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In the first phase of this project (funded by NSF biocomplexity grant BCS-0119819), we evaluated and modelled interactions among soils, natural and agricultural ecosystems, human demography, and the development of social and cultural complexity in two leeward study areas that supported extensive dryland agricultural systems: Kahikinui District on Maui Island, and Kohala District on Hawai‘i Island. Here we summarize the results of our research to date, organizing our presentation around the five explicitly interdisciplinary modules that we used to structure our research.

Module 1: Soils and Biogeochemistry

Research on soils and biogeochemistry in relation to Polynesian dryland agriculture was conducted at local, landscape, and archipelago-wide scales. On the landscape scale, we focused on understanding limits to the distribution of rain-fed intensive agricultural systems, sampling across rainfall gradients from dry areas below agricultural systems, through lands that were cultivated until the early 1800s, and into wetter areas above. Kohala supported a large and well-developed field system, covering at least 60 km² with a dense network of field walls and paved trails (Ladefoged et al. 2003); here we sampled soil properties on multiple transects across both 150 ky and 400 ky old substrates. At Kahikinui, we sampled a matrix of lava flows ranging in age from 11 ky to > 226 ky, within which the agricultural system was embedded.
Figure 2. A, Map of Kohala showing the dryland field system in relation to rainfall, elevation, and the young Hawi vs. older Pololu Volcanic formations, together with the locations of soil sampling transects. B, Resin-available P measured along transects on the young (dashed line) and old (solid line) substrates. Vertical lines show the lower and upper boundaries of the field system on each substrate (From Vitousek et al. 2004).

These landscape-scale soil analyses demonstrate that soil fertility peaked within the agricultural system in both areas, with base saturation and available P lower in drier sites and much lower in wetter sites, compared to sites within the agricultural area (Vitousek et al. 2004, Kirch et al. 2004). High levels of available P within the field system reflect both a greater fraction of total P in available form, and larger pool of total P in these soils. Using Nb as an immobile index element, we determined that many formerly agricultural soils are absolutely enriched in P, relative to parent material – an enrichment that pre-dated the development of the field system, as demonstrated by analyses of soils from under field walls and from sites with similar rainfall outside the agricultural system (Vitousek et al. 2004). In addition, we observed lower soil fertility on older substrates within both Kohala and Kahikinui (Kirch et al. 2004). Analyses of rainfall gradients on older substrates across the Hawaiian archipelago extend this pattern (Chadwick et al. in prep.); the spectrum of sites with both fertile soils and adequate rainfall for intensive agriculture progressively narrows and eventually disappears on substrates much older than 400 ky.

Overall, we conclude that within Kohala and Kahikinui, Hawaiian cultivators found, farmed, and intensified production on lands that were poised between being too wet and too dry. The distribution of intensive rain-fed agricultural systems was constrained on its lower end by conditions that were too arid to support intensive agriculture reliably (Ladefoged and Graves 2000), while at their upper margin many millennia of leaching had depleted soil fertility to a point where intensive rain-fed agriculture was infeasible (Vitousek et al. 2004). In essence, Hawaiian cultivators in intensive dryland agricultural systems were farming the rock; their field systems extended to the wettest point that still supplied nutrients via basalt weathering. This pattern makes sense in that while long-fallow shifting cultivation can make use of nutrients accumulated over a period of time, intensive dryland agriculture requires relatively rapid renewal of nutrient supply (from weathering or cultural inputs) if productivity is to be sustainable. On an archipelago-wide scale, substrates young enough to support sufficiently fertile soils were confined to the younger volcanoes, primarily on the Island of Hawai‘i and Haleakala Volcano on Maui (Fig. 1). The critical implication of our finding is that prior to European contact, Hawaiians had expanded dryland agriculture to cover all of the sites in which intensification was feasible, thus reaching at least the geographic limits to such dryland intensification, if not absolute limits of productivity. We believe that this agricultural context relates directly to the highly aggressive, territorially expansionist strategies of the Hawai‘i and Maui Island polities in the centuries immediately prior to European contact (Kirch 1984; Vitousek et al. 2004).

Module 2: Natural and Modified Vegetation

In order to monitor the cumulative impact of agricultural intensification on natural ecosystems, we systematically sampled macrobotanical and microbotanical materials from a peat core near the upper margin of the Kohala field system, and from excavations in agricultural fields, from residential sites, and from soil test pits in both study areas. Pollen from the peat core indicates substantial upland vegetation change during the period of Hawaiian agriculture, with an overall decline in trees and periodic increases in shrubs and species of open areas. Microscopic charcoal influx indicates at least one local fire coincident with the final decline of tree pollen; analysis of earlier fire history is ongoing. Within the Kohala field system, we evaluated the composition of the pre-cultivation vegetation, insects, and land snails at a range of altitudes, the spatial and stratigraphic distributions of carbonized wood and seeds, the identity of fallow weeds, and crop plant distribution (Jeraj et al., in prep.). We found an increase over time in carbonized seeds of the native weed Chenopodium oahuense, confirming fallowing as a component of agricultural strategy in the Kohala field system; observations of wood charcoal suggest that burning of more substantial vegetation occurred sparingly throughout the field system, and that natural fires pre-dating human settlement of Kohala were lacking.

In Kahikinui we used wood charcoal, carbonized seeds, pollen, and phytoliths from dry contexts to reconstruct native vegetation and its compositional change over the time span of pre-contact settlement (Coil 2004, in prep.). Shrub taxa increased while arboREAL taxa declined over time, as vegetation around areas of settlement was increasingly altered by human activities. Phytolith assemblages from Kahikinui
frequently contain abundant palm-type phytoliths (Coil 2003); the absence of palm wood in Kahikinui charcoal samples demonstrates the value of a multi-proxy approach to reconstruction of vegetation. As in Kohala, natural fires in Kahikinui were limited, with no evidence of burning prior to the initial human use of the area.

Identification of wood charcoal prior to radiocarbon dating has allowed us to create a body of dates free from “old-wood” or “inbuilt age” bias. In Kohala, the relative chronologies of field expansion and intensification developed through analysis of surface architecture (Ladefoged et al. 2003) can now be compared with radiocarbon dates from wood charcoal buried during field wall construction (Ladefoged et al., in prep.). For Kahikinui, a larger suite of 169 radiocarbon dates not only offers chronological control for the sequence of agricultural intensification, but allows us to estimate changing human population over a four-century period (see Module 4, below).

Module 3: Agriculture
For both dryland study sites, we used a combination of archaeological, biogeochemical, and quantitative modeling approaches to reconstruct details of agricultural practice and sequences of intensification over time. In Kohala, 398 ha were intensively surveyed and 6,500 archaeological features were precisely located by GPS; all archaeological data have been integrated into a GIS incorporating excavation data from 55 residential features, as well as environmental information. In addition, 88 geoarchaeological trenches provided soil samples for nutrient and archaeobotanical analysis. Relative chronologies of agricultural infrastructure construction in three intensively surveyed areas have been established (Ladefoged et al. 2003; Ladefoged and Graves, in press), and one of these has been independently evaluated with a suite of 18 AMS $^{14}$C dates (Ladefoged et al., in prep.); additional sections of the field system will shortly be AMS dated. Geoarchaeological and soil nutrient analysis of soil samples from the trenches bisecting agricultural walls, fields, and trails demonstrates spatial and temporal variability in planting techniques (Ladefoged et al. in prep). In aggregate, we can now refine a model of agricultural intensification in leeward Kohala as one of “cropping cycle intensification” (Kirch 1994, in press), a sequence which moves along a pathway from long-to-short fallow over time, requiring increased labor inputs into smaller and smaller individual plots. This sequence most closely approximates the classic Boserup (1965, 1981) model of agricultural intensification (see also Morrison 1994; Johnston 2003).

The younger, drier, and more mosaic-like landscape of Kahikinui required a more localized and varied adaptation of Hawaiian crop-planting practices. Archaeological evidence of intensive cultivation of sweet potato and other dryland crops is extensive, including walls, terraces, mounds and other features (Coil and Kirch, in press). Detailed investigations at several kinds of gardening sites included a large swale surrounded by residential complexes and an agricultural temple; excavations confirmed intensive gardening over 3-4 centuries, resulting in substantial geomorphological and pedological modifications. A ritual garden feature and shrine were also identified and excavated within the swale complex. A second swale site had a shorter cultivation sequence and higher anthropogenic nutrient inputs from the surrounding residential complexes (Hartshorn et al., in prep.). Open-field agricultural sites in Kahikinui lack walls and terraces, but excavations and stratigraphic trenches revealed abundant evidence of digging stick depressions which had penetrated a tephra/cinder/tephra soil sequence. Comparisons of soil properties within and outside of the features yield significant reductions of key plant nutrients (but not of elements not utilized by plants), confirming that the levels of harvesting in these dryland systems were sufficient to result in measurable nutrient depletion.

These field observations and measurements are complemented by results from soil-agriculture models for the dryland system. We modified a version of the Century model (Parton et al. 1987, 1988) formulated as an analytical system to handle (a) soil hydrology in volcanic substrates (Chadwick et al. 2003), (b) more rapid analysis of stochastic inputs and outputs, and (c) sensitivity analysis. Our model is a system of differential equations relating carbon and nitrogen in plants, litter, soils in terms of fluxes. The system contains nonlinear nitrogen fluxes and variable dynamics of C/N ratios for such crops as sweet potato. In addition all kinetic factors (e.g., growth, decomposition) are functions of rainfall, temperature, and plant-available mineral nitrogen. Our simulations of dryland systems yield complex dynamics (aperiodic or chaotic) with seasonal forcing (Lee and Tuljapurkar, in prep.). While previous studies have shown that temporal variation in rainfall may poorly predict variation in plant production because of interactions with nutrient dynamics (Burke et al. 1997; Oesterheld et al. 2001), our results raise the possibility of a previously unrecognized dynamical mechanism for this phenomenon.
We then used rainfall and temperature data at or near the field sites to build stochastic models (time series Seasonal Autoregressive Integrated Moving Average models, Monte Carlo resampling) of weather across time and across the elevation gradient, and modeled sweet potato yields in dryland fields with only rain-derived nitrogen inputs. The mean and variability of rain change with elevation—as do nitrogen dynamics—so we expected the mean and variability of productivity to change as well (Burke et al. 1997; Hooper and Johnson 1999). Figure 3 illustrates amplification of rainfall (cm/yr) variation by soil dynamics into yield variation (metric tons/ha/yr). We find that: (a) variability of yield is as much as 2x the variability of rainfall at low elevations and drops to below 1x only at elevations above the upper boundary of the field systems; (b) the downside risk of low annual yield is larger at low elevations but so is the potential benefit of high yield; (c) the spatial correlation between yields at different elevations falls rapidly with distance so that elevations 270

Figure 3. Amplification of rainfall variation by soil dynamics translates into yield variation.

meters apart have correlation coefficients of only 0.5. Modeled yield is limited by interactions of N and precipitation at lower, while observations suggest that available phosphorus (P) should be a limiting factor at high elevations – implying a localization of agriculture consistent with empirical findings (Lee and Tuljapurkar, in prep.).

This model offers an important baseline from which to explore the intensity of agriculture across space, the effect of external nutrient inputs, and other questions. For example, consider the distribution of yields over time along an elevation gradient, as in Figure 4. For each elevation, the stochastic model yields a steady state probability distribution of annual yields. The solid line to the right shows the cumulative probability of yields at the lower elevation boundary of the Kohala field system; the dashed line indicates yield distributions at the upper boundary. Note that downside risks of low yield and upside potential of high yield are both higher at the lower elevation, even though our initial assumption of constant N inputs means that the average yield does not change significantly.

Since spatial correlation falls fairly rapidly with distance up the slope, there is clearly potential to reduce overall yield variation by farming at several different elevations. The model’s prediction fits well with the pattern of land use in which territorial units run parallel to slope, so that any social territory incorporates land within all elevation zones. Indeed, a uniform spatial average across elevation leads to the probability distribution displayed by the square symbols. It is interesting that this average across elevation reduces the downside risk of low yield years without sacrificing much upside probability. To generalize from this example, any hypothesized spatial (or temporal) distribution of agricultural effort can be analyzed in the model as a spatial average across field locations in which the level of effort is used to weight yields at different locations. Thus allocations of agricultural effort across space, which are determined by social organization, can be translated into a distribution of means and variability of agricultural yields over time (Lee and Tuljapurkar, in prep.). Moreover, the stochastic distribution of yields can be used as input to our demographic analysis of the effect of variable food supply on human vital rates, allowing us to generate testable hypotheses linking soils and agricultural practice to social and demographic change over time.

Figure 4. Yield risk over time and space for upper and lower portions of the Kohala field system.
Module 4: Population and Demography

Prior paleodemographic research in Hawai‘i had drawn upon ethnohistoric estimates, radiocarbon date distribution curves, and archaeological house counts to derive regional and archipelago-wide estimates of population growth (Cordy 1981; Hommon 1976; Dye and Komori 1992; Dye 1994). Our approach has been to use stochastic demographic models to place bounds on historic vital rates (age-specific mortality, fertility) that are consistent with long run population trends (Tuljapurkar et al., in review), and to test these general models with empirically grounded reconstructions of populations in our two study areas.

For archipelago-wide modeling, prehistoric skeletal mortality data from four Hawaiian collections display low infant mortality and high adult mortality relative to other world populations. We developed a data-driven model for prehistoric mortality by using singular value decomposition to identify a two-parameter family of relational models, focusing on the levels of mortality of young (<15 yr) and of reproductive adults, and the total fertility rate. When age-specific mortality and fertility are held constant, they entrain a long run growth rate. If age-specific mortality and fertility vary stochastically, the long-term growth rate results from the joint effect of average rates and variation in those rates. Figure 5 shows the range of possibilities with constant rates (left panel), suggesting that mortality must have been high for either young or adults. The right panel shows fertility and mortality varying stochastically over time; we suggest that it is much more plausible that average mortality was low for young and adults. The high variability, however, means that cohort survival was quite variable over time. Given the high levels of variability in food supply from our climate/soil models, and ethnohistorical evidence of warfare, the right-hand panel represents likely combinations of mortality and fertility.

With model mortality schedules in hand, and bounds on the possible combinations of mortality and fertility, we are now positioned to evaluate demography in particular landscapes – and to model explicitly the effects of variable food supplies on population dynamics. For Kahikinui, our sample of 169 14C dates reflects exponential growth from ca. A.D. 1400 (initial settlement of this arid landscape) until European contact, with no reduction in the frequency of samples for the later time intervals and thus no basis for inferring a logistic process (Kirch, in review). This contrasts with prior evidence for the archipelago as a whole, indicating an exponential growth curve until ca. A.D. 1400-1500. Significantly, people began to settle and utilize the Kahikinui lands at the same time that the archipelago-wide growth curve reached its peak. The occupation of Kahikinui was thus a population “overflow” from other regions, beginning only as the main period of “inland expansion” was coming to a close. This pattern presumably reflects the marginality of Kahikinui in terms of water, resources, and agricultural potential (Kirch et al. 2004). Kahikinui is a high risk environment, one that people tackled only when other options became closed to them (Dixon et al. 1999). We also applied a “house count” method (Hassan 1981; Turner 1990) to estimate specific population sizes and densities for a representative sample area of approximately 6.75 km², containing 544 individual stone structures grouped into 117 residential complexes. We conclude that the maximum density achieved in the lowland zone was between 43-57 persons/km², depending on average household size. The figures for the ahupua‘a territory as a whole are between about 19-25 persons/km² – on the low end of ethnographically-documented population densities in Polynesia, realistically so in view of the environmental marginality of Kahikinui.

For Kohala, we based a demographic model on 195 residential features in a 1.3 km² detailed study area in the southern part of the field system (Ladefoged and Graves, in review). Our data suggest that this
area might have been developed relatively late in relation to other portions of the field system (Ladefoged and Graves 2000; Ladefoged et al. 2003). Within this area, we estimate population grew from a density of 20 persons/km² to 91 persons/km² as the field system expanded and intensified. If these figures are extrapolated to the entire Kohala field system, we calculate a peak population of ca. 5,025 within the system. These levels are much higher than Kahikinui, corresponding to the higher agricultural potential of Kohala and its formalized field system. Initial estimates of population growth along the Kohala coast show expansion as well (Graves et al. 2002).

Module 5: Social Structure and Control Hierarchies

As the dryland agricultural economies of Hawai‘i and Maui were undergoing the sequences of intensification and linked demographic change outlined above, their sociopolitical systems were simultaneously becoming more complex. We have made significant progress in tracking the development of a control hierarchy associated with the emergence of archaic states on these islands late in the precontact period. In Kahikinui, this control hierarchy is manifested materially in a system of temples, marked archaeologically by complex and varied stone foundations. As ethnohistorically documented (Valeri 1985), this temple system corresponded to a hierarchy of major gods, with two primary temple classes: those associated with food production (heiau ho‘ouluulu) versus war (heiau kaua). Prior efforts at dating Maui Island temples using ¹⁴C (Kolb 1992, 1994) suggested a quantitative increase in temple construction between ca. A.D. 1400 and 1650 – but ¹⁴C dating in the last 500 yr is confounded by ambiguous regions of the radiocarbon calibration curve, and other problems (Taylor 1998). We developed a chronology of temple construction in Kahikinui via ²³⁰Th dating of branch corals used as dedicatory offerings (Kirch and Sharp, in press). This approach offers significant advantages over ¹⁴C dating; uncertainties in ²³⁰Th ages for ca. 400 year old corals are 7-12 years at 95% confidence intervals (Edwards et al. 2003).

Calculated dates for the coral offerings fall in a narrow range from 1568 ± 8 to 1635 ± 6 – within an interval of <70 years, and as little as half that time when we account for coral growth rates. Our sample includes small and mid-sized temples, as well as the largest temple structure in the district. The timing of intensive temple dedication implies that fundamental change in the sociopolitical structure of the district occurred far more rapidly than previously documented. The Hawaiian ethnohistorical record of chiefly genealogies and oral traditions (Abad 2000) sheds light on the broader context in which this abrupt social restructuring took place. For Maui Island, two formerly independent chiefdoms were brought under the control of a single leader during the reign of Pi‘ilani, ca. A.D. 1570-1600. His grandson Kamalalawalu (ca. A.D. 1610-1630) extended the Maui polity by taking over the nearby islands of Lana‘i and Kaho‘olawe, expanding the Maui polity from about 940 km² to more than 2,360 km² - just the kind of territorial expansion predicted with archaic state formation (Marcus 1992; Spencer 1998). A parallel process of sociopolitical change apparently occurred on Hawai‘i Island at the same time (Abad 2000). Accordingly, the temples provide tangible archaeological evidence of the speed with which a fundamental sociopolitical transition occurred in proto-historic Hawai‘i.

In Kohala, we used three lines of evidence to evaluate the changing nature of control hierarchies over time. First, we identified at least three, and possibly as many as six, levels of territorial divisions that occurred through time—a process of territorial subdivision that is probably reflective of increased elite managerial control (Ladefoged and Graves, in press). Second, the spatial distribution of eight heiau (temples) changes in relation to temporal rearrangements of ahupua‘a boundaries, with the youngest heiau apparently reflecting infilling of simplified religious structures within established ahupua‘a (Mulrooney and Ladefoged, in review). These results also suggest that there was a longer timeframe for religious development in leeward Kohala in relation to Kahikinui. Finally, the size and shape of the agricultural fields become more standardized over time, probably reflecting higher levels of managerial control over production (Ladefoged et al. 2003, Ladefoged and Graves 2000).

Synthesis of Modules

Although our modular structure provides an efficient way to conduct interdisciplinary research, our overriding goal is synthesis across the disciplines of archaeology, biogeochemistry, demography, ecology, and pedology. We have made substantial progress in this synthesis, with the results of each module providing inputs and linkages to the others. Thus for the indigenous Hawaiian political economies that were based primarily upon intensive dryland agriculture, we now understand more fully critical aspects of: (1) the time scale of the intensification process; (2) how intensification operated at both local and landscape scales, and its effect on natural ecosystems; (3) how intensification was constrained by
fundamental biogeochemical gradients; (4) how population growth, as well as particular aspects of mortality and fertility were dynamically linked to stochastically fluctuating production systems; and (5) how, as the system intensified, a top-down control hierarchy was imposed.

Achievements in Education and Outreach

Undergraduate and graduate education has been inextricably linked with our research—explicitly so in the Kohala field system, where much of this research has been carried out through an archaeological field school (Hawai‘i Archaeological Research Project, [www.harp.hawaii.edu](http://www.harp.hawaii.edu)). This school has involved 16 graduate students and 12 undergraduates in the past three summers. Another 7 graduate students and 10 undergraduates from other institutions have worked in the field on aspects of the research—and interactions among research groups and modules have been seamless and highly productive, with students often shifting from coring a montane bog to digging soil pits to picking charcoal from trenches in a single week. Two doctoral dissertations at U. C. Berkeley are based in part on research carried out through this project, and 4 postdoctoral fellows have received all or part of their support from the grant. We are confident that students and postdoctoral fellows have received both substantial training in the specific areas they have worked, and intensive indoctrination in the benefits of interdisciplinary research. About half of our students are women; 5 are Native Hawaiian, and 4 belong to other minority groups.

In the course of our work, we have made a systematic effort to reach out to the Hawaiian public, and particularly to Native Hawaiians, with our findings. The extent and intensity of precontact dryland agriculture are not widely appreciated in Hawai‘i—and where they are understood, the contemporaneous scarcity of agriculture as intensive in the continental tropics is little recognized. Our outreach has been direct (through numerous public talks), through the educational system (through talks to Native Hawaiian programs at the University of Hawai‘i (Manoa and Hilo) and at Kamehameha Schools (a multi-campus K-12 school for Native Hawaiians), and through the media. The U. Hawaii team also developed a 2 segment video series on archaeology and the Kohala Field System for 7th grade public schools in Hawaii. We also contribute annually to the orientation of students in the University of Hawaii Hawaiian Internship Program for Native Hawaiian undergraduates (www.hawaii.edu/~uhintern). Our research program has received substantial media coverage in Hawai‘i, including a front-page story and photograph in the local newspaper for leeward Hawai‘i (West Hawaii Today). Finally, we have developed a web site featuring key results of our project ([www.hawaii-biocomplexity.org](http://www.hawaii-biocomplexity.org)).