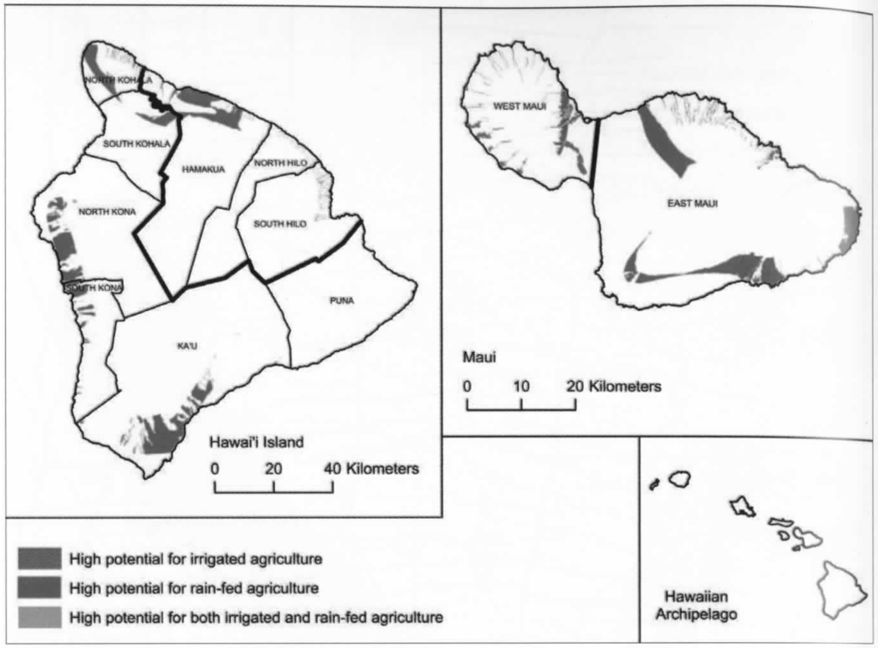

PLATE 16.
Traditional political units (moku) on Maui and Hawai'i Island, in relation to the distribution of areas with high potential for irrigated and dryland (rain-fed) intensive agriculture.

3

Hawaiian Agro-ecosystems and Their Spatial Distribution

Thegn N. Ladefoged, Patrick V. Kirch,
Oliver A. Chadwick, Sam M. Gon III,
Anthony S. Hartshorn, and Peter M. Vitousek

The capacity of agriculture to support precontact Hawaiian populations varied throughout the archipelago. On the wet windward sides of the islands, agriculture focused on intensive irrigated pondfields that produced large quantities of taro (*Colocasia esculenta*; in Hawaiian, *kalo*). In contrast, production in the dry leeward zones was primarily restricted to rain-fed cultivation of sweet potato (*Ipomoea batatas*; in Hawaiian, *'uala*) and to a lesser extent yams (especially *Dioscorea alata*; in Hawaiian, *uhi*) and dryland taro. The labor requirements for these crops were different, with rain-fed production requiring approximately twice the labor of irrigated production per fixed unit of land (Spriggs 1984; Yen 1973). Furthermore, irrigated pondfields can produce more than twice the total tonnage of food per hectare as rain-fed systems (Kirch 1994; Massal and Barrau 1956; Spriggs 1981), and this production is usually more reliable. These large-scale production differentials had implications for precontact population densities, surplus production, and sociopolitical transformations in the various regions of Hawai'i.

While archaeologists (e.g., J. Allen 1991; Kirch 1985, 1994) have recognized the variable characteristics of rain-fed and irrigated production and studied these in localized environments (see below for discussion of specific areas), until recently, there has been a paucity of research assessing the extent to which different agricultural strategies were developed throughout the archipelago. Our GIS analysis (see Ladefoged et al. 2009) identified the specific climatic and environmental conditions necessary for both wetland and rain-fed production. That analysis classified the Hawaiian landscape into zones suitable for each pathway of intensive agriculture. We compared the results of our models with detailed archaeological data from five locations (Wainiha, Kaua'i; Hālawa, Moloka'i; Wailau, Moloka'i; Kalaupapa, Moloka'i; and leeward Kohala, Hawai'i Island) where there is good documentation of the distribution of the physical remains of agricultural systems, such as terraces, irrigation ditches, and rain-fed field walls and boundaries. We also considered some of the ethnohistorical and ethnographic evidence for the distribution of intensive agriculture, including accounts by early European visitors to the islands and, more importantly, the systematic, archipelago-wide ethnographic survey undertaken by E. S. C. Handy in the 1930s (Handy 1940; Handy and Handy 1972). Handy's work is especially useful for its record of wetland planting localities; given the abandonment of most intensive rain-fed systems during the first half of the nineteenth century, he greatly underestimated areas of rain-fed planting. Indeed, he did not document some highly intensified, large rain-fed complexes, such as the leeward Kohala field system.

We concluded that at the time of European contact, the distribution of intensive agriculture varied and further development, both expansion and intensification, may have been feasible (see Ladefoged et al. 2009). This analysis also suggested that total production capabilities varied across the archipelago. In this chapter, we expand on our original assessment of the coincidence between the GIS model results and the archaeological, ethnohistorical, and ethnographic data and discuss the implications of the convergence and disparity of the data sets for understanding late prehistoric Hawaiian sociopolitical trajectories.

GIS MODELING OF THE DISTRIBUTION OF HAWAIIAN AGRICULTURE

Irrigated Pondfields

Irrigated pondfields (*lo'i*) were the main focus of precontact Hawaiian wetland agriculture, with taro being the major crop. The development of large systems of intensively cultivated taro required consistent and plentiful surface water, large areas of arable soil with low slopes, and elevations low enough to yield warm temperatures and high insolation. Our GIS model (see Ladefoged et al. 2009) predicted the distribution of irrigated pondfields based on the geospatial intersection of five major variables—water source, elevation, slope, gravitational flow, and geomorphic setting:

1. *Water source:* Continuous perennial streams provided the primary source of water for pondfields, although springs and zones of groundwater emergence or stream reemergence near the coastal zone also supplied water. These streams provided sufficient moisture for flooded crops to grow and replenished the nutrients available to crops (see Palmer et al. 2009; chapter 2 in this volume). To define areas of potential pondfields, we used stream and rainfall data from the Hawai'i Statewide GIS Program (State of Hawai'i 2008). We identified major streams and, based on rainfall levels (above 2,000 and 3,000 mm) in areas through which these streams flowed, determined the portions of streams that could be supplied with enough water to support irrigated pondfields (plate 3). Our model assumed that all of the appropriate stream segments could distribute water to areas extending up to 500 m from the stream.
2. *Elevation:* Temperature is a critical variable for the production of taro. Rain-fed taro was grown at higher elevations, but the vast majority of irrigated pondfields were below 300 m in elevation. This elevation corresponds to a mean annual temperature of greater than 21°C, a level that the model defines as a minimum for the development of intensified irrigated pondfields (plate 4).
3. *Slope:* Taro pondfield systems typically have very gentle gradients that deviate only slightly from horizontal, allowing for both flooding and the continuous movement of water across the growing plants. While some pondfields were constructed on steep colluvial slopes, the alluvial flood plains of valleys and extensive alluvial and colluvial coastal plains provided the most favorable conditions. Based on archaeological survey data provided by McElroy (2007) and Earle (1980), we defined a slope threshold of 10 degrees or less for large intensive taro pondfield systems (plate 5).
4. *Gravitational flow:* Even given sufficient water flow, elevation below 300 m, and suitable slopes, the detailed topography of riparian corridors can prevent water from reaching areas where pondfields could otherwise be developed. We identified areas where steep gulches would have restricted gravitational water flow and removed

these from the modeled areas of potential pondfield development (plate 6).

5. *Geomorphic setting:* Geomorphic locations suitable for intensive pondfields were identified on the basis of the attribute for geomorphology ("geomdesc") in the US Department of Agriculture's Soil Survey Geographic Database linked to a GIS coverage (United States Department of Agriculture 2009). Zones with malleable soils in areas suitable for water manipulation and diversion were isolated from those without these characteristics and formed the final condition of the irrigated model (plate 7).

Rain-Fed Systems

Sweet potato and the secondary crops of yams and dryland taro were the staples of the intensive rain-fed precontact agricultural systems (Handy 1940; Yen 1974). Sweet potato tolerates cooler temperatures than irrigated taro, so it could be grown at higher elevations; it also tolerates—indeed requires—drier soils than irrigated or dryland taro. Typically, it is cultivated in well-drained mounds of loose soil. Rain-fed systems also required relatively high levels of soil fertility, which varies as a function of rainfall, temperature, and the age of volcanic substrate (see chapter 2 for details). Accordingly, the rain-fed agriculture model was based on the intersection of GIS-derived rainfall and elevation figures, as well as soil fertility:

- *Rainfall:* The lower rainfall boundary of many Hawaiian intensive rain-fed systems corresponds closely to the 750 mm/year rainfall isohyet (Kirch et al. 2004; Ladefoged and Graves 2000; Ladefoged, Graves, and Jennings 1996)—as is observed elsewhere in the tropics (Purseglove 1968). We took this to be the lowest average rainfall at which the effort of building and maintaining an intensive rain-fed system was rewarded with good yields frequently enough to be worthwhile to the cultivators (see Ladefoged et al. 2009).
- *Elevation:* The rain-fed GIS model used 900 m as the upper elevation boundary for rain-fed systems; this corresponds to a mean annual temperature of about 18°C, which is similar to the boundary of intensive sweet potato cultivation in the leeward Kohala field system (Ladefoged and Graves 2000) and other regions of the world (Ngeve, Hahn, and Bouwkamp 1992).
- *Soil fertility:* Soil fertility in volcanic landscapes is a function of the age of substrate, the amount of rainfall, and ambient temperature (Chadwick et al. 2003; Vitousek et al. 2004). In general, soil nutrients are greatest on young substrates; they decrease rapidly with increasing age in wetter sites but can remain high for hundreds of thousands of years in drier sites. Soil nutrient dynamics are also influenced by temperature; soil minerals weather more rapidly at high temperatures than low, all else being equal (Dessert et al. 2003). By defining explicit thresholds (see Ladefoged et al. 2009 for details), the model incorporated the influences of rainfall, temperature (as reflected by the proxy of elevation), and age of substrate on soil nutrient depletion throughout the archipelago and identified areas that would be suitable for intensive rain-fed agriculture (plate 8).

ASSESSING MODEL RESULTS WITH ARCHAEOLOGICAL, HISTORICAL, AND ETHNOGRAPHIC DATA

Irrigated Pondfields

The modeled predictions for the archipelago-wide distribution of irrigated agriculture are shown in plate 9 and summarized in table 3.1. The concentration of irrigated systems on the older islands of Kaua‘i and O‘ahu is consistent with the dissection of their volcanoes by erosion and the development of extensive areas of alluvial and colluvial soils. We had assessed the irrigated model results through a comparison of the predictions with the distribution of irrigated agriculture recorded in three windward valleys (see Ladefoged et al. 2009). We found a 98.5 percent correspondence between the archaeological remains and the model predictions in Wainiha Valley (Kaua‘i), a 78 percent correspondence in Hālawa Valley (Moloka‘i), and a 66 percent correspondence in Wailau Valley (Moloka‘i). The discrepancies between the archaeological remains and the model results in the three valleys were generally attributed to the construction of terraces in areas excluded by the model as having too steep slopes. In some locations within the valleys, the models predicted the existence of archaeological remains, but none were recorded. In general, these discrepancies were attributed to the field recording of semi-isolated production patches in larger areas that were probably used to grow crops at one time.

We briefly considered the correspondence between the model results and the ethnohistoric and ethnographic accounts of agriculture but did not provide a detailed assessment (see Ladefoged et al. 2009). We have now examined that data along with additional archaeological data and make the following observations.

TABLE 3.1
Predicted Areal Distributions of Wetland and Rain-Fed Field Systems and Estimated Yields and Labor Costs across the Hawaiian Archipelago

	Hawai‘i	Maui	Moloka‘i	O‘ahu	Kaua‘i
High potential for irrigated agriculture (km^2)	14.37	25.74	8.75	83.31	57.62
High potential for rain-fed agriculture (km^2)	556.56	139.36	7.49	34.06	0.00
High potential for irrigated and rain-fed agriculture (km^2)	0.98	2.45	0.35	3.22	0.00
Total agricultural area (km^2)	572	168	17	121	58
Irrigated agricultural production (metric tons, wet weight)*	38,383	70,483	22,764	216,329	144,043
Irrigated agricultural production (metric tons, dry weight)	13,050	23,964	7,740	73,552	48,975
Rain-fed agricultural production (metric tons, wet weight)**	278,278	69,678	3,743	17,029	0
Rain-fed agricultural production (metric tons, dry weight)	83,483	20,904	1,123	5,109	0
Total annual production (metric tons, dry weight)	96,534	44,868	8,863	78,660	48,975
Annual labor input, irrigated agriculture	2,239	4,112	1,328	12,619	8,403
Annual labor input, rain-fed agriculture	162,329	40,646	2,183	9,933	0
Total annual labor input	164,568	44,757	3,511	22,553	8,403
Average annual production per worker (metric tons, dry weight)	0.6	1.0	2.5	3.5	5.8

Data from Ladefoged et al. 2009.
* Assuming 25 mt/ha/year
** Assuming 5 mt/ha/year

For Kaua‘i, the model predictions coincide with Handy's (1940:58–73) description of wetland planting areas around the island, with especially extensive areas in Puna, Ko‘olau, and Halele‘a districts. The Wailua Valley, which lies in the heartland of the Puna District, was the political core of the ancient Kaua‘i kingdom, noted for several important temple sites (Bennett 1931). By the time of Handy's and Bennett's surveys of traditional Hawaiian agricultural areas, much of the land had already been converted to sugar plantations, but Bennett was nonetheless impressed at the extent of agricultural terracing in those valleys that had not been subjected to plantation development. He wrote that "in the valleys in which little disturbance has gone on, particularly the Nāpali section, the maximum of tillable soil was utilized. On the sides of the valleys the terraces run almost to the base of the great cliffs, where the nature of the talus slopes is not too rocky" (Bennett 1931:21). Indeed, it would appear that, because of the conser-vative slope cutoff value and the coarseness of the digital elevation model, the model may underestimate the extent of terracing in the Nāpali District valleys.

On O‘ahu, the model results can be compared with Kirch's (1994:252) map of primary irrigation zones, which is based on archaeological survey data and Handy's (1940:73–101) detailed ethnohistorical and ethnographic descriptions of wet taro planting areas on the island (plate 9). In general, the model defines more specific areas than those identified by Kirch. While modeled areas of wetland potential often extend outside the boundaries of Kirch's zones, the areas within those zones are more precisely defined. Kirch (1994) did not depict any zones of irrigated production in central O‘ahu; however, the model identified areas of production on the Wahiawā Plateau. Although Handy (1940:81) referred to some terraces along Wahiawā Stream, the areal extent of the model predictions seems too large. The model predictions are probably the result of historic land modifications that make the area appear more suitable for precontact agriculture than in fact was the case. Certainly, what we know of the archaeology of central O‘ahu (McAllister 1933) suggests a low precontact population; the region lacks any large temples or other sites that might reflect a high population density associated with large-scale irrigation.

At a finer-grained scale, we can also compare the GIS model predictions with results of detailed archaeological surveys of the physical remains of irrigation systems in several localities on O‘ahu, including Mākaha (Green 1980; Yen et al. 1972), Anahulu (Spriggs and Kirch 1992), and upland Kāne‘ohe valleys (J. Allen 1987), which span the spectrum from marginal leeward through intermediate to fully windward valley settings. In

Mākaha, the model predicts small patches of moderate potential straddling the upper reaches of Mākaha Stream, a limited pendant-shaped area of high potential in the valley's mid-reaches, but no potential in the lower part of the valley, as permanent streamflow ends well before the coast is reached. These predictions match the archaeological record very well, with the small terraced system mapped and excavated by Yen and others (1972) in the upper valley and with one main irrigation ditch watering a section of the middle valley immediately below Kāne'ākī Heiau, the valley's major temple site (Green 1980:47, 77).

For the Anahulu Valley and coastal region of Waialua District, correspondence between model predictions and archaeological evidence is again good; the large areas of high potential for irrigation in coastal Waialua are empirically evidenced in the ethnohistorical documents analyzed by Kirch and Sahlins (1992), and the smaller trace of high and medium potential running up the narrow Anahulu Valley corresponds with the numerous small terrace systems mapped in detail by Spriggs and Kirch (1992). Finally, for windward O'ahu, where the model predicts a dense concentration of high potential for irrigation, Allen's (1987) work in Luluku at site G5-85 documents the prehistoric construction of large-scale, complex irrigation terracing pushing back against the steep slopes of the windward escarpment as early as AD 1400.

For the island of Moloka'i, the GIS model confines irrigated taro cultivation to the eastern half of the island, especially in the four large windward valleys (Waikolu, Pelekunu, Wailau, and Hālawa), and in valley mouths and on alluvial coastal plains along the southern coast as far west as Kawela. These correspond with the Ko'olau and Kona districts of the island, respectively, which were the two major centers of population concentration during the early postcontact period (Coulter 1931). Handy spent limited time on Moloka'i, but the model predictions conform well with his summary of wet taro distribution (Handy 1940:101–03) and with the notes compiled by Southwick Phelps (1937). It is worth noting that the spatial distribution of irrigation potential over Moloka'i correlates strongly with the distribution of major precontact heiau, or temple sites. These sites were mapped by John F. G. Stokes in 1909 (his data are incorporated in Summers 1971), and the largest are closely associated with the southeast-coast irrigation zones and with the major windward valleys. 'Ili'ili'ōpae, one of the largest state temples of human sacrifice (*luakini*) in the archipelago, is located near the center of the southeastern irrigation zone.

The fit between the model predictions and the archaeological remains is not as good in Kawela, on the southern leeward coast. Here the model predicts an area of high irrigation potential on the alluvial floodplain at the valley mouth, with some smaller patches extending inland up the twin forks of Kawela Stream. Archaeological surveys by Weisler and Kirch (1985:135–38) revealed the presence of one major irrigation ditch leading onto the alluvial floodplain, as well as small terrace systems in the narrow gulches inland. However, ethnohistorical documents—especially commoner land claims made during the Mahele, or division of lands between the king, chiefs, and commoners (1846–1854)—indicate that the Kawela floodplain was cultivated not in taro but in sweet potatoes; claims to taro land were limited to the small inland patches. Thus, Weisler and Kirch interpreted the irrigation of the Kawela floodplain as seasonal for rain-fed agriculture, corresponding to times of sufficient winter streamflow.

The GIS model identifies the Kawela area as having high potential for wetland agriculture because Kawela Stream is classified as intermittent and extends above the 3,000 mm isohyet. The discrepancy between the model predictions and the archaeological evidence is probably due to the model's inclusion of all such intermittent streams in identifying potential areas for pondfield development. This was necessary because of errors in coding some perennial streams as intermittent in the GIS coverage (Pelekunu being an example). Kawela Stream is an example of a true intermittent stream, one that could not support irrigated agriculture. In terms of relative water flow, it is probably quite close to streams classified as nonperennial in the data set. Notably, all the surrounding streams are classified as nonperennial and therefore identified as having a low potential for pondfield agriculture.

The spatial distribution of irrigation potential on Maui corresponds to the different ages of West and East Maui and to the lack of permanent streamflow on southeastern Maui due to the rainshadow effect of Haleakalā Volcano. West Maui's high potential for irrigation is confirmed by Handy's (1940:103–09) description of specific planting localities, which correspond very well to model predictions. These localities include the valleys and broad alluvial plains from Ukumehame northward to Honokōhau and, on the windward side, the four substantial valleys known collectively as Nā Wai Ehā (The Four Waters): Waihe'e, Waiehu, Wailuku, and Waikapū. Handy (1940:107) called Nā Wai Ehā "the largest continuous area of wet taro cultivation in the islands," although this may be an exaggeration when compared with windward O'ahu and northeastern Kaua'i. Little archaeological work has been done on Maui irrigation systems, but the interiors of many of the valleys are known to contain extant terrace sets. Irrigation systems on the coastal plains of leeward West Maui, described by early

European voyagers (e.g., Menzies 1920:105, 112), were largely obliterated by late nineteenth- and twentieth-century sugarcane cultivation.

On East Maui, the GIS model predicts fairly extensive zones of irrigation potential along the windward Hāmākua and Ko'olau districts. Handy (1940) again reported terraced taro cultivation in Hāmākua and Ko'olau, including the famous complex at Ke'anae and Wailua, where taro continues to be grown to this day.

As noted (see Ladefoged et al. 2009), the model identifies no potential for irrigated agriculture on Lāna'i or Kaho'olawe. This is because rainfall on the two islands is so low that no streams have headwaters in areas receiving more than 1,500 mm of rain. Handy's (1940:103) description that on Lāna'i "wet taro was cultivated throughout the upper valley of Maunalei District, and in a small area midway up from the sea in the deep valley running down the Kaunolu side of Kalulu district" does not coincide with the model results. This discrepancy could be attributed to the development of spring-fed systems in the valley, a production mode not accounted for by the model.

On Hawai'i Island, the GIS model indicates that the windward, northeastern side of the island has the highest potential for irrigated agriculture. Because of the island's relatively young age, it contains just a few deep dissected valleys. Most notable are Waipi'o, Waimanu, Honoke'ā, Honopue, Honokāne, and Pololū. Handy (1940:120–24) suggested that Waipi'o and Waimanu were the most productive, with Ellis (1827/1963:256) describing the Waipi'o valley bottom in 1823 as "one continued garden…all growing luxuriantly" and Bingham (1849:379) estimating that upward of 1,500 people lived in the valley in 1855. Ellis (1827/1963:273) also wrote highly of Pololū, indicating that the valley was well watered and cultivated. Archaeological research in Pololū has documented an extensive system of terraces and irrigation ditches, although there is some question about whether these were used for flooded pondfields, intermittent irrigation, or both (Tuggle and Tomonari-Tuggle 1980). In addition to the deeper valleys on Hawai'i Island, the GIS model predicts that many of the smaller valleys and gulches could have sustained irrigated agriculture. A few valleys in North Kohala have been the subject of recent archaeological work, which confirms the existence of extensive terracing and irrigation ditches in alluvial valley bottoms (McCoy and Graves 2007, 2008, 2010).

Rain-Fed Systems

The results of the predictive model for intensive rain-fed agriculture are summarized in plate 9 and table 3.1. In our 2009 study, we assessed these results with archaeological data from the leeward Kohala field system (Hawai'i Island) and the Kalaupapa field system (Moloka'i). We found a 90 percent and 99 percent correspondence, respectively, between the archeological remains and model predictions for the two areas. In Kohala, the model accurately tracked the archaeologically identified southwest boundary of the field system defined by the 750 mm rainfall isohyet. The model also captured the influence of geologic substrate age, although it did not incorporate the effect that more recent tephra could have had on older substrates. At a more general level, the model results can be compared with the distribution of agriculture recorded in other zones of Hawai'i Island. Newman (n.d.:115) first presented a map of the distribution of agriculture on Hawai'i Island, and refined versions have been published in Kirch 1985, 1994, and M. Allen 2004:197, with a more spatially limited map in Burtchard and Tomonari-Tuggle 2004:52. These maps show only the general distributions of agriculture at a very coarse scale and are based on limited archaeological observations and extrapolations (plate 9).

For Kona, there are extensive ethnohistorical accounts of gardening (see Kelly 1983 for a summary). Writing in the 1820s, Ellis (1827/1963: 31–32) described the area as "divided into small fields, about fifteen rods square, fenced with low stone walls.… These fields were planted with bananas, sweet potatoes, mountain taro, paper mulberry plants, melons, and sugar-cane, which flourished luxuriantly in every direction." The approximate mapped distribution of the Kona field system (plate 9) and the GIS model results correlate reasonably well. The mapped distribution is so generalized as to miss lava flows from Hualālai and Mauna Loa volcanoes that cross the prime climate for agriculture but are too young (too lacking in soil) to support an intensive field system. Also, the model identifies numerous *kīpuka* (islands of older substrate surrounded by younger flows) outside the mapped bounds of the field system, in which intensive agriculture would have been feasible. The remains of intensive cultivation have been recognized in some of these kīpuka. Overall, the model suggests that intensive agriculture might have been practiced over a more extensive—but less continuous—area of Kona than the mapped distributions record.

The modeled distribution of the Waimea field system is much larger and displaced well to the east of the distribution of the system depicted by Burtchard and Tomonari-Tuggle (2004) (plate 9). The Waimea area is ethnohistorically known to have supported a substantial population prior to European contact, likely requiring a large agricultural area (see Clark 1987 for a summary). The southern and western areas depicted by Burtchard and Tomonari-Tuggle (2004) are below the 750 mm/year rainfall isohyet and probably utilized irrigation and thus were excluded from the model predictions. Much of the modeled area around Waimea lies under the modern town, making archaeological identification of the remains of a Hawaiian field system unlikely. However, the northwestern portion of the area identified by the model as a potential field system has remained as grazing land—and the remains of a Hawaiian field system are evident there. The eastern portion of the modeled area is outside the distribution of the field system mapped by Burtchard and Tomonari-Tuggle (2004:52). However, portions of this area do correspond very closely to the area of "scattered fields" identified by Newman (n.d.:115) that extends from Waimea toward the Hāmākua coast.

In the area extending south along the Hāmākua coast, Newman (n.d.: 115, see fig. 9a) depicted "scattered fields"; Kirch (2007a: fig. 6) depicted a major zone of dryland cultivation or field systems; Kirch (1994:252) depicted the zone farther inland. The modeled results overlap or are close to some of these areas but are much more limited and precisely defined. The archaeological evidence for agriculture in both the zone extending to the Hāmākua coast and the area extending southeast parallel to the Hāmākua coast is minimal. It is possible that these areas were not fully intensified prior to European contact, in which case further development would have been feasible. Historic activity has impacted many of these areas, but additional research on both soil fertility and the distribution of precontact agriculture might be rewarding.

Finally, on Hawai'i Island, in south Ka'ū there is overlap between the area of intensified rain-fed agriculture predicted by the model and the distribution of field systems depicted by Newman (n.d.:114)—although the model predicts a larger area extending farther north. Kirch's (1994) distribution of field systems in the area does extend to the north, but it is offset from the area predicted by the model to the west. Handy (1940: 165–66) noted the cultivation of taro and sweet potato throughout the area. Although postcontact plantation agriculture has altered the Ka'ū system substantially, the western portion of the area identified by the model has remained under grazing. Publicly available imagery (Google Inc. 2009) shows clear evidence of a continuous 7.5 km^2 area of rain-fed field system just where the model suggests it should be.

For Maui, the GIS model predicts four major zones of high potential for rain-fed field systems: (1) a band of colluvial soils along the eastern flank of the West Maui mountains, in the Nā Wai Ehā region; (2) a strip on northeast Maui in Hāmākua Poko, running inland in the vicinity of the modern towns of Makawao and Pukalani; (3) a zone in Hāna on the east end of the island; and (4) a lengthy southern zone stretching from Kaupō through Kahikinui and Honua'ula districts and wrapping around into Kula District. The first region is confirmed by Handy's (1940:160) remark that "from Waihee to Waikapu there is much good land below and bounding the ancient terrace area on the kula and in the lower valleys which would be ideal for sweet potato culture," although Handy noted that dryland taro was the predominant crop in this field system. With respect to Hāmākua Poko, Handy (1940:160) again surmised that "the semi-dry slopes of Hāmākua [Hāmākua Poko] must have been planted with sweet potatoes," but presumably these rain-fed systems had been abandoned well before his 1930s fieldwork and were covered by sugar (as they are now). We have observed, however, the remains of a rain-fed field system in the upper-elevation portions of this region, above the area where plantation agriculture has obliterated the traces of prior land use. For Hāna, Handy (1940: 111–13) suggested that large portions of the region were dominated by rain-fed agriculture, and this coincides nicely with the model results.

For the southern zone of rain-fed agriculture predicted by the model, there is good correspondence with both ethnohistoric and archaeological sources. Handy (1940:161) called this "the greatest continuous dry planting area in the Hawaiian islands," and noted that Kaupō in particular was "famous for its sweet potatoes, both in ancient times and in recent years." Most of Kaupō District consists of an extensive fan of late-rejuvenation-phase Hāna Volcanic Series lavas; a recent archaeological survey on this Kaupō fan has confirmed the existence of an intensive field system marked by closely spaced terrace rows running along the contour and divided into larger sections by stone walls running from the coast inland (see chapter 4). One of the island's largest temple sites, Lo'alo'a, along with a number of other heiau, is situated within this field system zone.

To the west, in Kahikinui, an extensive archaeological survey of more than 12 km^2 has documented a near continuous zone of upland habitation and gardening concentrated between about 400 and 750 m above sea level (Dixon et al. 1999; Hartshorn et al. 2006; Holm 2006; Kirch et al. 2004). Agriculture in this area was within swales in *'a'ā* flows (lava with a rough surface), without a formal field system defined by walls and trails. This area corresponds well with the GIS model predictions, although the model defines a band somewhat narrower but more continuous than that actually confirmed by archaeological ground survey. Little work has been done in Honua'ula, but upland Kula surveys by Michael Kolb (personal communication 1995) have again confirmed extensive upland residence and rain-fed terracing. The model predictions for an extensive southern zone of rain-fed farming extending across the leeward face of Haleakalā Volcano are well confirmed by available archaeological data.

As our 2009 analysis noted, on the Kalaupapa Peninsula of Moloka'i, there is good correspondence between the model results and the ethnohistorical and archaeological evidence. The model identified an area of late-stage volcanic rejuvenation dating to about 300 kyr (Sherrod et al. 2007) as suitable for intensive rain-fed agriculture. Handy (1940:158) quoted an 1857 Hawaiian-language newspaper source that extolled the peninsula as "a good land because the crops planted are successful and the gain is large." This was written shortly after the 1849 California Gold Rush, during which the lack of food in San Francisco led to a boom in sweet potato production in Hawai'i, including at Kalaupapa (Ladefoged 1993). Archaeological surveys and excavations in Kalaupapa have firmly demonstrated that the intensive field system covering much of the peninsula began to be developed as early as AD 1400 (Kirch 2002; McCoy 2005, 2006; McCoy and Hartshorn 2007). Archaeological surveys have also confirmed the absence of any significant rain-fed cultivation on the older Moloka'i volcanic shield surfaces, as at Kawela (Weisler and Kirch 1985). An extensive survey of 7.7 km^2 shows that most precontact settlement was focused on the irrigable lands at the mouth of Kawela Stream and on the low ridges immediately inland of the coastal plain. Attempts to cultivate the upland interfluve surfaces were extremely limited and appear not to have been successful.

According to the model, no areas on either Lāna'i or Kaho'olawe were suitable for intensive rain-fed agriculture. On Kaho'olawe, annual rainfall is below the 750 mm minimum, and on Lāna'i, those portions of the island that receive more than 750 mm of rain are either too young (less than 4 kyr of alluvial and colluvial deposits) or too old (greater than 700 kyr). This is at odds with Handy's (1940:158–59) statement that "sweet potatoes were planted in every part of the [Lāna'i] island where there were settlements: on the shore, in valleys, on the *kula* [dryland cultivation areas], and the upland." This discrepancy might be attributed to the parameters of the rain-fed model, which specifies that substrates younger than 4,000 years are unsuitable for intensive agriculture—lava flows generally take that long to develop or acquire (via deposition of tephra) nutrient-rich soils that could be used for intensive rain-fed agriculture. As it stands, the model does not recognize that once volcanics have weathered and developed into nutrient-rich soils, they can be redeposited as recent colluvium or alluvium that could support intensive rain-fed agriculture. Unfortunately, the GIS geology coverage did not consistently distinguish volcanic substrates from colluvial and alluvial substrates. On Lāna'i, the large recently deposited alluvial Pālāwai basin might well have supported intensive rain-fed agriculture, but because it is classified as less than 4,000 years old, it was eliminated. Unfortunately, historic disturbances in the area make it impossible to determine the nature and level of intensification of rain-fed cultivation in this area.

The model predicts fairly extensive areas with good farming potential in parts of southeast O'ahu, corresponding to areas underlain by late-rejuvenation-phase lavas and pyroclastics of the Honolulu Volcanic Series. Ethnohistorical sources likewise point to these landscapes as having been intensively utilized for sweet potato cultivation. Handy (1940:156) referred especially to the "region around Makiki and Round Top" as "the most favorable locality on Oahu for sweet potato cultivation," noting a particularly good combination of cinder, humus, and rainfall conditions. Round Top is called 'Ualaka'a in Hawaiian (Rolling Sweet Potatoes), and King Kamehameha I is reported to have established a major plantation on these slopes (Kamakau 1961).

However, some of the areas on O'ahu predicted as having high potential for rain-fed farming are questionable, especially the steep slopes of tuff cones on eastern O'ahu and patches predicted in the Kahuku region of northern O'ahu. All of the latter are on calcareous paleodune deposits of Holocene and Pleistocene age (Sherrod et al. 2007), not the volcanic substrates on which the model is based. Because the model only uses substrate age as an input, it lumps these often lithified calcareous dunes with the agriculturally more suitable Honolulu Volcanics. The former, however, would have very low nutrient supply, and we doubt that they were ever cultivated.

The model does not identify any areas as being suitable for intensive rain-fed agriculture on Kaua'i, the oldest of the large high islands. Young colluvial and alluvial substrates may have provided the opportunity for such systems—particularly in the Mānā coastal plain on southwestern Kaua'i, where irrigation may have helped to support rain-fed crops in a low-rainfall area.

The nearby island of Ni'ihau includes small areas of rejuvenation-stage volcanic substrates in the appropriate age range for rain-fed agriculture—but the lack of spatially referenced rainfall information for Ni'ihau precludes any GIS-based analysis of its agricultural potential.

DISCUSSION

Lock and Harris (1996:215–16) argued that "reconstructing the evolving relationships that existed between former cultural and physical landscapes" is not only central to modern landscape archaeology but also "particularly well suited to examination and exploration in a GIS environment." At the same time, they cautioned that GIS analyses "must be theory-driven rather than hopeful, hi-tech 'fishing trips'" (Lock and Harris 1996:239). There are now well-developed procedures for site-predictive (see Ebert 2004 and Wescott and Brandon 2000 for reviews) and locational (see Kvamme 2006 and Mehrer and Wescott 2006 for reviews) modeling. While criticisms of and cautions about these approaches still abound (see Wheatley and Gillings 2002), McCoy and Ladefoged (2009:271) noted that in a typical modern "digital model, existing locational data on archaeological sites is linked to one or more environmental variables, which in turn are used to assess the likelihood of similar sites in unsurveyed areas. Confidence in these predictions usually rests on how well the model 'finds' known sites."

We proposed a landscape model of precontact rain-fed and wetland Hawaiian agriculture that was grounded in theoretical understanding of significant topographic, hydrologic, biogeochemical, and agronomic variables (see Ladefoged et al. 2009). The rain-fed model specifies critical values for rainfall, elevation, and age of geologic substrate and focuses on soil nutrient requirements. The wetland model highlights the availability of water via streams, the ability of specific rainfall levels to recharge and sustain stream flow, slope, elevation, geomorphology, and the effect of topography on gravitational dispersion of water.

The GIS model predictions of the distribution of intensive agriculture and the ethnohistorical, ethnographic, and archaeological evidence of these activities coincide in many places throughout the archipelago, suggesting that the variables and parameters of the models are appropriate. There are, however, instances in which the model predictions and the evidence do not coincide. This occurs when the model predicts a high potential for intensified agriculture but the evidence for it is lacking and when the model predicts a low potential for intensive agriculture but there is good evidence for it having occurred.

Some of these discrepancies can be attributed to inappropriate variables or parameters in the model, erroneous data, or disturbance of archaeological remains. For instance, the rain-fed model considers only the age of geologic substrate, rainfall, and elevation in calculating soil fertility, not the type of substrate. As most of the archipelago is volcanic, this is generally a good approach, but there are some areas, such as Kahuku on O'ahu, where infertile nonvolcanic substrates (for example, calcareous paleodune deposits) are classified as having high potential for intensive rain-fed agriculture. This is clearly in error.

Another problem with a model parameter is that the rain-fed model eliminates any geologic substrate younger than 4,000 years. This is done because lavas generally take that long to develop deep, nutrient-rich soils that can be used for intensive rain-fed agriculture. What the model fails to account for is that once volcanics have weathered and developed into nutrient-rich soils, they can be redeposited as recent colluvium or alluvium that can support intensive rain-fed agriculture. Several alluvial areas on Kaua'i could be cases in point, as would areas on Lāna'i. The model does not distinguish young volcanic flows from young colluvial and alluvial areas because of the way the GIS geology coverage was coded. Errors or ambiguities in the GIS data can also cause discrepancies between the model predictions and the evidence. In Wahiawā (O'ahu), the identification of areas for intensified wetland agriculture is probably due to historical modifications changing the topography and water flow in the area. Examples of recent disturbance to archaeological remains causing ambiguities between model results and ethnohistorical evidence were found in Ka'ū and a number of other places throughout the archipelago. In Kawela (Moloka'i), Waimea (Hawai'i Island), and elsewhere, slight changes in the location of rainfall isohyets would have significant impacts on the results of the models, increasing areas that could have been used for intensive irrigated agriculture.

Not all discrepancies between the model predictions and the evidence can be attributed to erroneous data or parameters. More interesting are "red flag" discrepancies (see Altschul 1990; Kohler et al. 2007; Kohler et al. 2000) that suggest that social or political factors might have been omitted from the models. Agricultural development throughout the archipelago, in terms of both expansion into unoccupied areas and intensification of productivity within an area, was a function of the dietary requirements of populations and the desire for agricultural surpluses. In most cases, surpluses in precontact Hawai'i were used to finance elaborate ritual activities and support a nonproducing elite. Instances in which the model predicts a high potential for agriculture but the archaeological and ethnohistorical data do not verify this and the environmental data and model parameters seem to be accurate might suggest that further agricultural development was possible. For example, the rain-fed model identified an extensive area with high potential for intensive agriculture that runs from Waimea to Hāmākua on the island of Hawai'i, extending along the windward coast. Newman's (n.d.) map depicted scattered fields in this area. The inland portions of this zone extend upwards of 16 km from the coast, and, as noted by Ladefoged and Graves (2000), travel distance to coastal settlements was likely a significant factor in decisions about intensifying production. This zone in Hāmākua may be an example of an area where further expansion and intensification were possible but not actualized. This possibility should encourage additional fieldwork to determine whether traces of rain-fed Hawaiian agriculture are present in the area and whether the soils are indeed as fertile as the model suggests.

A number of areas throughout the archipelago satisfy the conditions of both the wetland and rain-fed models. O‘ahu has a total of 3.2 km^2 with potential for both wetland and rain-fed intensified agriculture, and Maui approximately 2.5 km^2. The archaeological remains in most of these zones are undocumented, but the potential for investigating complex processes of intensification are there. Many of these areas were probably first developed with extensive swidden plots, which were later elaborated into intensive rain-fed and irrigated systems. A measure of the extent of intensification is whether landesque capital investments for intermittent irrigation were constructed first and intensive wetland irrigation systems were constructed later. The extent to which these areas were not intensified to their full potential would suggest that there was still capacity to develop terrestrial production within the archipelago.

* * *

As indicated in chapters 1 and 2, the particular geological nature of Hawai‘i—a hot-spot archipelago with an age-graded sequence of islands—is one of the environmental characteristics that makes the archipelago especially valuable as a model system. When this is combined with the islands' windward-leeward gradients in rainfall and with the effects of orographic precipitation, a remarkably orthogonal set of contrasts emerges between old and young substrates and wet and dry substrates, all formed on a consistently similar oceanic basalt lithology. In this chapter, we have used GIS modeling to show how this environmental matrix controlled the potential for development of two major kinds of Polynesian agroecosystems: irrigated pondfield cultivation of taro and intensive rain-fed cropping of sweet potato, dryland taro, and other plants.

As can be seen in plate 9 and table 3.1, the resulting agricultural landscape was anything but uniform. Whereas the geologically older islands of Kaua‘i and O‘ahu were dominated by irrigation systems, the younger islands of Maui and especially Hawai‘i boasted vast tracts amenable to the development of intensive rain-fed field systems. Although some wetland potential was present on both Maui and Hawai‘i, in sheer area this was greatly overshadowed by the rain-fed zones. Our 2009 analysis specified how differences in the area of production for the two modes of agriculture had implications for the annual tonnage of crops that could be grown on each island and the associated labor requirements. There were large disparities between islands, with average annual production per worker being more than nine times greater on Kaua‘i than it was on Hawai‘i Island (see table 3.1). Differences in production and labor requirements within islands also contrast, and chapter 7 explores variation among districts on Maui and Hawai‘i Island.

That a significant wet-dry contrast underlies agricultural variation throughout the Hawaiian Islands is not a new observation. Kirch (1994; see also Kirch 2007a) pointed to the importance of this wet-dry contrast in fueling the respective political economies of the independent polities that vied for hegemony over the archipelago at the time of Captain Cook's arrival in 1778–79. In particular, he argued that the greatest political dynamism was in the east, on the younger islands—where the vast rain-fed field systems provided a basis for supporting a large population, but one that was often at risk because of recurring drought. He also suggested that over time, as the rain-fed production systems were increasingly intensified, their ability to continue to yield increased rates of surplus, critical to the chiefly elite, may have declined.

Our quantitative GIS model, as presented in this chapter, allows us to estimate far more precisely the nature of the archipelago-wide differences in potential agricultural production and thus both underscores and refines the earlier, coarser-grained qualitative arguments of Kirch (1994). In the next two chapters, we turn to a summary of key results achieved in our archaeological and paleoecological investigation of two of the main zones of rain-fed agricultural production: Kahikinui on Maui and the leeward Kohala field system on Hawai‘i. In these chapters, we address some of the issues regarding the chronology of development of these systems, the sequences of intensification, the population levels they may have supported, and some preliminary evidence for nutrient depletion over time. (We are only now beginning to investigate similar processes in windward zones, and we will integrate that data with the leeward findings in the future.) After a consideration of some of the key linkages between food and demography in chapter 6, we will return to the archipelago-wide spatial scale in chapter 7, with a consideration of some of the implications of the wet-dry contrast for Hawaiian sociopolitical evolution.