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EVOLUTIONARY THEORY AND THE HISTORICAL DEVELOPMENT OF DRY-LAND AGRICULTURE IN NORTH KOHALA, HAWAI'I

Thegn N. Ladefoged and Michael W. Graves

This GIS analysis of the dry-land agricultural field system in Kohala on the island of Hawai'i reveals patterning that is explained by evolutionary ecological principles set within a selectionist framework. The ca. 55 km^2 fixed-field system was developed through establishment, expansion, and intensification from the sixteenth until the early nineteenth century. During this time, differential growth rates and levels of intensification occurred in diverse locales. The development of the field system was characterized by changes in the size of the fields, variability in field size, the size of production communities, the level of distribution of production, and the spatial distribution of fields. The most important factors influencing the differential temporal and spatial changes included differences in the abundance of marine resources, variability in the distance between the coast and the inland fields, differences in the amount of variation of rainfall levels over a given distance, and the insurance or subsidy that chiefs could offer to residents to initiate farming in the least optimal locations. Selective pressures within the heterogeneous environment of north Kohala provided the context in which subsistence strategies shifted from a focus on optimizing energy returns to one of stabilizing returns via risk aversion.

El analísis GIS del sistema de tierras agrícolas no irrigadas en Kohala, Isla de Hawai'i, presenta regularidades que se pueden explicar haciendo uso de los principios ecológicos evolucionistas de índole seleccionista. El sistema de tierras agrícolas no rotativas de aproximadamente 55 km2 se desarrolló entre el siglo XVI y comienzos del XIX a través del asentamiento, expansión e intensificación ocupacional. Durante este período se dieron diferentes grados de crecimiento y niveles de intensificación en las diversas partes del sistema. El desarrollo del sistema agrícola se caracterizó por cambios en el tamaño de las parcelas a través del tiempo, la variabilidad en el tamaño de las parcelas entre sí, el tamaño de las comunidades productivas, el nivel de distribución de la producción y la distribución espacial de las parcelas. Los factores de mayor influencia sobre los diversos cambios temporales y espaciales incluyen diferencias en la abundancia de los recursos marinos, la variabilidad en la distancia entre la costa y las parcelas interiores, diferencias en el grado de variación de los niveles pluviales sobre una distancia determinada y los subsidios o garantías que los jefes podian ofrecer a los residentes para iniciar tareas agrícolas en los lugares menos propicios. Las presiones selectivas en el ambiente heterogéneo del norte de Kohala ofrecieron un contexto en el que las estrategias de subsistencia cambiaron de un énfasis en la optimización de resultados energéticos a un énfasis en resultados establizadores a través de la evasión de riesgos.

Evolutionists have long considered the appearance and development of agriculture. Much of this literature is informed by environmental or ecological concerns (Binford 1968; Flannery 1965, 1969) and cultural evolution (Braidwood 1967). While these perspectives are informative, we would rather shift the focus and place our research within the context of Darwinian evolution. Agriculture has been examined from this perspective by a co-evolutionary model for the origins of agriculture (Rindos 1980, 1984) in which related human and plant traits vary, are differentially replicated or reproduced through time, and come to share a symbiotic relationship in the evolution of agriculture. Both David Braun (1987) and Michael O'Brien (1987; O'Brien and Wilson 1988) have drawn on a similar framework to interpret changes in agriculture, technology, and mobility. Others have included comparative analysis of agricultural technologies to identify advantages shared by certain practices (Field 1998; Maxwell 1995) and the use of optimality or game theory models from anthropological evolutionary ecology (Cashdan 1992).

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Evolutionary ecology has focused on a range of subsistence practices, many of which are studied from a contemporary or recent historical perspective (see papers in Cashdan, ed. 1990). Most evolutionary studies accept that agricultural practices introduce instability to subsistence regimes (Rindos 1980:210, 1989) and that agricultural productivity involves some degree of uncertainty and therefore risk. Even though agricultural practices often produce instability, the shift to agriculture in some contexts has obviously occurred. Thus, evolutionary ecological efforts have focused on detailing the particular advantages enjoyed by agricultural practices or strategies by reference to a number of processes. These include temporal and spatial averaging (Cashdan 1992; Wills and Huckell 1994; Winterhalder 1990) and reducing variance in yield (Gremillion 1996). The adoption of insurance measures (Halstead 1989), such as part-time labor or food storage (Leonard 1989; Ortiz 1990), and food sharing or exchange (Hawkes 1992; Jorde 1977; Larson et al. 1996) also have been considered. Other cultural practices related to agriculture that have caught the attention of evolutionary ecologists include levels of mobility (Allen and McAnany 1994), the development of territoriality (Dyson-Hudson and Smith 1978), the formation of groups of varying size and complexity (Adler 1996; Boone 1992), and the degree of specialization in particular cultigens or technologies (Field 1998).

Despite the achievements of evolutionary ecology in identifying successful adaptations, these studies have been less effective in addressing questions of agricultural change and geographic variation in agricultural practices. It is here that archaeologists have contributed much to the historical study of prehistoric agriculture and have identified a number of factors that are important components of change and diversification (Earle 1980). In some instances the emphasis has been placed on climatic variation and deviation (Childe 1925; Dean et al. 1994; Larson et al. 1996; Wright 1977), whereas in others the focus has been on the expansion or reduction of areas suitable for agriculture (Allen 1997; Van West 1994), or the differential use of areas for different forms of agriculture and/or cultigens (Bulmer 1989; Morrison 1995). Others have emphasized the use of different localities by different households or social units (Bulmer 1989; Morrison 1996) and shifts in the effort (Gallagher 1989; Halstead 1989; Kirch 1984; Morrison 1994) devoted to agriculture.

Our study extends this tradition by using evolutionary ecology as a way of identifying proximate factors which affected the adaptive relations for dry-land agriculture in the district of North Kohala[1] on the island of Hawai'i. We consider these proximate factors over time to identify the role of selection in shaping the differential persistence of agricultural traits. In a recent *Antiquity* article Ladefoged et al. (1996) considered the environmental features which were thought to have limited the geographic extent and degree of intensification of dry-land agriculture in this region. That study did not consider the development of the field system over time. In this paper we extend that analysis to show how this large ca. 55 km^2 region of contiguous dry-land fields can be analyzed *historically* with the assistance of a geographic information system (GIS). In this analysis, therefore, we add a temporal dimension to our previous synchronic study. We identify the locations where portions of the dry-land field system were first established, their relation to variation in agricultural intensification, the occurrence of variable levels of intensification throughout the field system, the variable temporal pattern of intensification across communities (also known as *ahupua'a*) associated with the field system, and variation in the size and shape of agricultural plots in different environments. Finally, we draw on evolutionary ecological theory to describe several models that account for the geographic pattern of development of dry-land agriculture in north Kohala and then suggest how selection may have structured this geographic pattern through time.

The significance of evolutionary ecology for archaeology lies in the recognition that aspects of environmental structure and variability affect the relative success and failure of individual human endeavors (Boone and Smith 1998; Broughton and O'Connell 1999). The domain of human subsistence, including agriculture, is well suited to this perspective since there are a variety of potential agricultural practices that individuals may choose. These practices are acquired through learning, and theoretically they should produce a set of associated costs and benefits tied to particular constraints that are linked to both the physical and cultural environmental context.

While evolutionary ecology can provide satisfactory answers to questions of agricultural adaptation (the how of evolution) and the operation of agricultural systems, it has been less successful in delineating the role of selection in historical sequences (the why question of evolution). Adaptations, by definition, are always at least minimally successful at some point in time, and this is the one limitation of evolutionary ecology research (see Gould and Lewontin 1979). Current or even past adaptations do not provide the means to explain the historical and evolutionary trajectory of functional forms of human experience. For this kind of explanation, we must highlight the role of selection, which operates on all functional variability (sensu Dunnell 1978), not just on the successful forms, and which favors some cultural traits over others in terms of their fitness. Conceptualizing and measuring fitness, however, is a continuing challenge for evolutionary studies in archaeology (Lyman and O'Brien 1998; O'Brien and Holland 1995:182–193; O'Brien et al. 1998). Here, in addition to measuring changes in population, we suggest monitoring changes in the abundance and distribution of relevant classes of cultural traits, including artifacts associated with subsistence practices, and specifying the relative advantages of these changes, as a means for assessing fitness. For archaeological and evolutionary purposes, the success and/or failure of agricultural practices must include a preserved component, which is referred to as the extended phenotype of artifacts (O'Brien and Holland 1995:179). The preserved component in this study are the rock and earthen agricultural walls that were built to facilitate cultivation and transport, and demarcate agricultural space. We document functional variability in different aspects of these features over time and space as the outcome of selection on individual agricultural practices situated within different environmental contexts. We also introduce less-secure evidence related to other forms that functional variability can take, including the spatial scale of production and of distributional units, both of which we suggest have been similarly shaped by selection.

Although selection in biological evolution proceeds through differential reproductive success, and despite the obvious link between food production and human reproductive ability (see Rindos 1984), the hypothesis and selectionist framework we develop here also emphasizes replicative success (sensu Leonard and Jones 1987). Information regarding environmental variables, potential field locations, suitable cultigens, and practices involving the construction of field border walls and trail features used to demarcate agricultural plots, control erosion, and conserve water was transmitted from individual to individual through learning. The scale of temporal change (300–400 years), about 11 generations, and the geographic extent (55 km^2) of dry-land agriculture in north Kohala suggest that this information was transmitted not just from parents to offspring but also obliquely or horizontally among individuals living in different localities along the coast. Hence, selection shaped differential reproduction and the replicative success of the material cultural trait variation associated with fixed-field dry-land agriculture in a distinctive fashion, and we identify the process of selection by relying on empirical and experimental data to specify the fitness-enhancing properties of changing spatial and temporal cultural traits.

The role of human intention in evolutionary process is presently contested (Boone and Smith 1998; Jones et al. 1995; Lyman and O'Brien 1998; O'Brien and Holland 1995; O'Brien et al. 1998). Evolutionary archaeologists have tended to minimize the impact of human intention on long-term cultural change. It is clear, however, that human actions introduce behavioral and artifact variation, and this variation is then structured by selection (Lyman and O'Brien 1998:618; O'Brien and Holland 1992; Rindos 1989). Barton and Clark (1997:7) suggest that the focus should be "on why some (people) are more successful and some are less so—regardless of their intent." In a recent review, Lyman and O'Brien (1998:620) note that "Evolutionary archaeology does *not* deny a role to human adaptational intent but conceives the *major* mechanisms of change to be natural selection and drift." Yet O'Brien and Holland (1995:180, emphasis added) concede that "Intent certainly plays a proximal role in *shaping* variation...". We suggest that it is this conscious manipulation or shaping of variation in artifacts through human decision making that can be so important at particular points in the trajectory of evolutionary historical sequences. We will pay particular attention to the ability of certain individuals within a population, notably those in positions of authority, to generate and shape variation through their control over or management of the behaviors and artifacts of others. Dunnell (1978, 1980, 1995) highlights a potentially important implication of human intention in evolutionary studies when he notes that in "complex societies" there is "a shift in the scale of the unit on which evolutionary processes operate from the individual bounded by a skin to a large individual (group) com-

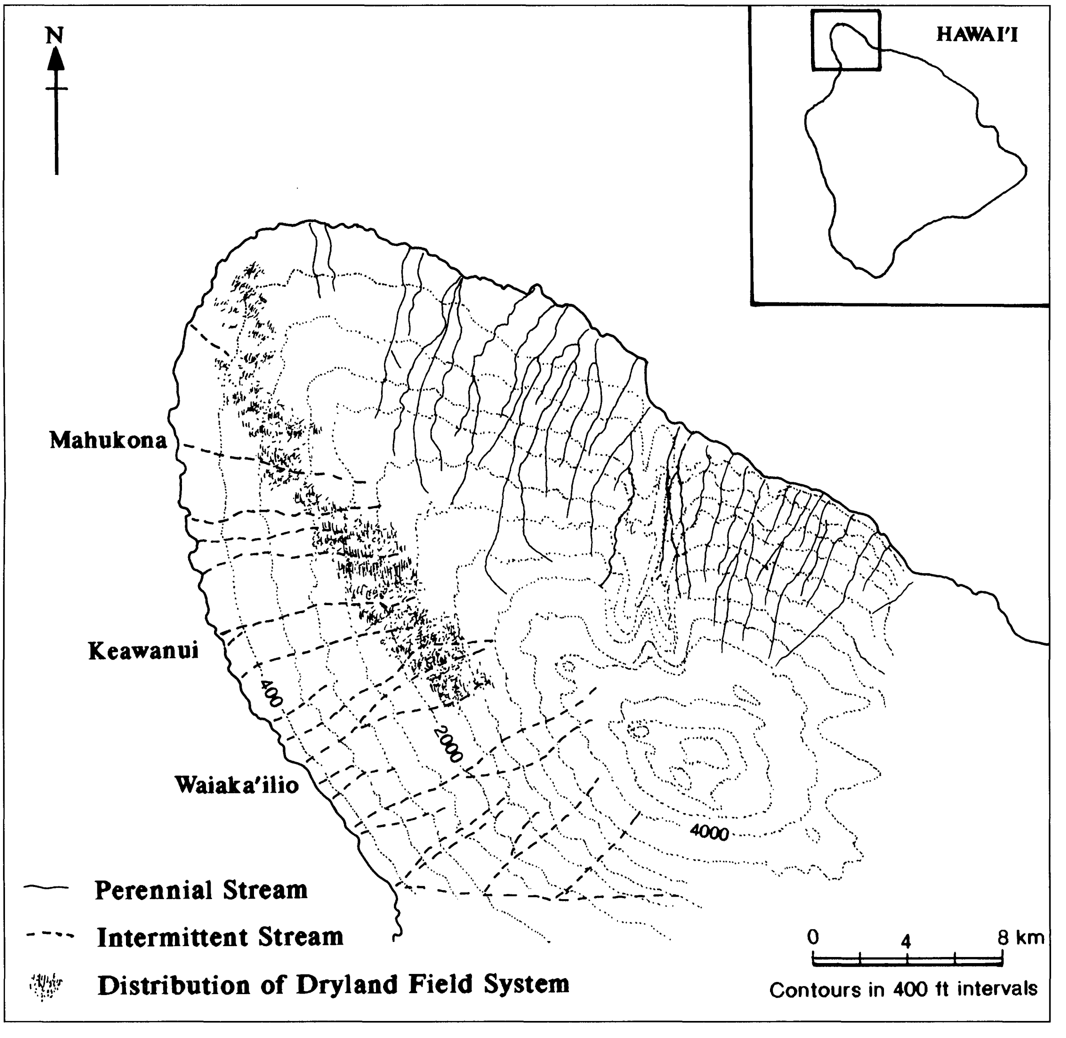

Figure 1. The topography of North Kohala District (after Clark 1987) showing some of its diversity, including valley systems along the northeast and the minor intermittent drainages and the major bays along the northwest coast.

posed of many, functionally differentiated organisms" (1995:41). His statement implies a role for intent and decision-making in the appearance of such groups, although it also is clear that the success or failure of such groups is structured by selection.

In the case of north Kohala, we note a shift in the evolutionary ecological variables that explain agricultural operations from one based on factors that optimize energy returns at low inputs to one based on factors stabilizing production and lowering risk at higher input costs. Additionally, we show how optimality is not a fixed quality or quantity associated with environmental structure, but rather varies over time and in relation to payoffs and associated costs. We suggest that the actions of the chiefly elite shaped behavioral options and that late in the historical sequence the elite came to manage agricultural production and distribution in some locales. In this instance, evolutionary change involved a shift upward in the scale at which selection operated, one of the features which distinguishes social complexity. Our goal is to suggest how evolutionary ecology can rise to the challenge posed by Lyman and O'Brien (1998) that in archaeology it must provide historical accounts of evolutionary change and thus make better use of the record with which most archaeologists work.

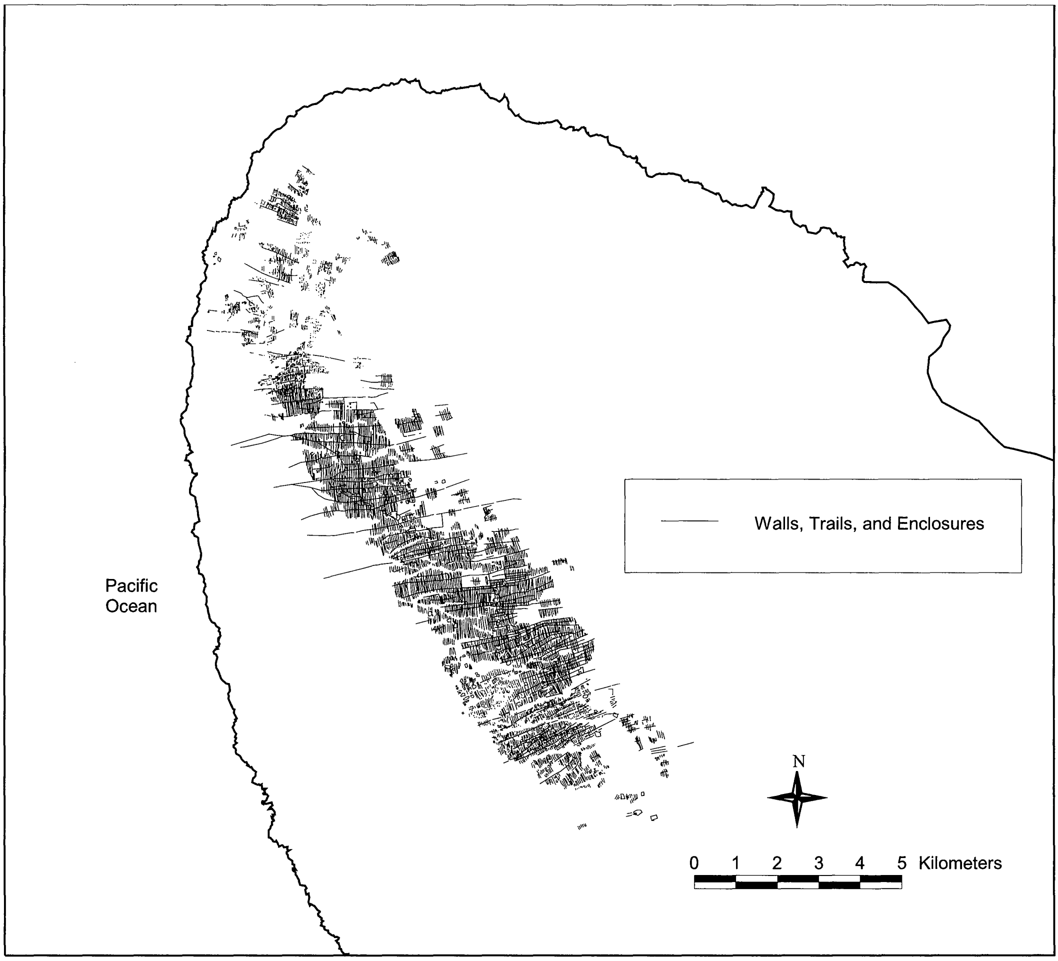

Figure 2. The agricultural walls, trails, and enclosures of the north Kohala dry-land field system as depicted in the geographic information system, northwest Hawai'i Island.

The North Kohala Dry-Land Agricultural Field System and Its Environmental Setting

The north Kohala dry-land agricultural field system is approximately 19 by 4 km in size and is situated on the leeward facing slopes of the Kohala mountains (Figure 1). The research emphasis in Kohala has been on the single *ahupua'a* or community of Lapakahi (Ching 1971; Newman 1970, 1972b; Pearson 1968; Rosendahl 1972, 1994; Tuggle and Griffin, ed. 1973; Tuggle and Griffin 1973; but see Ladefoged et al. 1996), although several recent projects have focused on other portions of the field system or associated coastal settlements of north Kohala (Adams 1994; Bonk 1968; Erkelens 1994; Kaschko 1982, 1984; Ladefoged et al. 1998; O'Connor 1998; Rosendahl 1982; Schilt and Sinoto 1980). The most visible and numerous archaeological features associated with the north Kohala field system are rock and earthen walls that are often referred to as "alignments" (Figure 2). These walls are field borders formed by as much as 1 m high and 2 m wide embankments that are situated roughly parallel (north-south) to the contours of the land (Rosendahl 1994:34). The walls served as windbreaks, inhibited erosion, and slowed evapo-transpiration (Newman 1970:28,143; Smith and Schilt 1973:314); they also probably helped retain and disperse surface runoff after rainfall (Rosendahl 1994:35). Trails in the area were shallow, sometimes rock-lined depressions, or slightly elevated linear embankments extending across the contour of the landscape (east-west). They

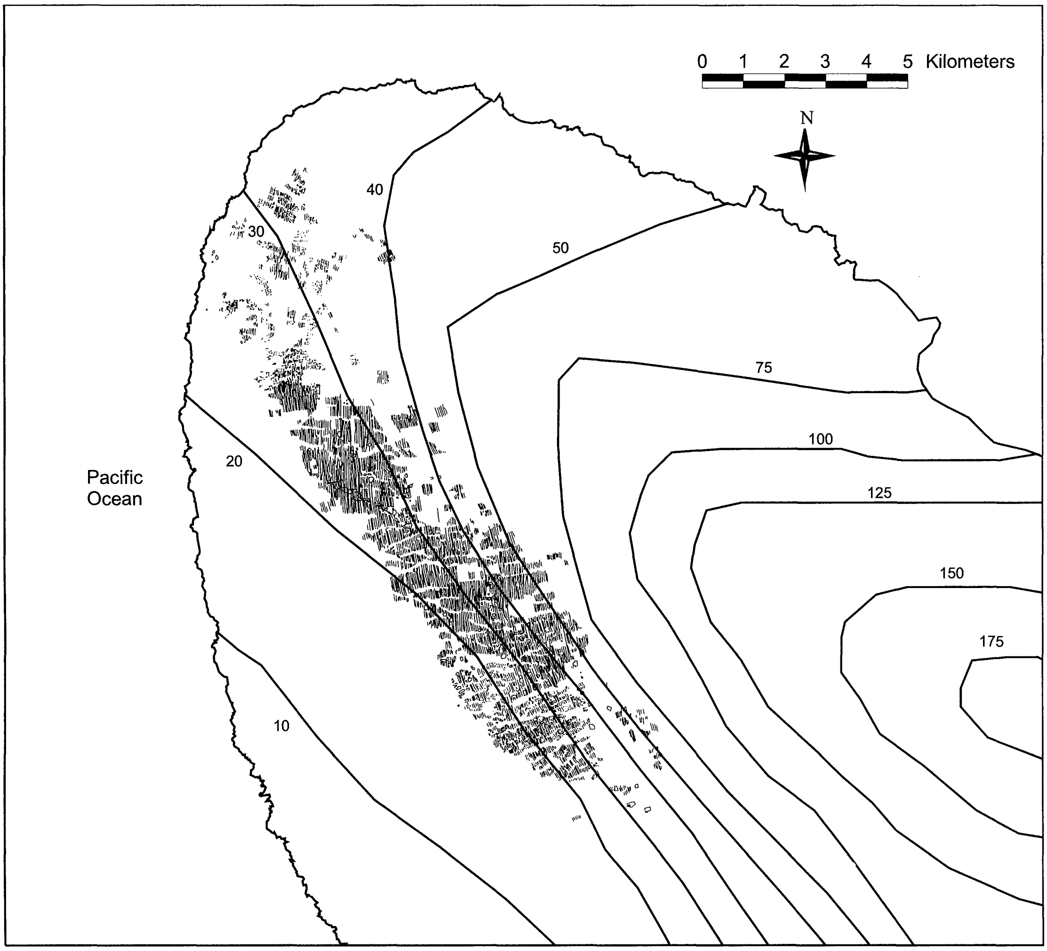

Figure 3. Annual rainfall isohyets in inches (after Armstrong 1983) in north Kohala with the agricultural field boundary walls superimposed.

generally intersected the long axis of border walls of field units and facilitated transport of people and goods from the coast to the uplands and back again. The rectilinear field units produced by the intersection of the raised walls and trails are associated with a variety of other features, including terraced garden areas, planting and clearing mounds, water catchments, enclosures, burial platforms and mounds, religious features, the foundations of residential structures, petroglyphs, and midden deposits (Rosendahl 1994:31–42).

Both archaeological and ethnohistoric sources document the array of cultigens grown in north Kohala. Carbonized segments of sweet potato (*Ipomoea batatas*), bitter yam (*Dioscorea bulbifera*), two species of cucurbits (*Sicyos* sp. and *Momordica charantia*), coconut (*Cocos nucifera*), and candlenut (*Aleurites moluccana*) were identified from excavations within the field system (Rosendahl and Yen 1971). Other available and edible plants would have included additional species and varieties of yams (*Dioscorea* spp.), dry-land taro (*Colocasia esculenta*), bananas (*Musa hybrids*), sugarcane (*Saacharum officinarum*), *ti* (*Cordyline terminalis*), and *'awa* (*Piper methysticum*) where suitable conditions for their cultivation prevailed (Newman 1970:119; Rosendahl 1994:63–64). Cultigens used for making bark cloth, containers, cordage, mats, and thatching also were likely grown within the borders and perhaps on the raised earthen walls of the fields (Handy 1940; Handy and Handy 1972).

The north Kohala field system is situated in the most environmentally diverse *moku* or district in all of Hawai'i Island (see Tuggle and Tomonari-Tuggle

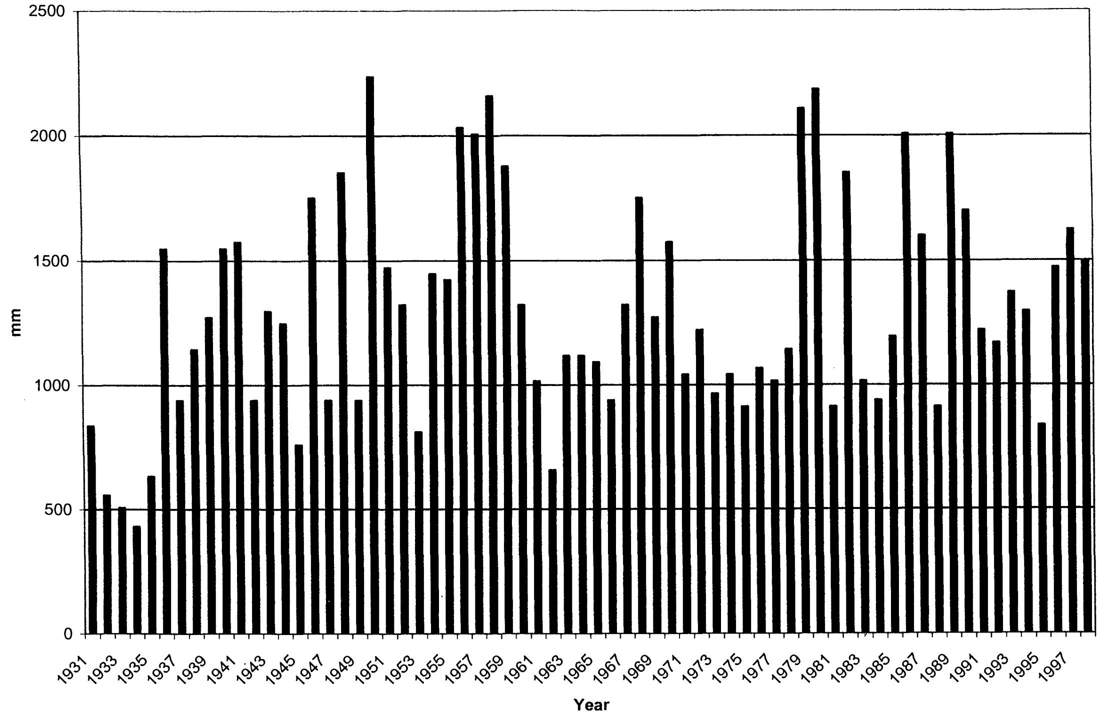

Figure 4. Annual rainfall at Kahua Ranch from 1931 to 1998.

1980). The district includes permanent stream valleys and minor drainages, wet coastal plains, arid coastal gulches, and the moderately wet upland gentle slopes on the leeward side of the Kohala Mountains where the dry-land field system is located (see Figure 1). Annual rainfall in Kohala ranges from less than 254 mm (10 inches) per year near the coast to more than 5080 mm (200 inches) in the mountains (Figure 3). The spatial distribution of rainfall is partly a function of elevation, for precipitation in Hawai'i is orographic and as elevation increases so does rainfall. It also is influenced by the dominant northeast trade winds, and localities nearer to the northeast windward side of Hawai'i are wetter than those farther away. Rainfall also is affected by the ridge line of the Kohala Mountains. Approaching the ridge line in the south of Kohala, variability in annual rainfall is geographically "bunched" so that increasingly shorter distances separate rainfall isohyets (lines connecting points of equal annual rainfall). At the same time, as elevation increases cooler temperatures occur, crop maturity is delayed, and in some areas woodlands are replaced by relatively denser forest. There is temporal as well as spatial variation in rainfall. Annual rainfall data for Kahua Ranch (located close to the uppermost walls in Kahua 2 *ahupua'a* at an elevation of ca. 1000 m) from 1931 to 1998 suggest that droughts frequently occur in the area (Figure 4).

Recently, Ladefoged et al. (1996) tested two related hypotheses about the north Kohala field system. The first proposed that variation in the distribution of rainfall, elevation, and soils constrained further geographic expansion of the field system boundaries (Kirch 1984:188–189, 1985:233–234, 1990:333, 1994; Murabayashi 1970; Newman 1970:117). The second hypothesis stipulated that because of limitations of the environment and culture, the north Kohala field system also had approached its maximum level of intensification (Kirch 1984:191, 1994:265; Newman 1970:152; Tuggle and Tomonari-Tuggle 1980:311). Our analyses (Ladefoged et al. 1996) demonstrated a link between several environmental variables and the boundaries of the field system, supporting the hypothesis that further contiguous geographic expansion of fixed-field dry-land agriculture was not feasible. The western boundary of the field system is defined by differential soil distributions and the ca. 457–508 mm (18–20 inch) rainfall isohyet. Because of the region's topography, this rainfall boundary is located farther and farther inland from the coast as the field system extends to the south (see Figure 3). Much of the eastern and the southeastern boundary is defined by an upper elevation of ca. 800 m where greater rainfall and cooler temperatures may have combined to increase the density of vegetation that needed to be cleared for agriculture and the time it took for plants to reach maturity.

Identification of intensification within dry-land field systems may seem anomalous. However, Kirch (1992:258–260) notes that the construction of agricultural infrastructure in the form of walls and the additional partitioning of plots with new, shorter walls can be viewed as one form of intensification–landesque capital intensification. While we have empirical support for the proposition that the extensive limits of the field system had been reached, there is no such evidence to suggest that intensification was so constrained by individual environmental variables. Rather, the level of agricultural intensification—measured by the density of walls—within the north Kohala field system varied across the more than 30 *ahupua'a* of North Kohala. As it turns out, the *ahupua'a* of Lapakahi where much of the archaeological research has been focused shows evidence of considerable agricultural intensification. Although there was geographic variation in the degree of intensification, there often was considerable variation in agricultural wall density within *ahupua'a* and between adjacent or nearby *ahupua'a* with similar environmental and geographic characteristics. Distance to the coastline of the field system, marine resource potential, and social factors were hypothesized (but not tested) to account for the observed differences in terminal levels of intensification in north Kohala (Ladefoged et al. 1996). This previous study took a synchronic view of the GIS data. One goal of the present paper is to describe and test evolutionary ecological models that include both social and ecological components in the *differential timing* of the establishment and intensification of dry-land agriculture in different parts of north Kohala.

Monitoring the Historical Development of the North Kohala Field System

Efforts to develop historical accounts of changing patterns of human occupation and land use in north Kohala have relied on extrapolating from small spatial samples to the larger field system. The pattern of agricultural development suggested by Rosendahl's (1972, 1994) extensive mapping of a section of the Lapakahi *ahupua'a* field system along with detailed mapping of its coastal settlement of Koaie (Tuggle and Griffin, ed. 1973) and supplemented by excavations and specialized analyses (e.g., Choy 1973; Connor 1968; Kaschko 1973; Newman 1970; Pearson 1968; Smith et al. 1973; Sugiyama 1973; Winter 1968) have been extrapolated to propose a sequence of occupation and agricultural change for all of north Kohala (Kirch 1984:181–192, 1985:233–235, 1990, 1994:258–259; Rosendahl 1994:20–22). Although there is debate concerning the timing of agricultural development in north Kohala (see Ladefoged et al. 1996:864), it is thought that the initial expansion of agriculture into the uplands surrounding the Kohala coast took place ca. A.D. 1300 to 1500 through a strategy of increased mobility and the adoption of shifting cultivation, likely involving regular burning of primary and secondary vegetation (Rosendahl 1972; Kirch 1984:181–192, 1985, 1990, 1994:258–259). The main development of the fixed-field agricultural system took place between A.D. 1450 and 1800 (Rosendahl 1972; Kirch 1984, 1995), although Rosendahl (1994:20–22) has recently suggested that the development of bounded fields occurred no earlier than the sixteenth century. By the late seventeenth century, the lateral expansion of the field system had been reached (Kirch 1984:189), and by A.D. 1800 the system was highly intensified. Kirch (1994:258) suggests the system was abandoned shortly after European contact in the late eighteenth or early nineteenth century, whereas Rosendahl (1994:20–22) suggests intensified dry-land cultivation continued well into the contact period, perhaps as late as A.D. 1850. Nonetheless, all researchers agree that the built portion of this large field system was constructed over a period of no more than about three or four centuries.

This developmental sequence for north Kohala remains largely unilinear in form and is based to a large extent on extrapolating from the work of Rosendahl (1972, 1994) and Newman (1970) in the single *ahupua'a* of Lapakahi. As an alternative, our GIS analysis of data from virtually the entire field system allows us to propose a sequence that incorporates differential rates of development in localized areas throughout the region. Although there are few chronometric dates that can be used to propose a chronology for the entire field system, Rosendahl

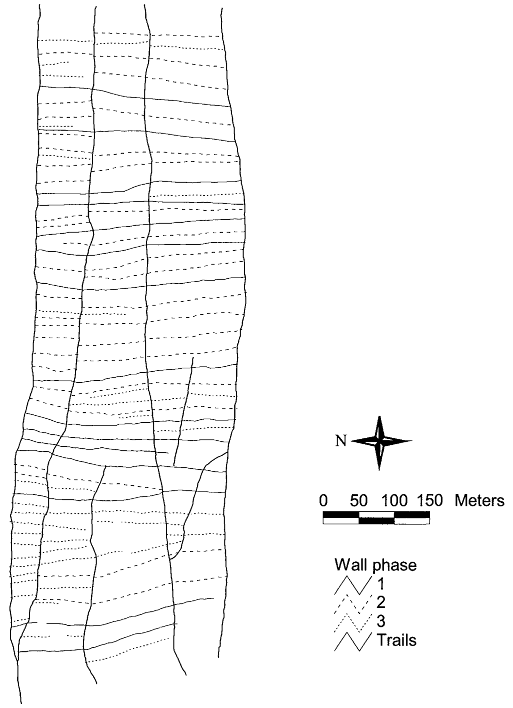

Figure 5. A section of the north Kohala field system from Lapakahi which shows trails (and their branches) and the field boundary walls (after Kirch 1984:185). Most of the earliest phase 1 and longest walls identified by Kirch (1984) extend from one major trail to the other. Phase 2 walls extend from one major trail but do not extend fully to the other and often are intersected by branching trails. Phase 3 walls are bounded by one or more branching trails and often are offset from other walls. Phase 1 walls average 265 m (s.d. = 67); phase 2 walls average 140 m (s.d. = 79); phase 3 walls average 76 m (s.d.= 40).

(1972:510) originally identified, and Kirch (1984:185) subsequently demonstrated, that the process of agricultural development in a section or *'ili* of Lapakahi *ahupua'a* (Figure 5) could be modeled by "matching and mismatching patterns of trail and field border (wall) interactions" (Rosendahl 1972:510). Recall that trails in north Kohala are relatively long and continuous coastal to inland pathways running east-west and that field border walls are the north-south embanked earthen and rock alignments which parallel the landscape contours. Kirch (1984:185) noted that the trails in the region often branch off from one another, in a drenditic pattern, so it is possible to determine the relative order in which the trails were built. The field border walls and trails often intersect.

This means that once the relative order of the trails has been determined it is possible to determine the relative construction order of the intersecting walls. When a wall extends continuously across a trail, the wall's construction is earlier than the trail. When a wall terminates at a trail, forming an offset with surrounding walls, it was built later than, or at the same time, as the trail. Kirch's analysis of agricultural development shows that the walls extending from one "boundary" (Cordy and Kaschko 1980) or major trail to another major trail were the earliest constructed. These major trails were those which extended from near to the coastal settlements to inland locations at Lapakahi (and most other *ahupua'a* in north Kohala) for various distances, running perpendicular to the slope. The longest field border walls extend from one major trail to the other, intersecting secondary trails where these occur, and would have been the first alignments constructed. Later additions of secondary and tertiary trails branching off from the major trails served to limit the length of new field border wall construction. Based on Rosendahl's (1972) detailed map of Lapakahi, Kirch (1984) observed that walls terminating at minor trails and which were not continuous across the section were later additions. Following these stipulations, Kirch (1984:185) concluded there were three phases of agricultural development. The first phase of development in Lapakahi involved the construction of 16 walls, 12 of which extended from one major trail to another (see Figure 5). The second phase involved the construction of a secondary trail and the addition of another 40 border walls which abut this trail. The final phase of development included the construction of several more trails and another 40 border walls. The process of agricultural development thus involved the infilling of larger field units by the construction of additional trails and shorter walls, which created ever-smaller field units.

This temporal sequence of field border wall construction can be modeled by the measurement of the lengths of the walls assigned to each of Kirch's phases. This measurement is relevant because the relative chronological order of the walls, based on their intersection with the branching trails, is consistent with decreasing size intervals of field border lengths. Using Lapakahi data, the mean length of the walls associated with each time period (phase 1=265 m, s.d. = 67; phase 2=140 m, s.d. = 79; phase 3 = 76 m, s.d. = 40) are statistically distinct and decreased across the three phases. This result confirms that the establishment of additional branching trails into the

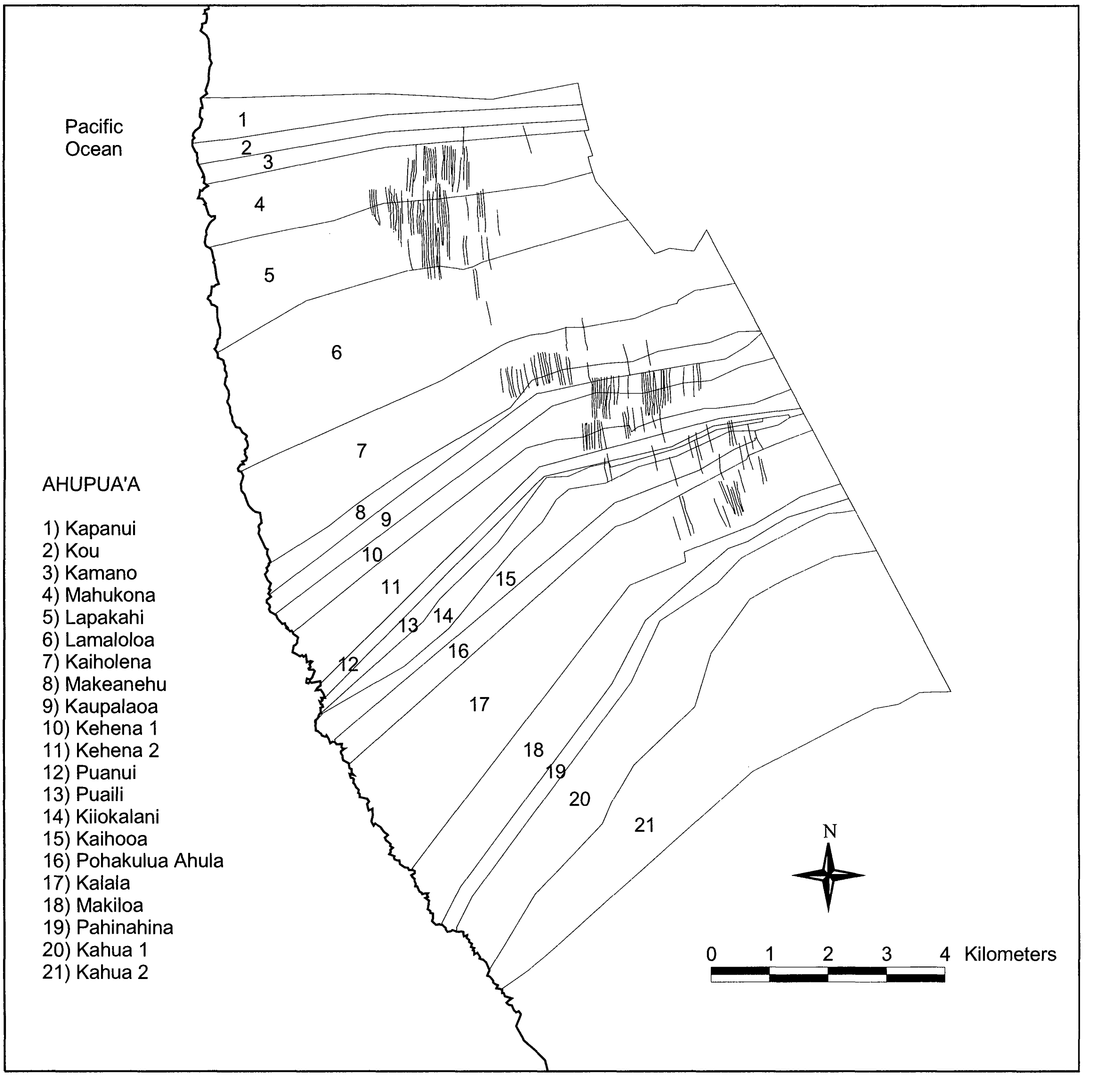

Figure 6. The contour field border walls assigned to TU 1 in north Kohala, showing locations where they are concentrated and their dispersion across a number of *ahupua'a* boundaries and at different elevations.

upper portions of the field system served to demarcate ever-smaller areas where additional walls would be built.

We extend Kirch's (1984) innovative approach to estimating relative agricultural development from the small section of Lapakahi to the entire north Kohala field system. Our GIS database of the north Kohala field system includes 4,579 sections of agricultural field border walls totaling 570 km in length, and 622 sections of trails totaling 190 km in length (see Ladefoged et al. 1996 for a discussion of the data set which is based on Tomonari-Tuggle ca. late 1970s). In this analysis we have removed the historic period cattle enclosures from consideration. Furthermore, the northern section of the field system has been disturbed by historic sugarcane production. Our analysis therefore focuses on the 3383 wall sections (totaling 504.4 km) that are located in the 21 *ahupua'a* extending from Kapaanui in the north to Kahua 2 in the south. In this area there are 433 trail segments totaling 166 km in length.

To model differential agricultural development, the region needs to be spatially subdivided and the agricultural walls in each subdivision assigned to a particular temporal unit. Ideally, these spatial subdivisions would be based on archaeological evidence

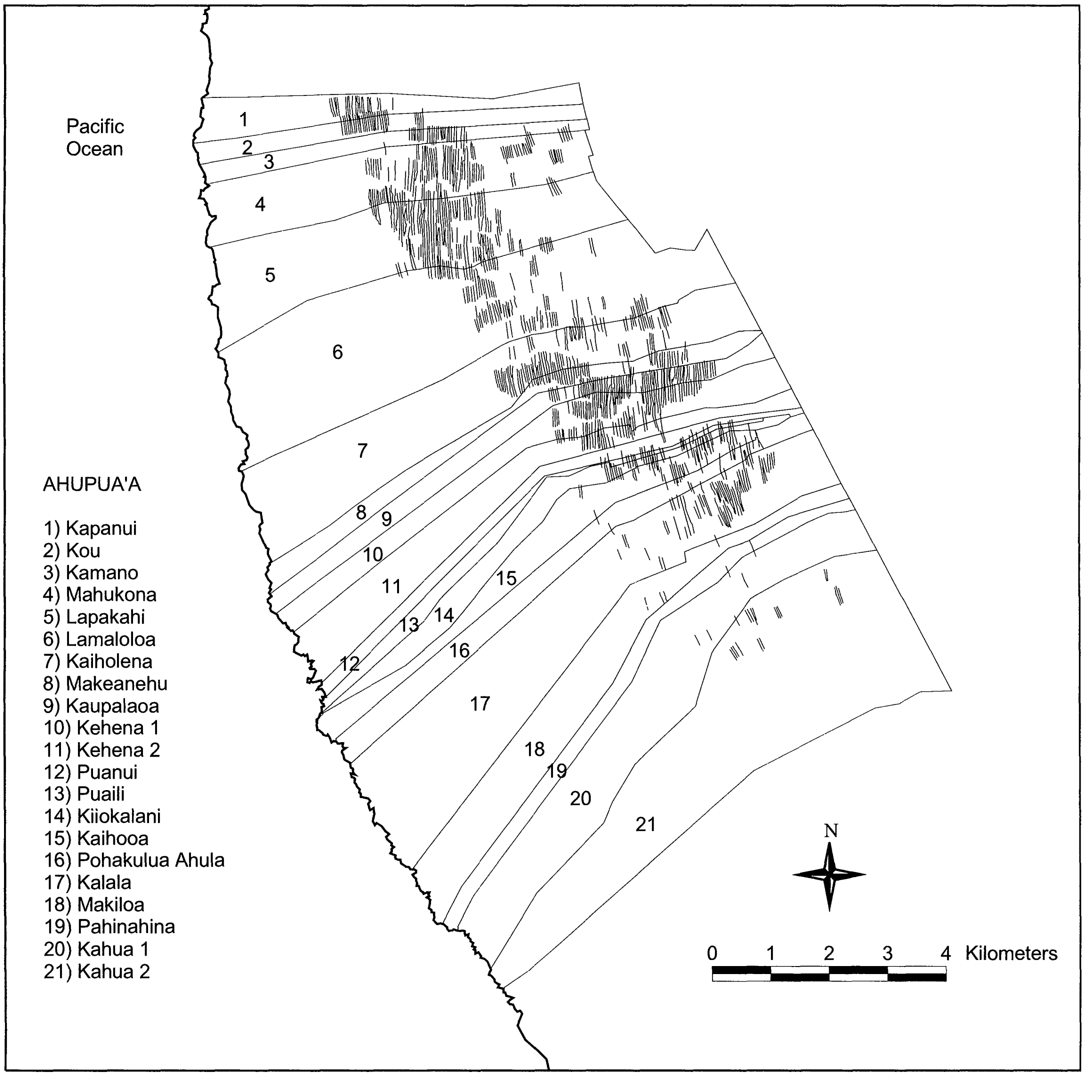

Figure 7. The contour field border walls assigned to TU 1 and TU 2, showing the infilling within established localities, their conformance to most *ahupua'a* boundaries and expansion of agricultural areas to the south, and up and down slope from established localities.

and would provide the units for analysis. Cordy and Kaschko (1980; and see Kaschko 1973) used the interconnections of trails in Lapakahi to define social units and model the process of subdivision. Unfortunately, trails are not well delineated on the aerial photographs which comprise the data base for the field system GIS. As an alternative, the community or *ahupua'a* boundaries originally recorded during the mid-nineteenth century and now depicted on USGS topographic maps were used to spatially subdivide the north Kohala field system. In many cases, these boundaries coincide with major archaeological trails and form boundary edges for the field border walls depicted in the GIS. This coincidence suggests that *ahupua'a* boundaries can be used as a proxy for spatially subdividing the north Kohala field system.

To monitor change in agricultural development in north Kohala, the length of each field border wall was first calculated, and then it was assigned to one of three temporal units based on intervals of wall lengths. Finally, each wall assigned to a particular temporal unit was then associated with the *ahupua'a* within which it occurred. Note that in some cases, walls extend across *ahupua'a* boundaries and the sections which fell within each *ahupua'a* were measured as well. We followed Kirch (1984) who suggested that the construction of subsequent branching trails limited the length of later field border walls, and that in general this led to a decrease in field border length through time. Each wall was assigned to a particular temporal unit on the basis of its length.[2] After considering a number of cut-off points for the three temporal units we chose three intervals: 1) walls whose length was greater than 400 m were placed in temporal unit 1; 2) those with lengths between 200 and 400 m were assigned to temporal unit 2; and 3) those less than 200 m were placed in temporal unit 3. The break between TU 2 and 3 corresponds with the separation between Kirch's phase 1 and phase 2 (which itself was based on the separation of walls abutting trails of different rank). The break between TU 1 and 2 was determined so as to have similarly scaled intervals where possible and was based on differences in the frequency of walls of different lengths in each of these two temporal intervals.

The Geographic and Temporal Pattern of Dry-land Agriculture in North Kohala

Agricultural development in the 21 *ahupua'a* of north Kohala can be monitored by considering the geographic distribution of the field alignments during the three temporal units (TU). The distribution of alignments assigned to TU 1 is shown in Figure 6. While Hawaiians were experimenting with fixed-field dry-land agriculture throughout the region at this time, there are two areas where the bulk of the early agricultural plots were established. The first area was in Mahukona and Lapakahi *ahupua'a*, and the second area focused on the *ahupua'a* of Kaupalaoa and Kehena 1. The three *ahupua'a* between Lapakahi and Kaupalaoa show evidence of limited agricultural development during this interval, but it was significantly less than these two areas. To the south of Kehena 1 and extending to Kalala, there is little evidence of agricultural development during TU 1; it was limited and substantially less than the four main *ahupua'a* comprising the two focal areas. South of Kalala there is no evidence of early fixed-field agriculture.

During the second interval of agricultural development, localities that were previously under cultivation were further subdivided, and plots were established in new localities both within and in adjacent *ahupua'a* (Figure 7). To the north of Mahukona and Lapakahi, at least three additional *ahupua'a* were brought under fixed-field agricultural production. The localities within Mahukona and Lapakahi that had been established during TU 1 show evidence of considerable infilling or additions at their peripheries with shorter field border walls assigned to TU 2. Several new localities, mostly at higher elevations and rainfall, within these two *ahupua'a* were established during TU 2. The *ahupua'a* between Lapakahi and Kaupalaoa which in TU 1 had few agricultural walls show signs of considerable expansion and intensification during TU 2. The second area of early established fields in Kaupalaoa and Kehena 1 was further developed with infilling between existing fields and the extension of fields up and down slope. A considerable number of walls were built during TU 2 in the *ahupua'a* of Puaili to Kalala. The four southernmost *ahupua'a* show evidence of limited, scattered field border wall construction during TU 2.

The final interval of agricultural development, TU 3, is marked for the most part by an infilling or intensification of the localities previously under production and extension down slope and up slope in a few areas. This interval also saw the establishment and growth of a new focal area for dry-land agriculture to the south of the main productive center (Figure 8). Notably, the southern *ahupua'a* of Makiloa, Pahinahina, and Kahua 1 show considerable addition of fields to the areas previously established during TU 2.

The overall growth pattern of the field system emerged by identifying these three temporal units, distinguished by distinct intervals of field border wall lengths. During TU 1, 171 alignments were constructed with a total length of approximately 99 km, followed by an additional 619 alignments with a total length of 169 km during TU 2, and a final 2592 alignments with a total length of 237 km were built in TU 3. The infrastructural additions during each TU indicate that only ca. 20 percent of the total length of the field system was built during the first interval despite the greater length of individual walls; the bulk of the construction of field border walls occurred during the latter two intervals, with 33 percent assigned to TU 2 and 47 percent to TU 3

Evolutionary Aspects of Dry-Land Farming in North Kohala

To place the field border walls within an evolutionary framework two issues need to be resolved: 1) how the engineering or design of these walls would have affected the success of dry-land cultivation; and 2)

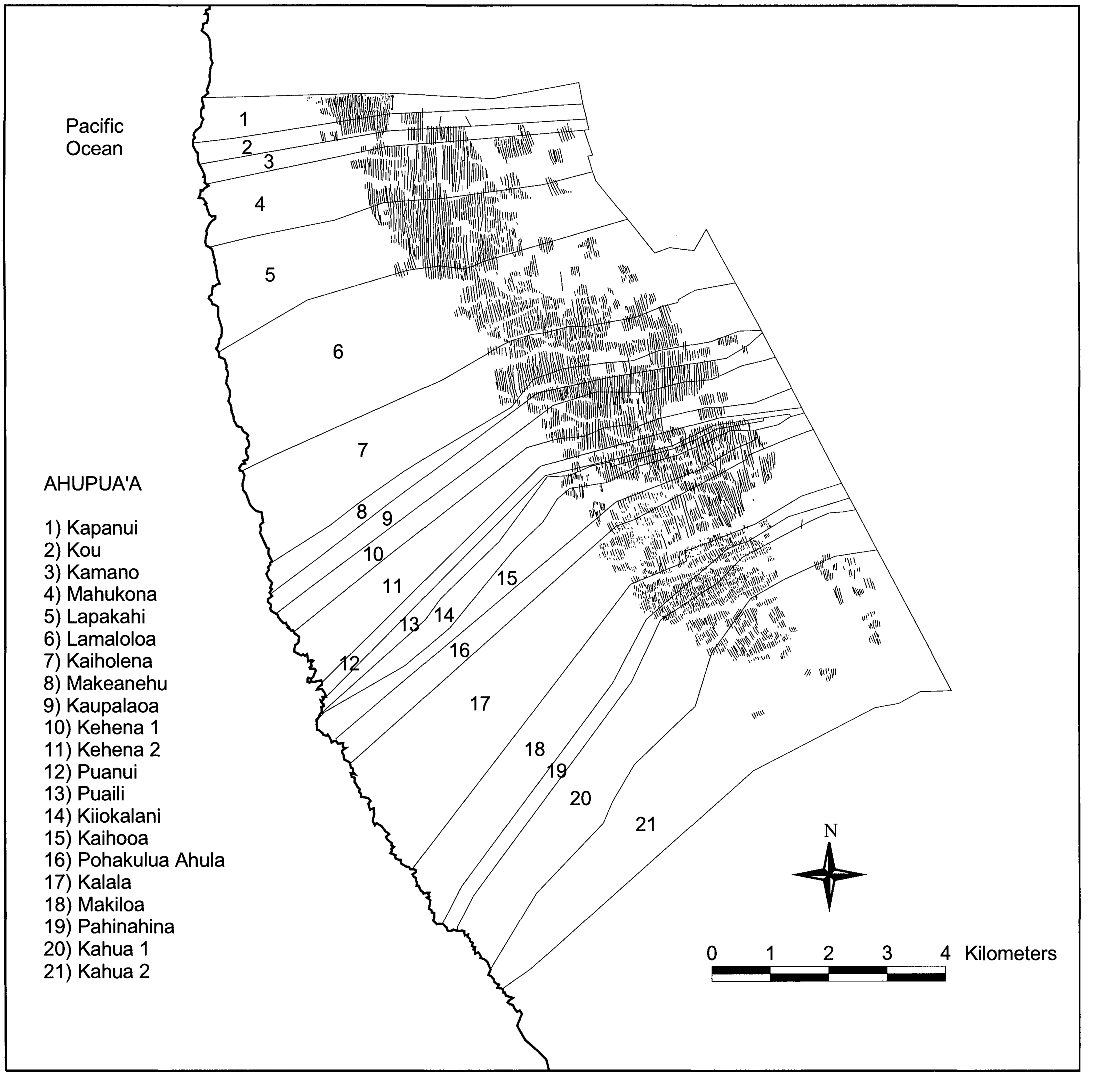

Figure 8. The contour field border walls assigned to TU1, TU 2, and TU 3, showing the final interval of infilling and development, especially in the southern *ahupua'a*.

the identification of traits associated with field border walls that we believe track functional variability in evolutionary terms. Regarding the first, Lyman and O'Brien (1998:629) advocate identifying the properties of artifacts that would have a positive fitness value, and whereas they speak of mechanical properties, one also can address this through physical performance properties. There are at least four aspects of field border wall construction that would sustain or improve harvest output. First, the dominant northeast trade winds blows through Hawai'i for more than 50 percent of the time throughout the year. While the trade winds bring moisture-laden air to the region and this results in rainfall, especially along the northeast coasts of the islands, along the leeward coast of North Kohala, this wind flow brings less rainfall. These winds also tend to blow across the contour of the land (Newman 1970:28) and when coupled with high annual surface insolation, this results in potentially high rates of evapotranspiration and greater stress on cultigens. The construction of field border walls parallel to the contours of the land created an uneven surface topography and breaks up wind flow along the surface of the ground (Newman 1970:143). This would have had the effect of decreasing evapotranspiration of moisture from plants and the soils in which they were planted. If plantings of shrubs or small trees, i.e., wind breaks, were placed on the field border walls, these would have further lowered the rate of wind flow directly over the surface of the fields.

Second, the clearing of land for agriculture involves the removal not only of large vegetation but also the disruption of herbaceous vegetation and ground cover. In the context of north Kohala with brisk winds, periodic rain storms, and a sloping landscape, erosion of soils would have been a potential problem. Indeed, the effects of erosion on prehistoric Pacific Island agricultural landscapes has now been well documented (Kirch 1997; Spriggs 1997). The construction of field border walls along the contours of the landscape in north Kohala limited the extent and impact of surface erosion to the area between these walls. While only a few excavations have been carried out in any of the fields of north Kohala, those by Newman (1970) at ca. 300 m elevation in Lapakahi do indicate that some of the field border walls were constructed over an earlier episode of clearing (indicated by a thin cultural layer) and possible erosion (indicated by a layer of variable thickness with few cultural materials).

Third, the construction of field border walls occurred by the removal of cobble-sized and larger rocks from the surface and near-surface contexts. There also is evidence from the detailed mapping done by both Newman (1970) and Rosendahl (1972, 1994) that stones were used in the construction of residential architecture and also were piled up as cairns within fields. The removal of these rocks from agricultural areas would have improved productivity by increasing the total area that could be farmed, reducing surface heat retention (and by extension evapotranspiration), and improving the suitability of the soils for the growth of root crops such as sweet potatoes.

Finally, the use of fixed and permanent field boundaries through the construction of walls and intersecting trails was a means by which different social units materially expressed their agricultural territories. As such, then, these boundaries served to regulate competition over land and excluded areas (and their attendant resources) from use or appropriation by others. The effort invested in building permanent field boundaries limited subsequent energy that might have needed to be redirected in addressing challenges from others over the same area of land. While not a design feature in the same sense as those previously listed, the exclusion of others from agricultural plots via wall construction increased the effort that could be directly devoted to agricultural pursuits by way of limiting competition.

For evolutionary archaeologists functional variability refers to those artifact classes whose distributional features are shaped by selection (Dunnell 1978). Whereas archaeologists usually examine the historical distribution of such classes and their association with changing environmental characteristics or parameters, we also may identify functional features by their association with environmental structure. The latter is the approach taken by evolutionary ecologists, and the features so identified are "adaptations," the outcome of selection at some interval of time. The artifacts we examine are agricultural walls. The attributes of groups of walls whose variation we analyze as measures of functional variability include: 1) the frequency of field border walls; 2) the density of field border walls, our measure of the level of agricultural intensification; and 3) the shape and size of agricultural plots. We evaluate the spatial distribution of these attributes of groups of walls in relation to three aspects of the environmental structure. These are 1) the variability in marine productivity along the north Kohala coast, 2) the distance from the coast to agriculturally productive areas, and 3) spatial variability in annual rainfall. We suggest that when the spatial distribution of attributes of wall groups correspond to environmental or geographic parameters or changes in these parameters, and we can use empirical or experimental data to specify the relative advantages of these changes, then they have been fixed by selection or were in the process of being sorted through selection.

Frequency of Fields

One measure of functional variability in dry-land agriculture is provided by the frequency of fixed-fields demarcated by permanent wall construction in different locations. Location refers to the geographic position of field borders across the north Kohala landscape. On Hawai'i, the earliest agricultural development of the uplands is thought to have occurred during the "Expansion Period" (see Graves and Ladefoged 1991a; Hommon 1986; Kirch 1985:303; cf. Rosendahl 1972, 1994), from approximately A.D. 1300 to 1500. At this time people lived in relatively autonomous coastal settlements, geographically separated from one another (Cordy and Kaschko 1980) and at some point during this interval the uplands were first used for shifting agriculture and subsequently dry-land fixed-fields were established.

Ladefoged et al. (1996:876) hypothesized that early coastal settlements and early uplands agriculture were situated at locations with access to good marine resources because these resources would have provided the bulk of the protein in the diet. This is consistent with other research suggesting a correlation in Hawai'i between population size and shoreline areas (Beckerman 1977). To assess this hypothesis we follow Kirch (1985:207–208), who observed there is considerable variation in the marine resources throughout the Hawaiian archipelago, especially with regard to the in-shore fisheries (from the shoreline to 60 m below sea level) that were traditionally emphasized by Hawaiian marine procurement (Newman 1972a). We note that along this section of Kohala there are three main bays that would have had relatively higher levels of marine resources due to the formation of large protected bays by extended points of land. These bays include: 1) Mahukona Bay in Mahukona *ahupua'a*; 2) Keawanui Bay in Kehena 1 and 2 *ahupua'a*; and 3) Waiakailio Bay in Pahinahina and Kahua 1 *ahupua'a* (see Figure 1). While upland agricultural development took place in various parts of the region during TU 1, it is geographically focused in the *ahupua'a* associated with two of these bays, Mahukona Bay and Keawanui Bay. The date of initial settlement in Keawanui Bay is unknown, but the initial occupation of Lapakahi adjacent to Mahukona Bay has been dated to approximately A.D. 1300—the earliest date for the north Kohala coast (Tuggle and Griffin 1973) and is consistent with our identification of early fields in the nearby uplands. Waiakailio Bay, the third area along the Kohala coast with high marine resource potential, was evidently not occupied until much later. The earliest known dates for the area are from excavations at a coastal residential site (50–10-05-4015) in Kahua 1. These dates suggest that the site was not occupied until approximately the seventeenth century (O'Hare and Goodfellow 1995:47–49). O'Connor's (1998) seriation of residential features in the area supports this result and suggests that the southern portion of north Kohala was occupied late and for a relatively short period of time just prior to European contract. Significantly, the uplands of the *ahupua'a* around Waiakailio Bay had relatively low levels of agricultural development during TU 1 and TU 2.

Another critical variable in understanding spatial and temporal variation in the number of dry-land agricultural fields is the distance from the coast to areas in the uplands where crops could be grown. This distance variable represents an additional cost in agricultural effort especially if, as has been suggested for other areas of Hawai'i (see Allen and McAnany 1994 for particular references and a discussion of the topic), there was periodic movement of people and goods from the coast to the fields and back again. This is similar to the view from optimal foraging theory (see Winterhalder 1981) that the time involved in search and transport of prey incurs additional costs for predators. Here, the travel time necessary to move resources, marine protein from the ocean and plant carbohydrates from agricultural fields, incurs an additional energy cost. Clearly, the longer groups can stay in the uplands without moving back to the coast (or vice versa), the lower the movement costs. However, the need for periodic movement of people and marine resources to the uplands and cultigens to the coast will set an upper limit on how long groups can remain in the uplands.

In the case of the north Kohala field system, the ability to produce reliable quantities of agriculture would to a large extent be a function of increasing rainfall, and this increases with elevation, which in turn increases with distance from the coast as one moves from north to south. Thus, we would expect an inverse relationship between the time when fields were constructed and distance from the coast to the nearest fields. This is indeed the case, with TU 1 walls (mean distance = 5.399 km, s.d = 1.605) generally being located closer to the coast than TU 2 walls (mean distance = 5.499 km, s.d. = 1.570), and TU 2 walls generally being located closer to the coast than TU 3 walls (mean distance = 6.161 km, s.d. = 1.412). An analysis of variance (ANOVA) suggests that the mean distance from the coast to the agricultural fields of each of the three temporal units are significantly different ($F = 133.28$, $p < .001$).

Density of Field Border Walls

The relative density of field border walls represents the second aspect of functional variability we examine from an evolutionary perspective. We use density here in order to control for the different areas associated with the 21 *ahupua'a* included in this

Table 1. Agricultural and Rainfall Data from the Kohala Field System.

Ahupua'a	TU 1 length (meters)	TU 2 length (meters)	TU 3 length (meters)	Ahupua'a area (hectare)	TU 1 density (m/ha)	TU 2 density (m/ha)	TU 3 density (m/ha)	Distance to field (km)	RV (mm/km)
Kapaanui	0	7804	5299	110.8	0	70.4	47.8	1.788	124
Kou	0	7878	3062	98.8	0	79.7	31.0	2.147	131
Kamano	406	6144	2005	96.2	4.2	63.9	20.8	2.722	136
Mahukona	18357	17479	13703	329.1	55.8	53.1	41.6	2.49	159
Lapakahi	25244	17871	16420	376.8	67.0	47.4	43.6	2.823	187
Lamaloloa	2926	26830	27397	473.2	6.2	56.7	57.9	3.759	247
Kaiholena	8624	16066	19192	255.1	33.8	63.0	75.2	4.51	272
Makeanehu	3487	6897	5969	111.7	31.2	61.8	53.5	5.206	275
Kaupalaoa	7982	10028	5804	104.1	76.7	96.3	55.7	5.411	289
Kehena 1	12983	11540	8470	178.3	72.8	64.7	47.5	5.449	315
Kehena 2	3652	3077	6063	81.3	44.9	37.9	74.6	5.452	319
Puanui	787	1520	7023	61.7	12.8	24.7	113.9	5.808	326
Puaili	526	1913	2187	22.0	23.9	86.9	99.3	5.748	322
Kiiokalani	1585	4499	4501	57.8	27.4	77.8	77.8	5.642	342
Kaihooa	2802	6884	10556	137.7	20.4	50.0	76.7	5.679	346
Pohakulua Ahula	1048	2316	8758	101.3	10.3	22.9	86.5	5.479	348
Kalala	8291	12357	22746	340.3	24.4	36.3	66.8	5.499	348
Makiloa	0	775	13748	109.4	0	7.1	125.6	6.023	342
Pahinahina	0	314	10814	74.4	0	4.2	145.3	6.365	340
Kahua 1	0	978	20866	198.1	0	4.9	105.3	6.502	345
Kahua 2	0	4530	20564	573.7	0	7.9	35.8	6.324	345

Note: TU 1 length = the total length of field borders associated with temporal interval 1; TU 2 length = the total length of field borders associated with temporal interval 2; TU 3 length = the total length of field borders associated with temporal interval 3; Ahupua'a area = the area within the ahupua'a that contains agricultural walls; Distance to field = the distance from the coast to the closest field border within an ahupua'a; RV = the change in annual rainfall per kilometer

study. Density was calculated by measuring the total length of field border walls constructed within a given temporal unit within an *ahupua'a* and then dividing this by the total agricultural area assigned to that geographic unit. The density of walls constructed in any given *ahupua'a* and assigned to one of three temporal intervals is a measure of effort and our proxy measure for agricultural intensification. As Table 1 and Figure 9 illustrate, there is considerable spatial and temporal variation across the 21 communities in north Kohala with respect to field border wall density. This variability can be linked to several proximate variables, including marine productivity, distance from the coast to agriculturally productive areas, and the distribution of rain.

Table 1 lists the distance from the coastline to the nearest field in each *ahupua'a* and the density of field alignments constructed during the three intervals. There is a non-significant moderate inverse correlation (r = -.295, p=.19) between the distance measure and the density of walls constructed in TU 1. However, there is a significant inverse correlation (r = –.610, p=.003) between the distance measure and the density of walls constructed in TU 2. During the middle temporal unit, as distance increased to upland agricultural locations in north Kohala, farmers devoted proportionately less energy to infrastructural investments despite the advantages of fixed-field agriculture. Furthermore, there is a strong positive correlation (r = .732, p < .001) between the distance inland and the density of field alignments constructed during TU 3. These analyses support the propositions that early agricultural walls were constructed in areas closer to the coast than later walls. This suggests that a few areas were targeted for fixed-field agricultural establishment because of their proximity to good marine resources, and that additional investments in agriculture during TU 2 were structured by distance from arable land to the coast across all of the *ahupua'a.* This last feature changed when late in the region's history a new set of socio-political environmental parameters appeared, and these provided a selective advantage to fixed-field dryland agriculture in areas of north Kohala where it was not previously well represented.

A second important factor related to the density

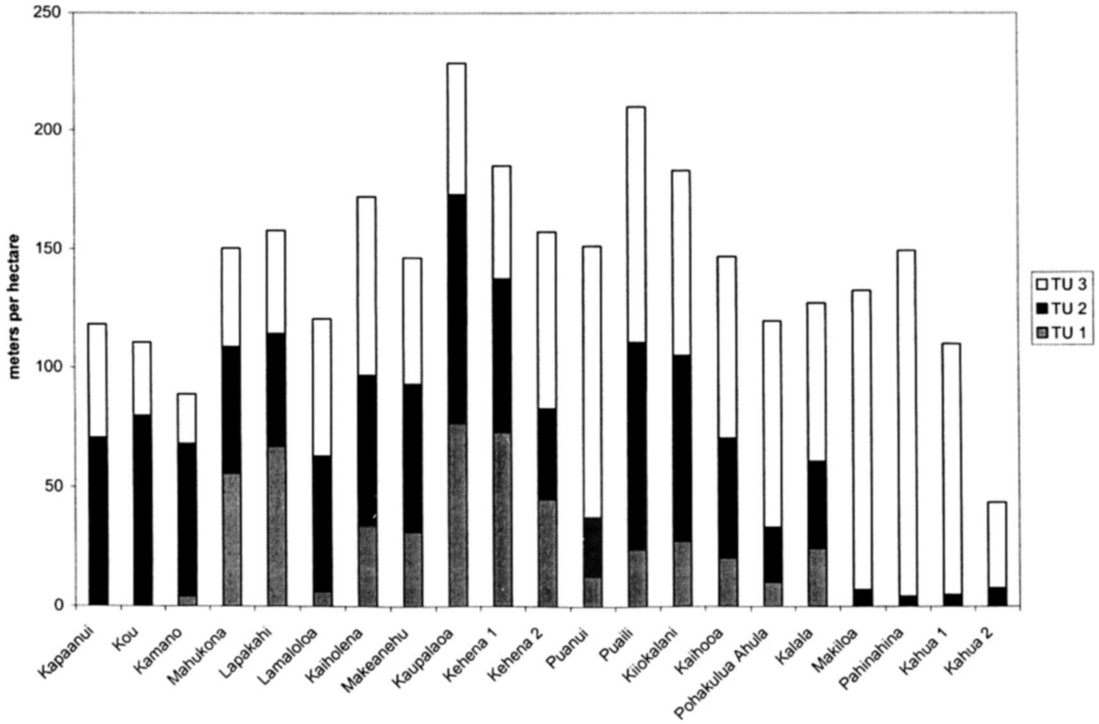

Figure 9. Levels of field border wall densities by temporal unit in the 21 *ahupua'a* of north Kohala employed in this analysis, ordered from north to south along the x axis.

of field border walls was the spatial variability in annual rainfall. The critical amount of rainfall for growing sweet potato is approximately 500 mm or 20 inches per year (Kay 1973, cited in Norman et al. 1984:248), but Purseglove (1968:82) maintains that they grow best with 762 to 1270 mm (30 to 50 inches) per year. The rainfall isohyets for north Kohala are depicted in Figure 3. All of the TU 1 walls, and 96 percent of the TU 2 walls, are located in areas that receive more than 508 mm (20 inches) of rainfall per year. In contrast 20 percent of the TU 3 walls are located in areas that receive less than 508 mm (20 inches) of rainfall per year, indicating that during this time walls were constructed in more marginal areas down slope but where transport costs would have been reduced.

In addition, areas in north Kohala with greater variation in the spatial distribution of rainfall are located in the middle to southern portions of the upland field system. In these areas the rainfall isohyets are compressed due to the increasing slope of the land, forming areas where optimal rainfall varies dramatically over a relatively short distance. A measure of this phenomena is the change in rainfall per kilometer distance. We have calculated this measure by dividing 762 (the difference between 1270 and 508) by the minimum distance in each *ahupua'a* between the 508 mm isohyet and the 1270 mm isohyet.[3] We refer to this measure as the rainfall variability index (RV), and the values of the index for each *ahupua'a* are given in Table 1. Smaller RV values indicate that similar amounts of optimal rainfall are distributed over larger areas, whereas larger RV values indicate greater variation in rainfall over smaller areas. There is no significant correlation between the density of walls constructed in TU 1 and the RV indices (r = –.144, p=.533), perhaps suggesting that during TU 1 people were experimenting with the placement of fixed-fields in various rainfall zones. The inverse correlation between the density of walls constructed in TU 2 and the RV values (r = –.575, p=.006) suggests that during this time additional walls were constructed in areas of optimal rainfall without compressed rainfall isohyets. In contrast the positive correlation (r = .619, p = .003) between the RV indexes and the density of alignments constructed during TU 3 suggests that the main agricultural thrust of intensification during this

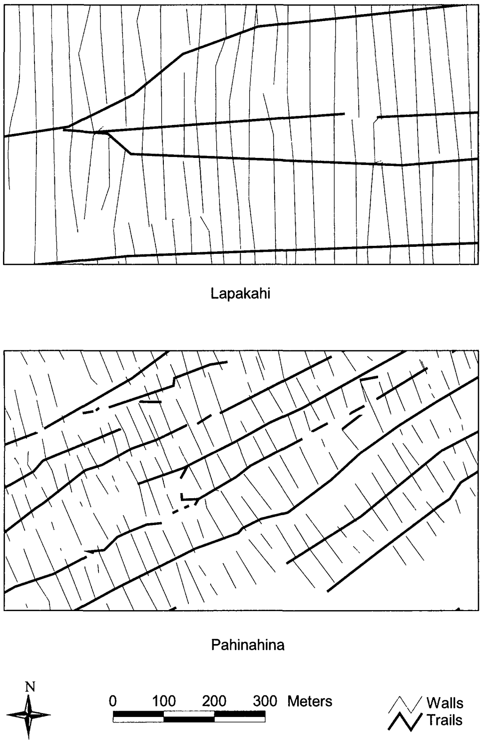

Figure 10. Representative maps of the fixed agricultural plots demarcated by field contour walls, and trails and/or field border alignments, in the *ahupua'a* of Lapakahi and Pahinahina from the final temporal interval showing differences in their size and shape.

time was located in marginal zones, areas with greater variation in optimal rainfall over smaller distances.

Field Size and Shape

The third variable related to the field border walls pertains to the size and shape of the plots of land demarcated by these boundary walls. Data on this variable are most reliable for TU 3 when the field system took its final form. To illustrate, Figure 10 shows a subsection of the fixed-field plots in Lapakahi and in the southern *ahupua'a* of Pahinahina. The plots in Lapakahi are quite variable in size, and we estimate that they range from ca. .32 hectares to 1.37 hectares. In contrast, the plots in Pahinahina are relatively uniform with an average size of ca. .28 hectares.

One other measure that can be used in a functional analysis of agricultural plots is their shape. Agricultural plots whose dimensions along two axes are similarly scaled, i.e., that are shaped more like a square, have a higher ratio of area to perimeter than do plots whose dimensions are differently scaled, i.e., shaped like a rectangle. Thus, for the same total length of wall built to demarcate an agricultural plot, a shape closer to the form of a square will have a greater amount of surface area than one in the form of a rectangle. Such energy costs are likely to be evaluated differently in different kinds of environments. In the case of north Kohala, square-shaped fields are associated with the southern agricultural areas and required less effort to build than comparable rectangular fields that are the norm to the north.

The addition of 237 km of agricultural walls during TU 3 marks the largest infrastructural increase of the three intervals. Approximately 110 km of the walls established during this interval, or 46 percent, are located in the seven most southern *ahupua'a* (out of 21 total). This feature highlights again the nonuniform geographic nature of agricultural change in north Kohala and suggests that the southern portion of the district was targeted for dry-land agricultural intensification at this time. The morphology and size of the plots in this southern zone suggest that they were built uniformly small and as relatively square-shaped fields. The greater effort required because of the longer distances to arable land in the southern communities was ameliorated by building walls in more marginal rainfall zones (below 508 mm) downslope, and by economizing on the shape of fields to maximize area to walled perimeter ratios. There is little evidence of infilling over much of this section of north Kohala prior to the establishment of these agricultural features in TU 3. Rather, a whole new section of the field system was built over a relatively short period of time with small, square plots as the standard. Notably, the intensity levels reached in the southern *ahupua'a* were not necessarily greater than those of other *ahupua'a*, instead the alignments in the areas were used to form small discrete fields of similar size.

Conclusions

The heterogenous and changing social environment of north Kohala provided the context in which agricultural variability was sorted through selection. The result of this selection was that some individuals and their agricultural practices successfully adapted over time and across the landscape. For analytical purposes we assume that several characteristics of the environment were relatively stable through time but varied spatially. These included the geographic distribution of marine resources, the distribution of rainfall that created differences in the distance between the coast to areas where fields could be established, and the distribution of rainfall levels across the *ahupua'a* associated with the field system. Other characteristics of the environment changed through time. These include a change in the distribution of the human population from optimal to less optimal areas in north Kohala and an increase in population densities within these areas (Kirch 1984:187–190; Tuggle and Griffin 1973:61–63). In addition, when the uplands of north Kohala were first colonized for dry-land agriculture, there would have been some uncertainty surrounding the production of sweet potato in this environment. Most parts of leeward or west Hawai'i had been previously uncultivated at higher elevations, and sweet potato was a cultivar that had probably been introduced to the islands only a few centuries before. The sweet potato did not have the long history of co-evolutionary domestication that existed with other cultivars (e.g., taro) grown in other areas of Hawai'i and Polynesia. Hence, it may have taken some time for individuals to gain sufficient experience to fully exploit the potential of the crop in different environments and for this information to be exchanged with other individuals. Archaeologists working in Hawai'i also have argued that the degree of social autonomy and the level of chiefly control also changed through time during the interval represented in north Kohala by the field system. Initially coastal villages would have had relatively low levels of political interaction outside of their immediate communities. The interaction that did occur would have been predominately kin based. Through time (by the middle of TU 2 or TU 3) this situation changed, and local communities would have been integrated into regional polities which were organized under the auspices of local and regional chiefs (Cordy 1981; Hommon 1976, 1986; Kirch 1985).

We suggest that selection in these changing heterogenous conditions resulted in a shift in the relative frequency of the construction of agricultural walls from better or more optimal areas for supporting both marine resource procurement and dry-land farming to those of less quality or higher cost as measured by the energy invested in transport to fields and management of cultivars and rainfall distributions. As this occurred, additional costs were imposed on new increments of agricultural development and intensification. Most of these costs were transport related, but others included infrastructural investments ensuring reliable year-to-year outputs, the requirement of an adequate balance between protein and carbohydrates in the diet, and the possibility of crop failure because of insufficient rainfall.

Both directional and stabilizing selection modified aspects of agricultural production in north Kohala. Directional selection refers to "processes favoring one tail of a distribution and causing a directional shift in the mode of the distribution over time" whereas stabilizing selection involves "processes that limit the diversity of phenotypic variation" (Jones et al. 1995:27). In north Kohala, directional selection operated on two different domains: 1) the scale of agricultural production and 2) the scale of agricultural organization. In the first case, we conclude there was a trend towards geographically smaller production communities through time. This change is documented by the comparison of the early field border walls which cross *ahupua'a* boundaries (suggesting those boundaries did not exist at that time) with later field border walls which are largely contained within *ahupua'a* boundaries. Additionally, research at Lapakahi (Rosendahl 1994) shows that over time and in some *ahupua'a*, smaller social groups equivalent with *'ili* (sections within *ahupua'a*) may have been the maximal geographic units of production. These smaller units would have been managed by local chiefs (*konohiki*) that had developed by the late prehistoric period (Hommon 1986; Kirch 1985). There is a similar directional shift in the average size of fields, towards smaller average field size over time. This change occurred through either the further partitioning of larger fields into smaller segments as in the case of Lapakahi and other northern *ahupua'a*, or the establishment of small fields late in time in the southern *ahupua'a* of the district. We also infer although with less direct evidence an increase in the spatial scale at which the distribution of production was organized, beyond households within *'ili* or *ahupua'a* to include multiple communities within the North Kohala District and extending possibly among communities in different districts. The successful expansion of dry-land fixed-field agriculture into the southernmost and more marginal *ahupua'a* and the construction of small relatively uniform plots in this area late in time are the evidence in support of increase in the scale of distribution of production.

Furthermore, stabilizing selection also operated in north Kohala to produce less variable field sizes over time. Thus, while fields become smaller on average, they also show less relative variation in size, and variation in yields from agricultural plots may have been reduced. An additional stabilizing trend was that successive agricultural developments occurred in relatively close proximity to other developments associated with the same time interval. This process departs from the earliest period of agricultural development in any area of north Kohala where the walls were built in dispersed locations. In later periods the construction of walls was concentrated in fewer *ahupua'a* or in more limited locations within these communities.

Taken as a set, these five traits (the size of production communities, the size of fields, the level of distribution of production, the amount of variability in field size, and the spatial distribution of fields) coevolved through time in north Kohala. We propose that they evolved primarily as a response to changing aspects of energy optimality and risk. Here, risk is defined as the probability of a undesirable event (Stephens 1990), in this case, agricultural production falling below some minimum level to support those individuals dependent on it. The changes in dry-land agriculture in north Kohala previously described are consistent with selection resulting in a shift from early conditions in which production would have involved moderately high levels of risk at relatively low energy input costs, to later conditions of lower risk with higher input costs in which the total output of production increased. The reliability of production also would have increased, despite the fields being located in more marginal areas, due to increased levels of overproduction and political integration via a shift in the scale of agricultural distribution.

Prior to the settlement of leeward north Kohala, there would have been few if any agricultural fields in the uplands. When the area was first settled, people's knowledge of and previous success with growing sweet potatoes would have been minimal or limited. Furthermore, populations would have been clustered into a few localities of relatively autonomous coastal settlements without the regional integration that developed later. One agricultural option for these people was the construction of a high-density field system of small-sized fields in one restricted area. This would have created an agricultural resource base that would have provided adequate amounts of produce, but it would have been highly susceptible to environmental perturbations. In a sense, the inhabitants would have been putting all of their potatoes in one basket. The archaeological evidence suggests that this was not the strategy that was initially employed. Instead, selective pressures resulted in an agricultural field system that complied with the "law of large numbers" (Cashdan 1992). This "law" suggests that by increasing the number and range of agricultural fields, the expected return of produce more closely approximates the average annual return. In an environment where local knowledge was low and environmental perturbations occurred, we hypothesize that selection would have favored the construction of large spatially dispersed fields of variable size in areas relatively close to the coast. These dispersed fields would have been associated with distinct autonomous coastal communities. This strategy would have minimized the moderately high risks of a relatively low-cost agricultural system. It should be noted, however, that risk also was reduced by focusing on areas well above the 508 mm (20 inch) rainfall isohyet and where abundant marine resources were available to complement the diet.

During TU2 the knowledge gained through experimentation of sweet potato cultivation was used to close the gap between the expected minimum output necessary to sustain individuals and the average annual return. Experimental biological research (see Krebs and Kacelnik 1991:128) suggests that a shift from risk-prone to risk-averse food acquisition can occur when there are relatively high payoffs during conditions of high variance. We therefore expect that once a group has gained enough experience in high variance contexts to achieve consistently high yields (or well above the threshold minimum), some individuals will seek to lower output variance, thereby lowering their exposure to crop failures in marginal areas. In north Kohala, both reproductive and replicative success due to increased knowledge during TU 2 resulted in lowered variance in agricultural output and lowered risk through the construction of less spatially dispersed fields in upland areas receiving relatively higher and less variable rainfall. This incurred a higher energy cost because of the partitioning of the larger fields into smaller plots through additional field border wall construction and the increasing distance (and attendant transport costs) from the coast to these areas for agriculture in TU 2.

During the later TU 3 period, spanning the late prehistoric to proto-historic periods, chiefs with increasing levels of influence and power were making decisions that had proximate and ultimately long-term consequences for larger and larger groups of people. There is considerable archaeological (Cordy 1981; Hommon 1986; Kirch 1984, 1985; Kolb 1994) and ethnohistorical (see Kirch 1992; Sahlins 1985, 1992; Valeri 1985) evidence that social stratification in Hawai'i had developed by this time to the point that there were large genealogical and material distinctions between classes of people. In this hierarchical society, chiefs were intricately involved in production activities (Earle 1997; Kirch 1994; Schilt 1984). The importance of political factors, rather than ecological factors, in north Kohala agricultural development during TU3 is indicated by the creation of plots in the southern *ahupua'a*. The greater distance from the coast to fields in the southern *ahupua'a,* and the location of these fields in areas of relatively lower rainfall (ca. 460 mm or 18 inches), would make them less desirable for coastal inhabitants. We suggest that this development represents a shift in the scale of selection operating on agricultural production and distribution, i.e., that these southern plots were brought under cultivation at a relatively late time only through the direct impetus of the chiefly elite.

The change in subsistence strategies in the southern *ahupua'a* of north Kohala during the third time period marks a shift in scale from contexts where individuals assessed the direct costs of their agricultural investment, i.e., transport, production reliability, to a context where individuals were influenced to a much greater extent by the political behaviors of others. The role of chiefs in this shift was vital. At this time, local and district level chiefs took on a greater role in managing production, including instigating the construction of regular-sized, discrete plots in the relatively unused marginal portions of the district to efficiently monitor agricultural production and extract a surplus. It should be noted that smaller and less variable social and infrastructural production units, and larger sized distribution units, are not simply a function of population increase. The smallest fields were developed or established during the time when the population of north Kohala was experiencing a declining growth rate (see Graves and Ladefoged 1991b and Kirch 1984, 1985 for a discussion of population growth curves).

The role of chiefs in instigating agricultural production in more risky areas is significant because a portion of the produce from these southern fields was probably reserved for ceremonies, and as such would not have been available to support the dietary requirements of the local population. This may have had a damping effect on local population densities (see Graves and Ladefoged 1995), and would have provided more leeway in terms of the success rate of the crops. The construction of the TU 3 walls in marginal areas below the 508 mm (20 inch) rainfall isohyet characterized by high spatial rainfall variability, i.e., high RV values, would suggest that high levels of production would have only been viable in exceptionally wet years. In drier years, production would have been less certain, but the potential for large production payoffs in wet years might have compensated for these potential shortfalls. The organizational scale of chiefly economies enabled the chiefs to underwrite poor harvests during bad years through distributional mechanisms, thereby creating a form of insurance (Ladefoged 1993, 1995).

The relationship of chiefs to redistributive economies has been debated for some years (Earle 1977; Peebles and Kus 1977; Sahlins 1958; Service 1962). The evidence from north Kohala is relevant to this issue. Where Earle (1977) saw chiefs as mobilizing the economy through the production of surplus for chiefly consumption and the offering of tribute, our analysis suggests that one strategy that chiefs in north Kohala adopted was to underwrite the development of marginal lands by commoners. This would have provided a larger distributive network for production so as to buffer chiefs and commoners from periodic shortfalls in output that accompanied dry-land farming in areas of less predictable rainfall.

Of course, with these changes in agricultural and economic practices came increased input costs. In north Kohala, these increased costs included additional travel time to fields, infrastructural construction in the form of field border walls and trails, and higher maintenance costs. In addition, output costs would have increased. For instance, agricultural produce would have to be transported to coastal settlements, and possibly between communities, and households or communities would have to meet the assessment by chiefs of levies or tribute. Hence, the evolution of agricultural practices that are risk averse are often associated with or are a product of increasing costs (see Clark 1990:49). Our study, therefore, may help archaeologists better conceptualize the evolutionary relationships among agricultural intensification, risk, and social complexity. The latter, represented here by an evolutionary shift in the scale of agricultural insurance and distribution, may lower individual subsistence risk in the context of environmental marginality, but at the same time it includes institutions and other personnel which are ultimately additional costs that must be borne in part by the larger scale of organization involving increased food, resource, and commodity production and, finally, more effort. Social complexity, viewed here as a shift in the scale of selection, is not a "free lunch" as others have noted but as the evidence from north Kohala indicates, by lowering the risk increasing complexity made the cost of the lunch affordable to more individuals.

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Notes

1. Kohala includes the districts of North Kohala and

South Kohala. We use the term "north Kohala" to refer to the area in North Kohala District where the dryland field system analyzed in this paper is located. It should be noted that much of the north Kohala field system is private property and access is restricted.

2. The mean length of the alignments in Phase 1 of Kirch's (1984) model for Lapakahi was 265 m and for Phases 2 and 3 the means were 140 and 76 m, respectively. These lengths are exceedingly small for use throughout the entire field system. Kirch's use of the plane table alidade maps made by Rosendahl (1972) of a small 26.2 hectare area of Lapakahi include several short alignments. Such short segments were not visible on the aerial photographs used to create the GIS that we used in this study. Furthermore, Kirch restricted his analysis to only one bounded *'ili*. Our regional data shows that most of the alignments that he assigned to Phase 1 are in fact segments of much longer alignments which clearly extend beyond the boundaries of the *'ili* he considered.

3. The 508 mm isohyet was chosen as this is the minimum amount of annual rainfall needed for sweet potato production (Kay 1973, cited in Norman et al. 1984:248), and the 1270 mm isohyet was chosen as this is the upper boundary of the optimal amount of annual rainfall for sweet potato production (Purseglove 1968:82).

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