of the Kohala ridge and the dominant tradewinds created rainfall zones that tracked upslope and away from the coast in a southerly direction along the leeward side of the peninsula. The late expansion into the southern margins of the field system was seen as a response to increased distance and travel time to the coast, with zones closer to the coast being developed earlier. The current model results, however, suggest that distance to the coast was not the only factor influencing the spatial and temporal patterns of agricultural development.

The LiDAR results demonstrate distinct patterning in the spatial distribution of agricultural development in relation to potential productivity. Areas with high densities of agricultural alignments are concentrated in the downslope zone of the central *ahupua'a* within the LKFS, an area with moderate levels of NPP and moderately high levels of NPPCV (Figs. 9 and 10). While historic disturbance has created some sampling issues, there is nonetheless a ca. 1 km wide zone just upslope from the area with high densities of agricultural alignments in the central-south *ahupua'a* where good LiDAR data are available. In this zone with relatively high levels of NPP and low levels of NPPCV, there are lower densities of agricultural alignments. In the southern *ahupua'a*, where NPP values drop-off markedly, there are similarly low densities of agricultural alignments, in both downslope and upslope directions, cross-cutting the range of NPPCV values. The spatial distribution of the different modes of agricultural development in relation to NPP is

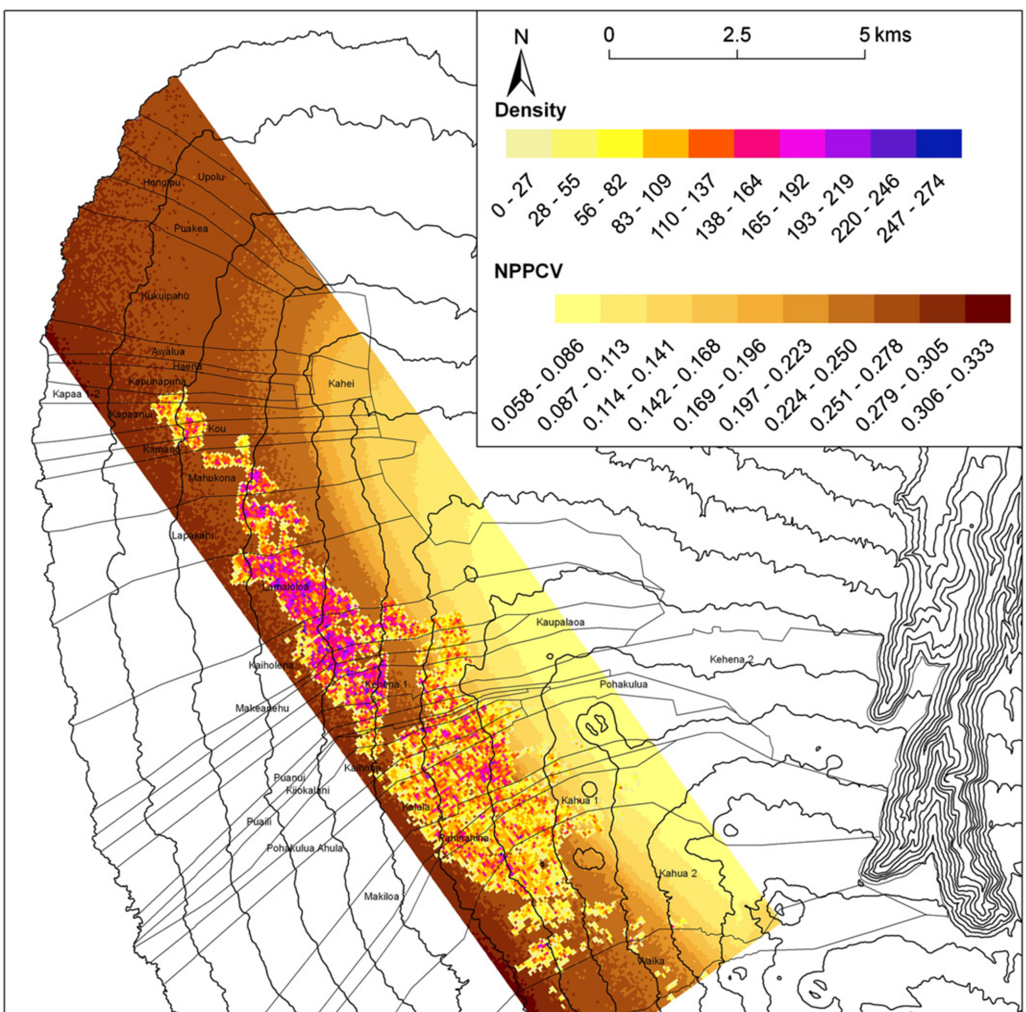

Fig. 10. The spatial distribution of density per 0.25 ha and NPPCV values. (For interpretation of the references to color in this figure legend, the reader is referred to the online version of this article.)

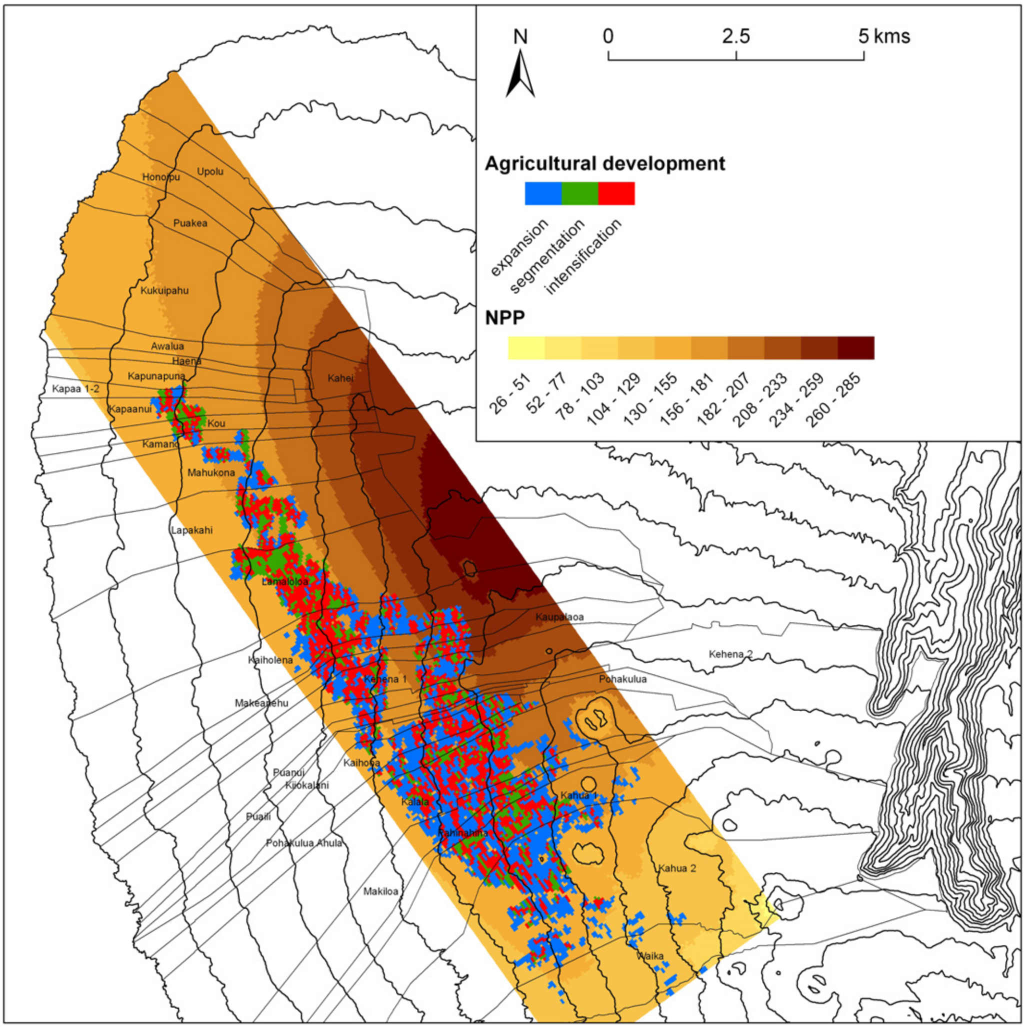

Fig. 11. The spatial distribution of the category of agricultural development and NPP values. (For interpretation of the references to color in this figure legend, the reader is referred to the online version of this article.)

somewhat similar to the spatial patterning in alignment densities (Figs. 11 and 12). The zones with high densities of alignments in the downslope section of the central *ahupua'a* with moderate NPP values and moderately high NPPCV values are dominated by high levels of agricultural intensification and segmentation. However, the upslope higher NPP zones of these areas with lower NPPCV values also have high levels of intensification and segmentation (although these are areas with relatively lower densities of alignments). In contrast, the southern zones with low NPP values exhibit lower levels of intensification and segmentation, and much higher levels of agricultural expansion.

One expectation might be that areas with high levels of NPP and low levels of NPPCV should exhibit the highest levels of infrastructural improvement. Yet this is not the case in the central *ahupua'a*, and there are several possible explanations for this discrepancy. Our NPP model resolves nitrogen, but it does not account for the depletion of phosphorus and other nutrients. It is possible that soil nutrient leaching in high rainfall zones of high NPP was a significant deterrent for continued agricultural intensification due to the greater nutrient demands of such a system. It is also possible that variation in alignment density is the result of variation in cultivation techniques or cultivars, and is not a direct reflection of the amount or intensity of agricultural activity in an area. As noted earlier, experimental results indicate that the field system alignments result in increased moisture levels ca. 2–3 m immediately upslope of the alignment centerline due to micro-orographic precipitation. The greater density of alignments at lower elevations may therefore be the result of an increased need to capture tradewind-laden moisture in these relatively drier locations. In contrast, higher elevation locations receiving higher levels of rainfall had less need for high densities of moisture-capturing alignments. It is also possible that different elevation zones within the LKFS were used for different cultivars. Perhaps the wetter higher elevation zones supported dryland taro more reliably, with that crop requiring less dense infrastructural improvements. The drier lower elevation zones would have been the focus for the more drought resistant sweet potato that required greater infrastructural improvements. Finally, it is also possible that lower elevation zones had to be fallowed more often than upslope zones. Fallowing would have allowed soil moisture, and to a certain extent nutrients, to accumulate in these zones. The higher density of alignments in the lower elevation zones of the central *ahupua'a* could have been a function of people periodically suspending their gardening activities in these areas before bringing them back into production. The construction of additional alignments might have facilitated the process by creating smaller management units, or could have been a byproduct of reestablishing gardens.

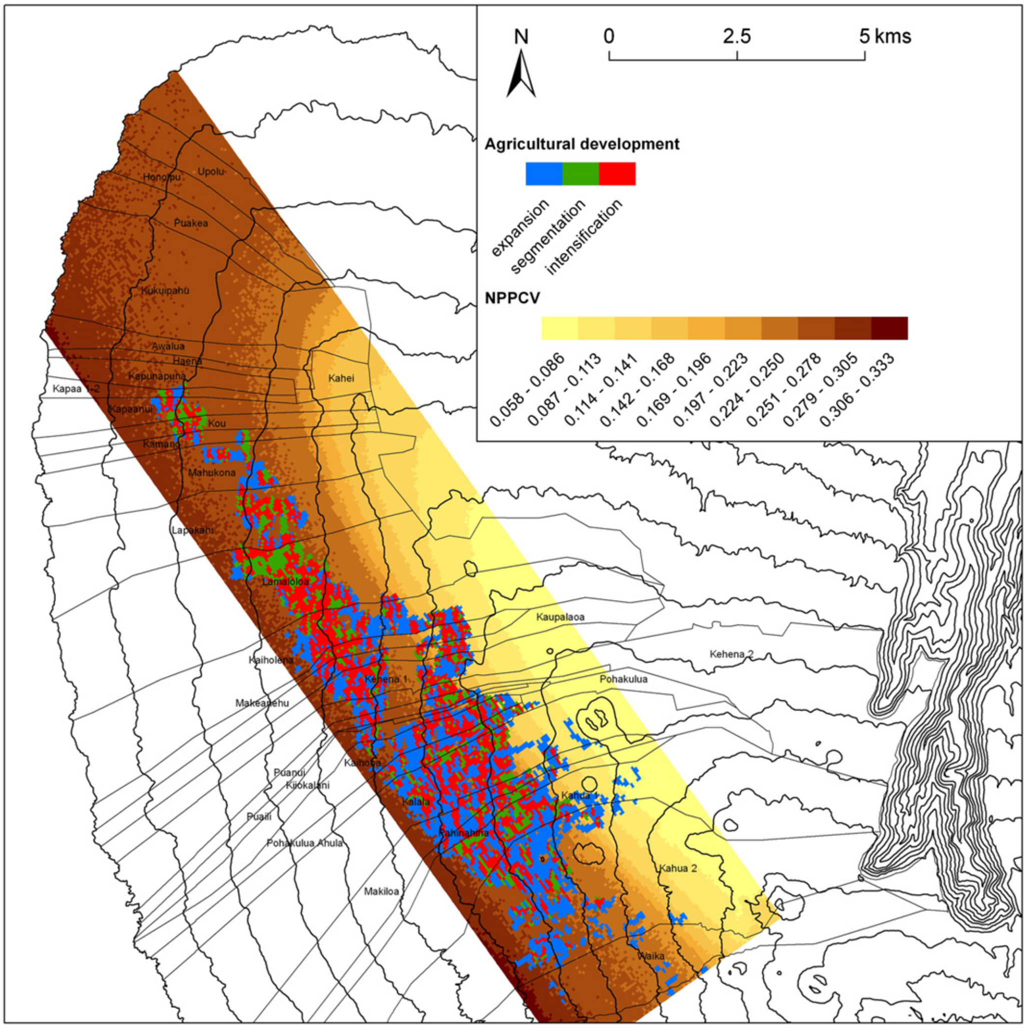

Fig. 12. The spatial distribution of the category of agricultural development and NPPCV values. (For interpretation of the references to color in this figure legend, the reader is referred to the online version of this article.)

The temporal associations of the LiDAR spatial patterning are still somewhat ambiguous; however, radiocarbon dates from residential and agricultural contexts (Ladefoged and Graves, 2008; Field et al., 2011, submitted for publication) and architectural seriation of religious features (Mulrooney and Ladefoged, 2005; McCoy et al., 2011b) are beginning to add clarity. Field et al. (2011) report a series of radiocarbon dates from the uplands of Kaiholena and Makeanehu *ahupua'a,* located in the central portion of the field system. These dates suggest that this central core of the LKFS was first occupied in the fifteenth century, with the number of households in the area stabilizing sometime in the period between A.D. 1520–1650. This is a zone with moderate NPP and relatively high NPPCV that was highly intensified, with high degrees of segmentation and intensification. It is reasonable to assume that the relatively early residential features in the area are associated with the beginnings of segmentation and intensification. In contrast, the radiocarbon dates from residential and religious features in the southern *ahupua'a* (see Field et al., 2011, under review; Ladefoged and Graves, 2008; McCoy et al., 2011b) suggest that the agricultural development dominated by expansion in the less optimal southern zones occurred somewhat later, probably after A.D.1650.

5. Conclusions

Earlier studies on the distribution and development of agriculture in the LKFS (Ladefoged et al., 1996; Ladefoged and Graves, 2000) relied on coarse-grained maps based on aerial photographs. Analysis of LiDAR data enables a more precise and accurate assessment of human activities in the field system. With the LiDAR data it is possible to identify a far greater number of alignments and trails and more accurately establish the spatial distribution and relationships of these features. For example, in the earlier study of Ladefoged et al. (1996) it was suggested that there was a maximum density of alignments within the field system of 614 m/ha. In contrast, the analysis of LiDAR data suggests densities reached over 850 m/ha (excluding trails). The earlier study documented density variation across the field system, but the LiDAR data enables us to define finer distinctions within smaller areas such as intra-*ahupua'a* variation in the central-south *ahupua'a*. Not only is it possible to establish higher and more variable densities, but the LiDAR data facilitates the refinement of the distribution of alignments. Infrastructural improvements are documented further south than originally thought, with alignments constructed in the southern portions of Kahua 2 and Waika *ahupua'a*. In addition, the finer spatial resolution of the LiDAR data enables the accurate identification of the spatial relationships between trails and agricultural alignments. This facilitates the analytical distinction between expansion and the two other forms of agricultural development, segmentation and intensification, something that was not achieved by Ladefoged and Graves (2000) using the aerial photograph data. Whereas previously development in the southern *ahupua'a* was characterized as being primarily expansion, the LiDAR analysis identifies much greater variability with zones of segmentation and intensification mixed with large areas of expansion. Expansion was still the dominant mode of development in the area, but it is clear it was not the only form of development. In the northern *ahupua'a* of Kapa'anui, Kou, Kamano, and Maukona, and the more central *ahupua'a* of Lamaloloa and Kaiholena, the LiDAR data provides evidence of segmentation and intensification, something that was not apparent in the aerial photograph data.

The analysis of a potential productivity model and airborne LiDAR data from leeward Kohala identifies different modes of agricultural development in relation to productivity. While a considerable portion of the field system has been disturbed by historic activities, the analysis suggests that people employed diverse cultivation techniques in different zones at different times. Highly intensified areas that underwent processes of segmentation and intensification were located in areas with moderate levels of NPP with moderately high levels of NPPCV, and were utilized relatively early on. Less productive areas were also utilized, but these zones were developed later in time and were generally marked by the process of expansion with lower densities of alignments. While the environmental matrix of potential productivity undoubtedly influenced the construction and distribution of agricultural alignments, it is likely that variation in alignment density was also a function of variation in cultivation techniques or cultivars. The results suggest that distance to the coast and optimal canoe landings, as previously suggested (Ladefoged and Graves, 2000), were not the only, and indeed, probably not the most significant, variables influencing agricultural practices. This analysis highlights the importance of fine-grained data distributed over large areas when trying to understand the environmental matrix that Hawaiians faced when evaluating the costs and benefits associated with variable agricultural development.

Acknowledgments

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