PROJECT DESCRIPTION

Human Ecodynamics in the Hawaiian Ecosystem, from 1200-200 yr B.P.

I. RESULTS OF PRIOR NSF SUPPORT

A. Prior NSF Support to Patrick V. Kirch, Principal Investigator: 1. NSF Grant No. SBR-9805754, Total $132,897, 6/1/98-5/31/01. 2. Project Title: The Dynamics of Economic and Sociopolitical Structure in Late Prehistoric Hawai'i: An Emergent 'Archaic State', Phase II. 3. Summary of Results: This project continued a long-term, multi-institution investigation of late prehistoric transformations in Hawaiian economic and sociopolitical structures. Fieldwork concentrated on two traditional Hawaiian land units (ahupua'a) in Kahikinui district, Maui, totaling 8 sq. km., with 1,789 archaeological sites recorded in a GIS database. Main results include: (1) Chronology of land use established through 120 14C dates, also providing a proxy measure of population change in late prehistory. (2) Areal excavations at both commoner and elite residences, yielding fine-scale data on household variation. (3) X-Ray fluorescence (XRF) methods (Weisler and Kirch 1996; Weisler and Woodhead 1995) used to source lithic artifacts from residential sites, providing evidence for inter-territorial exchange. (4) Reconstruction of pre-contact cultivation activities using archaeobotanical methods, as well as sedimentological evidence for slope erosion and soil inwash resulting from a shifting cultivation regime. (5) Analysis of faunal assemblages from the household sites revealing differential access to marine resources. (5) Documentation of a 3-tier hierarchy of temple structures (both in size and architectural complexity), and of a pattern of temple distribution correlating with sub-ahupua'a units. (6) Analyses of macro- and microbotanical remains (carbonized wood, opal phytoliths, pollen), outlining significant environmental changes (e.g., clearance of open canopy forest in the mid-altitude zones) that accompanied Polynesian expansion. (7) The project has contributed to human-resources development by including 5 undergraduate and 4 graduate students in various aspects of field and laboratory research; of these 9 students, 6 are women and 1 is Native Hawaiian; three doctoral dissertations will be based on project results (C. Van Gilder, J. Coil, L. Holm). 4. Selected Publications Supported by SBR-9805754: Kirch (1998); Millerstrom and Kirch (in press); O'Day (submitted); Stock, Coil, and Kirch (submitted). 5. Available data, samples, physical collections: The project has generated databases stored primarily in digital form as a series of MS ACCESS, AutoCAD, and ArcVIEW files at the Archaeological Research Facility, UCB. These databases will be extensively utilized in the research proposed here. 6. Relation of Completed Work to this Proposal: The proposed research will continue our field studies in Kahikinui, by incorporating the results of archaeological and paleoecological investigations with new perspectives and research questions, deriving from an explicitly interdisciplinary perspective.

B. Prior NSF Support to Peter Vitousek, Principal Investigator: 1. NSF Grant No. DEB 96-28803, Total $599,998, 9/1/96-8/31/99. 2. Project Title: Interactions of N, P, and Other Elements During Long-Term Soil and Ecosystem Development. 3. Summary of Results: This project evaluated how the flexibility of element cycles in forest ecosystems contributes to nutrient limitation. The underlying hypothesis was that the element with the least flexible cycle, rather than the one in shortest supply instantaneously, limits ecosystem processes in the long term. We evaluated several mechanisms controlling flexibility, including biochemical versus biogeochemical mineralization (Olander and Vitousek 2000), nutrient limitation to decomposition and its effects on rates of nutrient circulation (Hobbie and Vitousek 2000), and the regulation of N fixation (Vitousek and Field 1999, Vitousek and Hobbie 2000). In addition, we tested the Walker and Syers (1976) theory for nutrient supply during long-term soil and ecosystem development

(Vitousek and Farrington 1997), and put together a new synthesis of element inputs (Chadwick et al. 1999). This funding contributed to the thesis research of eight Ph.D. students and one postdoctoral fellow; so far it has helped to support 36 journal publications. 4. Selected Publications supported by DEB 96-28803: Vitousek and Farrington. (1997); Austin and Vitousek (1998); Chadwick et al. (1999); Vitousek and Field (1999); Hobbie and Vitousek (2000); Olander and Vitousek (2000); Vitousek and Hobbie (2000); Treseder and Vitousek (in press).

C. Prior NSF Support to Shripad Tuljapurkar, Principal Investigator: 1. NSF Grant No. DEB 96-96219, Total $113,924, 8/20/96-2/28/99. 2. Project Title: Mathematical Models of Dynamics and Evolution in Structured Populations. 3. Summary of Results: Development of theory of time-varying demography; completed editing of book on structured population modeling methods; additional work on life history evolution, including senescence, reproductive effort, and evolution of life cycle delays. Human resources: collaboration with several scientists including graduate students and postdocs; completion of book now often used for modeling methods. 4. Selected Publications Supported by DEB 96-96219: Tuljapurkar and Caswell (1997); Tuljapurkar (1997); Li and Tuljapurkar (1999a, 1999b), Tuljapurkar and Wiener (2000); Orzack and Tuljapurkar (in press).

D. Prior NSF Support to Oliver A. Chadwick and Peter Vitousek: 1. NSF Grant No. ATM 9807631, Total $83,583, 6/1/98 - 5/30/01. 2. Project Title: Sources and fates of ecosystem nutrients across the Hawaiian Islands. 3. Summary of Results: The goals of this project is to understand the evolution of nutrient cycling in soils in tropical volcanic ecosystems as a function of time, climate and landscape position. We have used geochemical (isotopic and trace element) and mineralogical tracers to quantify marine and mineral aerosol inputs over time, and plant uptake of various nutrients (P, Ca, Si). 87Sr/86Sr data demonstrate that Hawaiian ecosystems become dependent on atmospheric inputs for base cations within 20 ka of surface colonization. Over longer time scales (106 yr), eolian P becomes the major source of available phosphorous. We established a detailed chemical, mineralogical, and isotopic mass balance for the soils in our study areas, accounting for mass loss via leaching and additions from mineral and sea salt aerosol deposition. This allows us to estimate integrated aerosol inputs for various elements, and determine input-output budgets. 4. Publications Supported by ATM 9816636: Kurtz et al. (2000a, b); Capo et al. (2000); Chorover (1999); Hotchkiss et al. (2000); Miller et al. (in press); Schuur et al. (in press); Stewart et al. (in press); Whipkey et al. (2000); Vitousek et al. (1999); Chadwick et al. (1999); Kennedy et al. (1998).

II. DESCRIPTION OF PROPOSED RESEARCH

A. INTRODUCTION

We propose an innovative collaboration among archaeologists, demographers, ecologists, soil scientists, and paleobotanists, most with extensive research experience focused on past and/or present cultural and natural systems in Hawai'i. Our goal is to increase scientific understanding of long-term co-evolutionary interactions between people and their environments, or what may be termed "human ecodynamics" (McGlade 1995; van der Leeuw 1998; van der Leeuw and McGlade, eds., 1997), and to advance the use of past dynamics as explanatory models for contemporary global environmental change. Our theoretical orientation is that of ecosystem-culture "co-evolution" (Durham 1976, 1991; Butzer 1982, 1996; Kirch 1980). Our approach offers the real advantage of long-term historical data, provided by archaeology and paleoecology, combined with research on ecological and demographic processes (Redman 1999).

1. Why Hawai(i? Oceanic islands in general--and the Hawaiian Islands in

particular--offer unique opportunities for understanding the fundamental mechanisms underlying diverse areas of study, from evolutionary radiation and speciation (Carson 1986; Givnish et al. 1995; Baldwin 1998) through ecosystem ecology and biogeochemistry (Vitousek 1995; Chadwick et al. 1999), to the evolution of human culture (Kirch1985, 1997, 2000). These opportunities arise because islands generally are simpler than continents in important ways, and yet they are real, dynamic systems that incorporate the essential features of more complex continental systems. Islands thus can be used as model systems for understanding both land and culture, in much the same way that Arabidopsis thaliana is used as a model organism for plant molecular biology (Myerowicz and Somerville 1994). In our project, we propose to link our understandings of the ecology/biogeochemistry and the cultures of Hawai'i, to turn what has been a useful model system for each separately into an unmatchable model system for understanding their interactions.

2.

For understanding ecosystems, the extreme isolation and low species diversity, consistent geology and geomorphology, and wide and well-defined variation in climate and substrate age of the Hawaiian Islands allows investigators to focus on controlling processes with a precision that cannot be duplicated elsewhere. Environmental gradients in mean annual temperature (from <10-24 C), in annual precipitation (from <200->5,000 mm), and in substrate age (from hot rock to >4 myr) are among the clearest, broadest, and most orthogonal on Earth. Hawaiian ecosystems lend themselves to a combination of process measurements along these gradients (Herbert and Fownes 1999, Austin and Vitousek 2000), ecosystem-level experiments (Herbert and Fownes 1995; Vitousek and Farrington 1997), and simulation models (Raich et al. 2000), and these techniques have been used to address fundamental questions from the effects of individual species on ecosystem properties (Vitousek and Walker 1989; D'Antonio et al. 2000) through how temperature controls productivity, decomposition, and C storage (Townsend et al. 1995; Raich et al. 1997), to the causes, nature, and consequences of nutrient limitation (Chadwick et al. 1999; Vitousek and Hobbie 2000). Recently, paleoecological and paleoclimatic information has further enriched these analyses (Burney 1997; Hotchkiss et al. 2000).

The Hawaiian Archipelago also presents an ideal region for understanding complex interactions between human populations and their environments over a controlled, and relatively short, time scale. When the islands were first made known to Western science, on the famous third voyage of Captain James Cook in A.D. 1778-79, they were occupied by an isolated population of at least 450,000 indigenous Polynesians (Stannard 1989), with an economy based on complex systems of irrigated and dryland farming, aquaculture, and animal husbandry (Allen 1991, 1992; Kirch 1985). Archaeological research has narrowed the time frame of initial human incursion into the archipelago, based on 14C dating of habitation sites and of sediment cores exhibiting proxy measures of human presence on the landscape (e.g., microfossil charcoal, pollen of synanthropic taxa), to ~1200 ± 200 yr BP (Kirch 1985, 2000; Athens 1997). These Ancestral Polynesians arrived in Hawai'i accompanied by a suite of commensal and synanthropic taxa (crop plants, domestic animals, weeds, ectoparasites).

It can be inferred that the size of the colonizing human propagule was small, probably <200 persons (although periodically added to by additional voyagers). Over a period of ~1 kyr, this population of Homo sapiens grew logistically in numbers to achieve high density levels (~150-200/km2 in some areas), and extensively modified the biota and landscapes of the lowland (<1000 m) zones of all major islands (Kirch 1982; Athens 1997). Extinctions/extirpations of endemic avifauna (Olson and James 1984; Moniz 1997) and of pulmonate mollusks (Christensen and Kirch 1986), extensive deforestation in lower elevations and extinction of plant taxa (Athens 1997;

Athens and Ward 1993; Athens et al. 1992), repeated firing of some landscapes (Kirch 1982), and local erosion and mass wasting (Williams 1992; Yen et al. 1972), along with valley alluviation, have all been claimed or documented on the basis of extensive archaeological and paleoecological data sets. Along with other isolated Polynesian high-island ecosystems (e.g., Kirch 1996, 1997a, 1997b), the Hawaiian archipelago presents an unparalleled situation for studying the complex, non-linear interactions between an invading human population and a "pristine" environment, without prior cultural inputs.

2. A Case of Emergent Complexity. What makes the Hawaiian case especially compelling for understanding human ecodynamics is that the socio-cultural system underwent dramatic changes over the same ~1 kyr time span, including emergent complexity in economy, socio-political organization, and religious ideology. Reconstructions of Ancestral Polynesian society (Kirch and Green 2001) indicate that the colonizing group was structured as a "house-based," fluid kin structure, with heterarchical competition between local groups, each associated with its land or estate (Kirch 2000). Roughly 400-600 yrs after colonization, and within a phase of rapid, logistic population growth and geographic expansion, Hawaiian social units underwent variable amalgamation and dramatic hierarchization (Cordy 1974; Earle 1977, 1978, 1987, 1997; Hommon 1986; Kirch 1990a, 1990b; Sahlins 1958), leading to the situation at European contact, in which four major complex polities competed for hegemonic control of the archipelago. This highly complex, hierarchically structured society which emerged in late prehistory was marked by such features as: (1) ownership of land by chiefly elite; (2) obligatory tribute or corvée labor extraction; (3) high degree of economic specialization; (4) intensified agricultural and aquacultural production systems; (4) endemic conflict focused on defense of or increase in territories; (5) elaboration of a social hierarchy, including a class distinction between chiefs and commoners; and, (6) a complex religious and ideological system (Valeri 1985) which legitimized the authority of chiefs over resources and labor.

3. Advancing the Field of Human Ecodynamics. In short, Hawai'i presents exquisite possibilities for constraining analyses of both ecosystem state factors and human demographic and economic inputs, as well as cultural and social responses to environmental change. These interactions can be tracked over a time frame of ~1 kyr, a period sufficient to have witnessed the emergence of complexity resulting from dynamic coupling of human-natural systems, while filtering out short-term perturbations. Our project aims to make innovative use of the Hawaiian possibilities by empirically tracing the dynamic histories of coupled human-natural systems in two study areas on the islands of Maui and Hawai'i. Both regions have benefited from on-going archaeological and paleoecological investigations that provide temporally-controlled databases on prehistoric Hawaiian land use, settlement patterns, demography, subsistence economy, socio-political organization, and ritual (monumental) architecture. We will combine this archaeological approach with closely-integrated field, laboratory, and modeling studies carried out by our team of ecologist, soil scientist, palynologist, archaeobotanist, and quantitative demographer. We anticipate that this unprecedented integration of approaches will yield new insights into the complex and nonlinear relationships between human populations practicing complex strategies of land use and resource exploitation and ecosystem dynamics over time frames of several centuries.

While building on substantial prior research by each of us into relevant aspects of the problem, the active integration of several disciplinary theoretical perspectives and methods will allow us to move beyond a descriptive, qualitative "historical ecology" (Kirch and Hunt, eds., 1997) towards testable, dynamic, quantitative models that incorporate feedback processes; thresholds and nonlinearities; selection, risk, uncertainty, and vulnerability. We will build models at all levels--conceptual, mathematical, and computational (simulation)--and use these to test a series of specific hypotheses regarding the linkages between an (initially) expanding human population, a landscape of complex biogeochemical mosaics, and specific cultural behaviors such as the increased imposition of control hierarchies, increased scale of organization, or forms of territorial competition. We anticipate that this research will be of wide interest, both for its theoretical and methodological innovations and insights, to a range of disciplines including ecology, anthropology, archaeology, demography, and biogeography, among others. Theoretical contributions anticipated from the project may prove to have implications for how we think about sustainability (N.R.C. 1999).

B. RESEARCH STUDY SITES AND ARCHAEOLOGICAL DATABASES

In The Anthropology of History Kirch (1992) argues that peripheral or marginal regions--those most susceptible to risk and uncertainty--are often the best localities in which to study periods of rapid cultural and ecological change. We will focus on two study areas, whose human settlement histories are fairly well resolved through prior archaeological investigation, and which were relatively resource-restricted, from the point-of-view of Polynesian colonists. Both areas began to be exploited and occupied by small human groups during the Expansion Period (A.D. 1100-1650) of the Hawaiian cultural sequence (Kirch 1985, 1990, 2000). This phase was characterized by an archipelago-wide population increase, at an exponential growth rate (Kirch 1994; Clark 1988; Dye and Komori 1992a, 1992b). At the point of initial European contact, both regions were densely settled, with local variations corresponding to parameters of the spatial environmental mosaic.

1. The Kahikinui Study Area (Maui Island), encompasses the ancient political district (moku) of Kahikinui, on the southern slope of Haleakala volcano, rising from sea level to 3,000 m asl, a magnificent altitudinal gradient cross-cut by substrates of varied geological age. Kahikinui typifies a leeward climatic zone with pronounced seasonality ("kona" rains predominate) and a total annual precipitation of 250-1000 mm, which puts it on the margin for dryland cultivation of Polynesian crop plants, especially in drought periods. The vegetation of this leeward slope (Medeiros et al. 1986; Rock 1973[1916]) has long been noted as a prime example of the high taxonomic diversity characteristic of Hawaiian dryland forests. The eastern half of the district has older substrates of the Kula Volcanic Series (400 kyr) with deeply weathered soil profiles and considerable hydrologic incision (Stearns and Macdonald 1942; Bergmanis 1998). In stark contrast, the western part of the district consists of young lava flows of the Hana Volcanic Series (0-60 kyr), a rejuvenation phase of Haleakala, resulting in rugged, unweathered or barely weathered surfaces lacking significant stream incision. A further resource restriction in Kahikinui was imposed by the coastal geomorphology, largely one of low sea cliffs and an absence of coral reefs, hence relatively low biotic diversity and biomass, rendering marine protein exploitation marginal.

Since 1994, Kahikinui has been archaeologically investigated by three coordinated teams of archaeologists from U. C. Berkeley, Northern Illinois University, and the State of Hawai'i (Kirch, ed., 1997; Dixon et al. 1997, 1999). Two adjacent ahupua'a territories, Kipapa and Nakaohu, comprising an area of 8 sq km in central Kahikinui, have been intensively surveyed from the coast up to 1200 m above sea level where site density becomes very sparse (Kirch, 1997c, 1997d; Dixon et al. 1997, 1999).The resulting GIS database includes some 1,789 archaeological features (Figure 1).

Additionally, Kirch and his team have conducted extensive excavations in a series of habitation, agricultural, and ritual sites that have provided the basis for writing a detailed, local-level history of land use, local environmental modifications, resource use, micro-demographic distributions, group organization and interactions, and iconic (ritual) marking of the landscape with monumental architecture. A suite of more than 120 14C age determinations, now being augmented by U/Th dating of coral offerings from ritual sites, anchors this cultural history firmly in time, at a resolution of ± 75 yr. Frequency distributions of dated habitation sites furthermore provide the basis for a proxy estimate of the rate of population growth beginning with initial human incursion into the region, up to abandonment ca. A.D. 1870.

Using multiple lines of evidence including zooarchaeological faunal materials (O'Day, submitted), charcoal, opal phytoliths, and other plant microfossils (Coil, in prep), pulmonate gastropods, and other sources, we have begun to develop a temporally and spatially fine-grained reconstruction of biotic resources and their distributions over the period of Polynesian occupation. In particular, our most recent research has focused on hydrological changes in our study area resulting from deforestation in an upland belt of cloud forest (Hamilton et al. 1995) located above the main zone of archaeological settlement (Stock et al., submitted).

2. The Kohala Study Area (Hawai'i Island), Kohala has been the focus of extensive--and to date independent--archaeological, pedological, ecosystem, and paleoecological studies (Figure 2). The area encompasses the oldest volcano on the Island of Hawai'i, with an edifice that formed by 400 kyr ago (Pololu series) and substantial areas that were covered by post-shield eruptions about 150 kyr ago (Hawi series). The volcano's wet windward slope is divided by deeply incised valleys, the largest of which (Waipio Valley) was the major locus of irrigated taro agriculture and (probably not coincidentally) an important seat of the paramount chiefs of the island. The undissected leeward slope supports one of the most spectacular rainfall gradients on Earth, reaching from <200 mm to >3500 mm annual precipitation in a distance of 15 km (Giambelluca et al 1986).

Research by Chadwick and colleagues has demonstrated that continuous variation in rainfall on this gradient has led to some striking discontinuities in soil properties (Kelly et al. 1998, Chadwick and Chorover, in press). In particular, soil acidity is low and cation availability is consistently high as rainfall increases from <200 to 1400 mm/yr. Above that point, acidity increases and cations decrease sharply. Soil cations are derived almost entirely from basalt weathering below 1400 mm/yr rainfall, and from marine aerosol above that level (Stewart et al in press). While the potential for basalt weathering increases linearly as a function of rainfall, at this soil age all of the primary minerals have been depleted from sites receiving >1400 mm rainfall. This sharp transition occurs at higher rainfall in sites younger than 160 kyr and at lower rainfall in older sites (Chadwick and Gavenda, unpublished).

Leeward Kohala also supported one of the most extensive dryland farming systems in the archipelago, covering roughly 19 km by 4 km (~55 km2) (Rosendahl 1972, 1994; Kirch 1984, 1985, 1994). The Kohala field system is characterized by a reticulate grid of stacked-stone field boundaries (see Figure 2); it incorporates thousands of smaller free-standing stone architectural features, including habitation sites and ritual structures. Archaeological research has traced the temporal development of both the field system and associated coastal and inland residential patterns, beginning as early as 1000 A.D. and continuing into the first decades after European contact (e.g. Newman 1970, Pearson 1968, Rosendahl 1972, 1994, Tuggle and Griffin 1973, Cordy and Kashko 1980). Later research focused on the windward valleys and their irrigation systems (Tuggle and Tomonari-Tuggle 1980). Most recently, Graves and Ladefoged have applyied a GIS approach to model the spatio-temporal development of the leeward field system (Ladefoged et al 1996, 1998; Ladefoged and Graves 2000). Cropping-cycle intensification occurred during the period A.D. 1300-1800; it was focused on areas receiving from about 800 to 1500 mm of annual precipitation.

C. RESEARCH TOPICS AND APPROACHES

Our project addresses four interconnected research themes: (1) the spatio-temporal processes of agricultural development, as these were linked to geomorphic and biogeochemical gradients and landscape mosaics; (2) patterns of demographic change, including the shift from a largely density-independent to density-dependent situation, and how these were linked to resource use and agricultural intensification; (3) the emergence--over a 300-500 yr period--of socio-cultural complexity, including formal control hierarchies, pronounced disparities in access to resources, and control over labor and surplus; and (4) the dynamic effects of a growing human population and evolving culture on its natural resource base, including not only agricultural land, but also upland forests and other biotic resources. We propose to address these questions in a hierarchical framework, through integrated studies and models that are organized into five principal modules. For analytical purposes we describe these modules individually, but as we will show they are fundamentally linked, in that understanding any one area requires knowledge of the others. The five modules are:

a. Soils and biogeochemistry, which will include climate, soil fertility, erosion, biogeochemistry, and their controls on short and long time scales.
b. Natural and modified vegetation, including vegetation structure, dynamics of principal and indicator species, natural and human disturbance.
c. Agriculture (including animal husbandry), focusing on cropping systems, major crops, agricultural intensity, sources of nutrients, productivity, and sustainability.
d. Population and demography, including mortality and fertility, migration, technology.
e. Social structure, including household units, the evolution of hierarchies and socio-cultural structures, conflict/cooperation, religion.

All of these modules will be explicitly spatial, based on a GIS framework, and all will be evaluated at ~100 yr intervals during the ~1000 years between Polynesian discovery of the Hawaiian Islands and contact with Europe -thereby incorporating sweeping changes from colonization through agricultural intensification and increasing socio-cultural complexity, with their manifold effects and interactions. We anticipate that just as the dynamics of each of the modules will be time-dependent, the relative importance of coupling between modules will change substantially with the growth and elaboration of Hawaiian population, productive systems, and culture.

Module 1: Soils and Biogeochemistry

Biogeochemical Background. The biogeochemical template upon which agriculture develops is well-characterized in Hawai'i. The weathering of basaltic rock supplies most elements (except N) to young ecosystems (Crews et al. 1995, Vitousek et al. 1997), but by 20 kyr the primary minerals in rock--and almost all the calcium, magnesium, potassium, and silicon--have been depleted. Thereafter, marine aerosol in rainfall and cloudwater provides the only significant source of these elements (Kennedy et al. 1998, Chadwick et al. 1999). The loss of rock-derived elements and dominance of marine aerosol can be demonstrated unambiguously using isotopes of Sr, an alkaline earth element like Ca and Mg that has isotopically distinct (and in Hawai'i unusually consistent) sources in Hawaiian basalt and marine aerosol (Graustein 1989, Kennedy et al. 1998, Vitousek et al. 1999). Phosphorus is much less mobile than most elements (e.g. Uehara and gillman 1988; Schlesinger 1997), and rock-derived P contributes to forest nutrition for more than a million years.

Eventually, however, the P from basaltic rock is depleted, and several minerologic and geochemical tracers of continental crust (versus mantle-derived Hawaiian basalt) demonstrate that continental dust from central Asia, over 6000 km away, thereafter constitutes the most important source of P (Chadwick et al. 1999, Kurtz et al. in press).

These observations, together with those on rainfall gradients discussed above, explain the background against which agricultural intensification takes place. Forests can cycle nutrients efficiently, and remain productive in the face of low inputs--but intensive agricultural systems inherently lose nutrients through harvest, and inevitably leakage as well. While shifting cultivation can make use of nutrients accumulated over a period of time, permanent agriculture requires relatively rapid renewal of nutrient supply (from weathering, fertilizer, or in the case of pondfield systems flowing water) if productivity is to be sustainable. Weathering sources of nutrients essentially disappear above 1400 mm annual precipitation on leeward Kohala (Figure 3) (Stewart et al. in press); we suggest that it is no coincidence that the upper-elevation (wetter) boundary of the Kohala field system follows this rainfall isohyet closely (Figure 2; Ladefoged et al. 1998). Our hypothesis is that Polynesian agriculturalists were farming the rock- that they learned to intensify agriculture in the wettest areas that still supplied nutrients through basalt weathering. Similarly, in Kahikinui our survey data suggest that the areas of most intensive land use were younger "rocklands" of the Hana Volcanic Series, rather than the older Kula Volcanics. Although the deeper Kula-derived soils appear more suited to cultivation, we hypothesize that they are also more nutrient-depleted.

The pattern of human use of land described here is not uniquely Hawaiian or Polynesian; the concentration of human land use in seasonally dry areas of the tropics, where precipitation is close to annual evapotranspiration (Ewel 1999) and on young (e.g., Amazonian varzea) and/or unusually fertile tropical soils, has long been noted (Murphy and Lugo 1986). What is unique here is the precision with which the biogeochemical template can be characterized, and the general processes underlying human interactions with land can be elucidated in space and time. The spatial structure of lands in Hawai'i means that there are close and well-defined connections between fertile and infertile soils, and on a larger scale between dryland and irrigated agriculture (Kirch 1994), so the interactions of humans with their core and marginal lands can be evaluated straightforwardly.
Research Plan. Soil sampling will be designed to determine the relationship between soil fertility (and its component processes) and the distribution of intensive dryland agriculture, as both of these vary in space and time. Major components of soil fertility include acidity, base saturation, and the supply of cations, P and N. While we will focus on acidity and cations, both because the limits of the Kohala field system correlate so strikingly with base saturation and for efficiency of presentation, all of these major components of fertility will be evaluated.

We will begin by mapping the current distribution of soil properties in relation to the field systems of Kohala and Kahikinui, using structured, nesting sampling along transects. These transects will cross the field systems perpendicular to elevation, and extend into drier and wetter areas above and below the fields. We plan to space transects 2 km apart in both Kohala and Kahikinui, and collect soil samples at fixed intervals of 200 m; this spacing will capture the differences in substrate ages within each region (150 kyr old Hawi Volcanics and 400 kyr Pololu Volcanics on Kohala, <60 kyr Hana Volcanics and 400 kyr old Kula Volcanics at Kahikinui) as well as variation in agricultural intensity among ahupua'a on apparently similar sites (Ladefoged et al. 1998). At two randomly selected points along each transect, we will sample soils on a finer scale, using a repeated-interval design along two 1000 m transects oriented at a 60 degree angle to optimize the sampling of spatial structure in soil characteristics (Clayton and Hudelson 1995, Radeloff et al 2000). In Kohala, the transects will parallel the soils gradient characterized by Chadwick and colleagues (Chadwick et al. 1994, Kelly et al. 1998, Stewart et al. in press). A subset of the transects will be extended across the mountain, linking the proposed research with ongoing analyses of nutrient cycling and forest history in montane rainforest (Crews et al. 1995, Torn et al 1997, Hotchkiss 1998, Hotchkiss et al. 2000), and to areas of intensive agriculture in the windward valleys (Kirch 1994). If important features of the sites or potential sources of variation are missed by this design, they will be sampled separately.

Soil samples will be collected and analyzed at two levels of resolution. At each location, we will collect a single depth-integrated soil sample from 0-30 cm; at about 10% of the locations, we will dig trenches from the surface to bedrock (or to little-altered volcanic ash in some of the older, deeper profiles), and characterize soils thoroughly in the field and laboratory, collecting samples by horizon. The 0-30 cm spatially extensive samples will be analyzed for pH and exchangeable Ca; our prior experience with Hawaiian soils shows that soil pH, base saturation, exchangeable calcium, the presence of primary minerals in the soil, accumulation of meteoric Be-10, and Sr isotopic composition are all strongly correlated, reflecting the fact that all are controlled by the same processes. These extensive samples also will be analyzed for oxalate-extractable P using a new procedure that provides an excellent measure of the labile P pool (Guo and Yost 1999), and for mineralizable N.

We will dig >100 of the deeper, better-characterized intensive samples; these will incorporate all of the substrates involved in the study, and a range of time and intensity of human use. The trenches will be sampled for stratigraphy and charcoal as well as soil horizons, and a full suite of soil and isotopic measurements will be carried out - including cation exchange capacity, all major cations, mineral fractions, Sr isotopes, and weathering rates in addition to pH and calcium. We will also measure total C, N, and P, P fractions, and 15N as an integrated measure of the relative openness of the N cycle (Handley et al. 1999).

This combination of extensive and intensive measurements will enable us to map spatial patterns in soil fertility within and outside the field systems, and to understand the fundamental controls of these patterns. It will also provide a spectacular data set for the testing and extension of models of weathering and leaching, and of N input-output budgets and 15N abundances (Stewart et al. in press, Vitousek and Field in press). Concurrent measurements of the development of the field systems in space and time (Module 3 below) can be evaluated in relation to soil fertility, with a very high degree of precision. It must be noted, however, that as much as a millennium of Polynesian agriculture could well have altered the patterns in soil fertility that we measure today; harvest adds another substantial pathway of nutrient removal to background rates of leaching, which themselves are enhanced by intensive agriculture. We propose to address the cumulative and dynamic effects of human activity on soil fertility by making use of archaeobotanical samples collected in the course of excavations at Kohala and Kahikinui, and of charcoal collected from the intensive soil samples above. We plan to analyze Sr isotopes in dated residues of food plants and wood-derived charcoal through time across our transects, focusing on upper-elevation sites that now are near the transition from fertile to infertile soils. Any human-caused change from fertile towards infertile soils should be detectable as a shift in Sr isotope ratios from those characteristic of Hawaiian basalt towards those of marine aerosol. Changes in the residue of food plants in particular would be revealing; a change in Sr isotope ratios in charcoal but not food plant residues would suggest the transport into the field system of wood harvested above the transition. Finally, we propose to evaluate anthropogenic enhancement of soil erosion or redistribution by measuring the accumulation of meteoric 10Be in soils (Brown et al., 1989; Pavich et al., 1986; Pavich et al., 1985). The Sr and Be isotopic measurements will allow us to see not just the effect of soil fertility on people, but the effect of people on soil fertility as both of these vary in space and time. Together, these analyses will contribute substantially to research themes 1 and 4, and to research modules 2 and 3.

Module 2: Natural and Modified Vegetation
We propose to survey the species composition, canopy structure, dynamics, and disturbance frequency of vegetation across the study landscapes over time, to investigate spatial and temporal correlations among changes in ecosystems, land use, culture, and climate. We will apply a range of established and innovative methods derived from paleoecology and archaeobotany, in three sedimentary contexts: (1) surface-to-bedrock trench profiles, shared with the soil and biogeochemistry studies described in Module 1; (2) archaeological sites, which provide direct evidence of human impacts on vegetation (module 3), and (3) sediment cores from small lakes or bogs, which can provide greater resolution of temporal dynamics. Chronological control will be provided by AMS 14C radiometric dating, supplemented by biostratigraphic marker taxa, and if necessary, thermoluminescence for dating surface exposure.

We will use seeds, wood, and microfossils from the intensively-sampled soil trench profiles to constrain the landscape-scale spatial patterns of species distribution in the context of soil fertility, at ca. 100-yr intervals. Recent work has improved the efficiency of recovering pollen, phytolith, and diatom evidence of past vegetation and soil moisture conditions, as well as evidence for localized burning and flooding episodes (Coil, unpublished). In Kahikinui, excavation of 41 surface-to-bedrock soil trenches has already revealed stratigraphic levels containing arboreal, mixed or disturbed vegetation, agricultural soils, and grass- and palm-dominated assemblages, with discrete charcoal deposits recording fire events (Figure 4).

Analysis of charcoal layers in the trench excavations will reveal the spatial and temporal extent of disturbance by fire over the period of Hawaiian occupation. Embedding and thin sectioning of macroscopic charcoal fragments will allow us to distinguish species assemblages burned, while identification of phytoliths with signs of burning will improve the correlation of burning events with vegetation types as well as specific agricultural activities (Piperno 1994; Kealhofer and Piperno 1994). Macroscopic charcoal fragments (minimum diameter 125 microns) extracted from contiguous sediment samples in a few intensively-sampled sites will be interpreted by comparison with soil charcoal from known historical fires; a database of fires in Hawaii Volcanoes National Park over the past 30 years will provide the initial calibration series (Tim Tunison, pers. comm.). Statistical smoothing methods will be used to distinguish peaks representing local fire events from background charcoal (Cleveland 1979, Clark and Royall 1996, Long et al. 1998).

In sites with good preservation, fossil pollen allows more detailed reconstruction of vegetation structure and composition using modern analogs, ordination, and ratios of individual pollen types (Hotchkiss and Douglas submitted, Hotchkiss 1998, Calcote 1998, Prentice 1985, Overpeck et al. 1985). We have a database of >100 surface pollen assemblages with associated vegetation data from Hawai'i Island, and we have developed methods that distinguish 18 major vegetation types (Hotchkiss and Douglas, submitted). A smaller set of surface samples from upland forests on Kohala offers much more detailed vegetation data, allowing us to distinguish several levels of canopy openness (Hotchkiss and Vitousek, unpublished). Pollen records from leeward Kohala show transformation of leeward vegetation, including decreases in arboreal pollen and increases in grass, sedges, and herbs over the past 1600 years (Hotchkiss 1998, Lawrence 1982). On Maui, we are developing methods that distinguish the upper elevational limit of forest on a scale of about 100m. With additional samples, similar methods could distinguish the leeward forest limit. Paleoecological records from settings with continuous sedimentation will also allow more detailed investigation of the dynamics of vegetation change over time, including rates of disturbance, successional trajectories, and patterns of response to changes in the human, climate, or biogeochemical context. These sediment deposits will be concentrated in the uplands, but their resolution of temporal patterns can be finer (~30yr) and more continuous than the more spatially-extensive trench studies. We will use pollen and plant macrofossils in continuously-accumulating peat deposits to compare trajectories of change in species composition, canopy openness, and rates and styles of forest disturbance (species affected, frequency of fire, post-disturbance succession) during the several hundred years before human arrival, and during periods of population expansion, agricultural intensification, and cultural elaboration.

Comparison of both soil trench profiles and pollen records with botanical remains in archaeological sites will establish temporal correlations between changes in vegetation and changes in population and cultural practices such as use of native species, intensification of agriculture, and development of social hierarchy, thereby addressing modules 3-5. Excavations at Kahikinui spanning a range of altitude and substrate variation have yielded hundreds of samples of wood charcoal from features such as hearths and earth ovens, yielding evidence for human use of specific forest, woodland, and shrubland communities, with a high degree of spatial resolution. Direct AMS 14C dating of 60 identified charcoal samples has provided a preliminary basis upon which to reconstruct woodland and shrubland communities in and around areas of archaeological occupation and land use, as well as the spatial and temporal distributions of disturbance-adapted and economic taxa (Stock, Coil, and Kirch, submitted). We will extend this approach to Kohala, providing a record of human use of vegetation that is explicitly linked to contemporaneous archaeological evidence of changing land use and culture at both sites. Sr isotope ratios of plant remains from archaeological contexts (see Module 1) will further trace the temporal and spatial patterns of resource use.

Module 3. Agriculture

The processes that drive sequences of agricultural intensification have long engaged anthropologists, archaeologists, and geographers (e.g., Geertz 1963; Boserup 1981; Brookfield 1972, 1984; Sahlins 1972; Turner and Doolittle 1978; Turner et al. 1977; Kirch 1994; Morrison 1994). Progress has been made in theoretically differentiating several modes of "intensification" (e.g., expansion and innovation from intensification per se; cropping cycle and landesque capital modes of intensification; Kirch 1994), and in defining key linkages to both demographic and socio-political inputs (Brookfield 1972, 1984). Intensification, however, occurs across and in relation to an environmental mosaic, which in the case of Hawai'i includes dramatic environmental gradients. It is in this area that we can make significant progress in understanding how agricultural change proceeds, including critical non-linear dynamics as an expanding agricultural population moves onto landscape patches with dramatically different biogeochemical responses.

Over the past decade, archaeology has incorporated new theoretical concepts in the study of the spatial distribution of archaeological materials, including the conceptualization of landscape (Crumley and Marquardt 1990; Rossignol 1992;Tilley 1994; Knapp and Ashmore 1999), the emergence of a

distributional archaeology (Ebert 1992), and non-site/siteless archaeological survey (Dunnell 1992; Dunnell and Dancey 1983). New methods have also been developed, including remote sensing and global positioning systems (GPS), along with the application of a Geographic Information Systems or GIS approach to data analysis (Allen and Zubrow 1990; Aldenderfer and Machner 1996, Kvamme 1989, 1999; Ladefoged et al. 1998). These conceptual and technological advances now allow archaeologists to document and analyze large scale agricultural or social developments (Field 1998; Savage 1990; Van West and Kohler 1996) and paleo-environments (Behrens 1996, Chapman 2000).
Archaeological investigations focussed on the spatial distribution of agriculture are particularly well suited to GIS, and data bases for both Kohala and Kahikinui are well developed. It will be straightforward - and interesting - to add the biogeochemical matrix of both areas (as described above); for Kohala in particular, those additional layers will complement a well-developed analysis of environmental limits to the field system (Ladefoged et al. 1996).
Using GIS to understand the development of agricultural systems in time as well as space offers a more substantial challenge. Substantial progress already has been made in analyzing temporal changes in the field systems, which can be determined in part through occurrence seriation of features, combined with AMS 14C dating of charcoal within or under features. This work will be continued and expanded as a key part of this project. We propose to construct spatially- and temporally-resolved data bases of soil properties and vegetation prior to the development of the field system, using the methods described in Modules 1 and 2 above. With this information, the initial patterns of human use of the land can be overlaid on a biogeochemical and environmental matrix. At approximately 100 year intervals thereafter, we will update the information on soil fertility to reflect the consequences of intensifying agriculture, and similarly update the areas occupied by people and the intensity of agriculture across those areas. Changes in vegetation distribution and in disturbance regimes will be updated similarly.
Initially, these analyses will be carried out in two dimensions - distance along a transect across the field system, from the sea towards the mountains, and time - for both substrate types (younger and older volcanic formations) for each study area. If the approach is practical and fruitful, it will be expanded to a second spatial dimension across both field systems. This approach will link the distribution of resources (particularly soil fertility) on the landscape to human use of those resources, to the effects of human use on the resources themselves, and to overall changes in vegetation and ecosystems in both regions - as all of these vary in space and time. While this approach will not explicitly incorporate the controls of spatial and temporal dynamics of the field systems, it will provide a structure within which those controls can be determined by the work described under modules 4 and 5 - and a set of patterns against which our understanding of controls can be tested (e.g., Ladefoged and Graves 2000).

Module 4. Mapping Population Dynamics
The islands of Remote Oceania, settled late in human history, were both resource-rich and lacking in population-inhibiting diseases such as malaria; not surprisingly, they often witnessed explosive demographic growth following human colonization (Kirch 2000). For several island cases, archaeologists have confirmed the general applicability of a model of logistic population growth proposed by Kirch (1984). This model predicts a shift from early, colonizing populations marked by high intrinsic growth (r), low density, density-independent mortality, and limited cultural regulation, and which were well below carrying capacity (K), to populations in late prehistory characterized by low r, high density, density-dependent mortality, and the application of varied cultural forms of regulation, including abortion, celibacy, warfare, infanticide, or even cannibalism. These late populations

may have oscillated in size. For Kosrae (Athens 1995), New Caledonia (Sand 1995), Mangaia (Kirch 1996, 1997a, b; Steadman et al. 2000), and New Zealand (Davidson 1984; Brewis et al. 1990) aspects of this model have been empirically demonstrated, with local variations.

The Hawaiian case is of particular interest, given archaeological efforts to track pre-contact population sizes through proxy measures such as household census counts (Cordy 1981; Kirch 1984; Hommon 1976, 1986; Clark 1988; Dye and Komori 1992b). These studies have demonstrated that following initial colonization ca. 1200 BP, the archipelago was rapidly explored, and permanent settlements were established in areas where resources were especially favorable to a mixed farming-fishing subsistence regime. By 900-800 BP, populations began to expand rapidly out of the ecologically favorable zones, with proxy curves of "household population" growth exhibiting an exponential phase of the logistic process (Figure 5). It was during this Expansion Period of the Hawaiian cultural sequence (Kirch 1985), that leeward zones such as Kohala and Kahikinui began to be permanently occupied, and their resources increasingly exploited. Approximately three centuries later, ca. 500 BP, these leeward landscapes had been substantially modified through the development of intensified agricultural systems, supporting dense populations. In windward zones, this was also the period of major construction of irrigated agricultural complexes (Allen 1991, 1992). The rate of population growth, however, declined significantly in the period 500-200 BP, prior to European contact (which brought decimation from introduced diseases), suggesting that local populations were now approaching carrying capacity. Along with heightened efforts at agricultural intensification, other key socio-political indices of this late cultural phase include cycles of territorial conquest (Sahlins 1972), and the imposition of a highly-structured system of land tenure (the ahupua'a system).

We aim to "map" the local demographic transitions on a finer temporal as well as spatial scale. The expansion of human populations over the environmental mosaic was unlikely to have been regular or linear, since the landscape itself exhibits marked gradients and discontinuities. Through close archaeological mapping and dating of both residential and agricultural sites, from fieldwork in Kahikinui and Kohala - both ongoing and proposed here - we will be able to map the demographic dynamics over long temporal and spatial scales. These data will be used to construct and test models of small-group populations interacting with a spatial resource function (see below).

Module 5. Social Structure and Complexity

As observed above, contact-period Hawaiian society is anthropologically noted for its complexity, indexed by economic specialization (Earle 1977, 1978, 1987; Kirch 1990a), social stratification (Sahlins 1958), and specialized religious cults and ritual regulation of production (Valeri 1985). Anthropologists and archaeologists have characterized Hawai'i as a "ranked society" (Fried 1967), "complex chiefdom" (Earle, ed., 1991; Kirch 1985), or "archaic state" (Hommon 1986; Flannery 1972, 1995; Marcus and Flannery 1996; Kirch 2000). A variety of proximate or ultimate "causal factors" have been identified or proposed as having played some role in the rise of this complexity, which developed out of a less complex or specialized Ancestral Polynesian society, including: (1) demographic change, especially population increase (Cordy 1981; Kirch 1984); (2) agricultural intensification, especially irrigation (Earle 1978); (3) warfare, especially territorial conquest (Kirch 1985); (4) status competition among chiefly lineages (Goldman 1970); and (5) resource diversity coupled with a redistributive economy (Sahlins 1958). However, understanding of how such factors may have interacted--with respect to particular prehistoric landscapes--has remained at the level of metatheory, couched in qualitative terms (e.g., Cordy 1981, 1996; Kirch 1990a, 2000; Earle 1997; Earle, ed. 1991; Friedman 1982; Sahlins

1972).

A complexity perspective, now being taken up in the social sciences (e.g., Byrne 1998) including archaeology (e.g., van der Leeuw, ed. 1998), provides a powerful theoretical apparatus for modeling the transition from a less-to-more complex society in Hawai'i over a several hundred year period. Such models need to be landscape-specific, as well as temporally dynamic, if they are to show how the kinds of causal factors listed above were linked with the spatial distribution of biotic resources and biogeochemical gradients. The extensive, radiometrically-dated sets of archaeological data now being compiled for Kohala and Kahikinui, when combined with spatially-controlled environmental data contributed by our project, will permit quantitative modeling and testing of particular hypothesized outcomes.

In the archaeological realm, the Hawaiian case is especially suited for such modeling of the emergence of social complexity, because Hawaiian culture materially indexed complexity in a number of ways which are archaeologically recoverable. The Hawaiian archaeological landscape exhibits numerous material indices of complexity, which can be spatially referenced by GIS, and dated by AMS 14C or T/Uh methods. These include: (1) an elaborate system of temples (heiau) dedicated to a variety of cults (each with its own deity), and operating on a hierarchy of levels (from "state temples" of war and agriculture, to territorial-level agricultural and fertility temples, to household shrines, and specialized economic shrines), constructed on stone architectural platforms and terraces (Dixon et al., 1995; Kirch 1990c; Kolb 1992, 1994a, b; Kolb and Radewagen 1997); (2) residential or household sites, with rank or status reflected in differential quantities of faunal and floral remains, high-grade stone tools, or in architectural features such as size and number of ancillary structures (O'Day, submitted; Weisler and Kirch 1985); and (3) formal property boundaries and land division markers, such as permanent field boundaries, stone-lined trails, free-standing walls, mounds, and cairns.

In both Kahikinui and Kohala, prior archaeological research has already resulted in extensive databases which can be directly utilized in the proposed research. For example, in Kahikinui we have now recorded, surveyed, and in many cases dated a series of more than 40 temples and shrines (Kolb and Radewagen 1997), which reveal a 3-tiered hierarchy. Such structures functioned, in part, as the physical manifestation of a complex control hierarchy which was imposed by the governing elite on the local social and economic systems. Such a control hierarchy was, we hypothesize, increasingly necessary to monitor labor inputs, and to keep close track of agricultural system outputs and possible levels of surplus extraction, as the dryland farming systems came under increasing demographic pressures in late prehistory. Working out the temporal and spatial distributions of such sites provides a measure of where and when the social system itself was focusing on particular points of stress in the system. In Kohala, equal progress has been made in mapping the vast field system, and in analyzing the patterns of both expansion and intensification, as these are reflected in details of the reticulate grid of stone walls and features (Ladefoged and Graves 1999). These features provide a fine-grained history not only of field development, but of land tenure and territorial control. We will continue our investigation of such structures in as yet unsurveyed portions of Kahikinui, and expand this line of research in Kohala, while fine-tuning the chronology of both sites.

Modeling

Research this diverse and complex can only be integrated through models, and only through such integration can the implications of complex interactions among systems be realized in full. A number of models are already in place within the modules, as described above. We propose to couple the modules, using these and other models within a hierarchical, spatial framework that we develop. A primary demographic model will describe the small unit household on a restricted site. We will scale up spatially by modeling the spread of and interaction among many units over space and time, extending to coarser-scale, complex social units. Space can be described by continuous-space models (drawn from the reaction-diffusion genre) and/or discrete space models (drawn from the cellular automaton genre) (Diekmann et al. 2000). We will work initially with discrete space units that cover households and small population units, and cover the larger habitat with a discrete grid matched to the resolution of our spatial sampling work. A set of overlapping models will describe the interaction between people and environment. These models will include:

Site selection, to relate the locations of habitation to spatial characteristics (weather, topography, soil fertility); we will employ a logistic regression for presence-absence with spatial covariates in our GIS database (Manly et al. 1993, Boyce et al. 1994). Initial site selection will depend on pre-contact attributes. Site attributes and selection criteria will change over time, as a function of site dynamics, population density, social organization and technology.

Site utilization, to estimate a production function for agriculture that describes resource flow into the population given technology (crop choice, production system, inputs). The production function will be used to calibrate mortality and fertility as a function of per-capita resources. Production functions will change over time along with soil fertility, vegetation, agricultural practices. Weather, climate cycles, and natural disturbance will be important factors.

Site dynamics: The site utilization model will be coupled to soil fertility and vegetation models to describe the impact of settlement on local biotic and abiotic factors. This is a key module for describing the impact of agriculture and extraction on soil and vegetation, and will be a key driver of longer-term population growth and spread.

Local demography will be described by age-specific mortality and fertility. Mortality is given by death rates m (A,T,X) for individuals of age A at time T in spatial location X. A useful approach is to employ model mortality schedules: identify a reference mortality pattern b(A) and describe variation in terms of a response schedule c(A) and a response function k(X,T):

$$\log m(A,T,X) = b(A) + k(X,T) c(A)$$

The reference schedule b(A) is estimated from comparative data, such as the paleodemographic life table data discussed by Kirch (1984) for pre-contact Hawai'i; see also Preston et al. (1993). Fertility is modeled similarly by defining a response function for fertility analogous to that for mortality; comparative data come from paleodemographic and anthropological studies (Basu and Aaby 1998, Bocquet-Appel and Bacro 1997, Lasker and Kaplan 1995, Uche 1990) and reconstructions of early demographic history (for a French example, see Bonneuil 1997). Our demographic models will also reflect social and cultural practices (marriage, fertility control, competition, warfare). Spatial dependence of the response functions will contain: density and resource limitation for given site attributes, the impact of site dynamics, local population density, social structure (e.g., competition, warfare, resource sharing) (see Hassan 1981; Kaplan 1994, 1997; Nelson et al., 1994; Swedlund 1994; Weiss 1973; Wood 1994).

Population spread will be modeled as a result of household birth, death, fission events; site selection and utilization functions, population density, interaction between local populations, and the role of social structure and technology in making possible use of marginal sites.

Social structuring will be modeled in a couple of ways. One approach is to hypothesize rules for the formation of aggregations based primarily on site selection and utilization, and test their consequences against observed aggregations. A second will use utility functions to describe the value of particular social structures (e.g., in terms of defense, resource sharing, insurance provided against crop loss or failure, etc.) .

We will employ a suite of methods from nonlinear dynamics (Guckenheimer and Holmes 1983, Ott 1993), mathematical ecology and demography (Caswell 2001; Diekmann et al. 2000; Tuljapurkar and Semura 1979; Tuljapurkar 1990; Tuljapurkar et al. 1994), computer simulation, and statistical estimation. We aim first to evaluate the qualitative dynamics of human populations, and then to focus on quantitative analyses that can be used in hypothesis testing.

Since such integrative modeling is relatively rare, we point to two examples. One is the Artificial Anasazi project (Dean et al. 1998) that uses archaeological, ecological and cultural information to define demographic, behavioral, and geographical characteristics for model individuals, and then generates and analyzes outcomes by simulation (using SWARM http://www.swarm.org). The other is the ARCHAEOMEDES project on land degradation (van der Leeuw, ed., 1998), in which Winder et al. (1998) developed probabilistic models for the transformations of both habitat state and demographic states over time. Both show how complex information of the type we will collect can be synthesized, turned into dynamic models, and tested against observed historical patterns.
At this stage, our framework is only partially developed, but we have hypotheses concerning the implications of linkages between the modules. Soils, vegetation, and agriculture should represent one fully interactive set of modules; demography, social structure, and agriculture should represent another. Under "normal" conditions, coupling between these sets isn't absent, but we expect that connections between these sets (except through agriculture) are not as strong as linkages within them.

Stresses to agriculture--crop failures due to drought or conflict--create a more fluid situation where human populations and social structures shape what happens to land, and soil fertility and vegetation directly shape how populations and societies can respond. In this context, climatic variability would have posed considerable risk in leeward regions, where farming was rainfall dependent (Dixon et al. 1999; Ladefoged and Graves 2000). For example, we hypothesize that dry years (when the optimal rainfall for agriculture would have moved onto poorer soils above the established field systems) would have encouraged greater deforestation as people relied temporarily on nutrients stored in the forest biomass, when drought made it impossible to farm the rock. Social structure and population would influence the strength and timing of this effect. A small population living by shifting cultivation may use more land constantly than a larger population using more intensive permanent cultivation systems. However, a complex society based on intensive cultivation will also make use of other land - and drought or conflict can force a large population near its carrying capacity to draw periodically on marginal habitat for sustenance, and so have a much larger effect over a short term (and possibly cumulatively) than a small population practicing shifting cultivation.

D. THE PROJECT TEAM, COORDINATION, SCHEDULING, & EDUCATION
1. The research team assembled for this project joins leading experts in archaeology, ecology, pedology, demography, and paleobotany, most with extensive experience in the Hawaiian Islands. Bringing together these disparate areas is a challenge; we believe that the best approach is to integrate the research at all stages, with all of the investigators participating actively in all areas of research (however far it may be from their own expertise). In particular, we will combine disciplinary approaches

in our field teams, allowing for intellectual feedback during data collection as well as during synthesis. For example, investigation of soil profiles (including sampling for laboratory analysis) will benefit from having multiple archaeological, pedological, geochemical, and paleobotanical perspectives brought to bear on field interpretation and sampling. While everyone will be engaged in everything, investigators will have the primary responsibility for particular modules. Vitousek and Chadwick have worked extensively on biogeochemical gradients in Hawai'i, and they will be responsible for module 1; Hotchkiss and Coil have developed independent but related approaches to reconstructing vegetation histories, and they will be responsible for module 2; Kirch, Graves, and Ladefoged have analyzed the Kahikinui and Kohala archaeological landscapes, and will handle module 3; Tuljapurkar has expertise in quantitative modeling and human demography, and with Kirch will be responsible for module 4, and Kirch will take the lead for module 5. While all will be involved in linking the modules to address the major research questions, Tuljapurkar will coordinate that modeling - and Kirch will be the overall project leader. Such an interdisciplinary research team has rarely before been assembled to tackle problems of coupled human-environment systems over longer time periods; the closest parallel would be the ARCHAEOMEDES project which investigated the natural and anthropogenic causes of land degradation and desertification in the Mediterranean basin (van der Leeuw, ed., 1998). We seek to integrate a broader range of disciplines more fundamentally, in a more narrowly defined study area.

2. Scheduling. We propose a project of four years duration, with the following schedule: Initial Planning: We will commence with a workshop (to be held on-location in Hawai'i) involving key participants, in which research questions, methods, sampling procedures, data reporting standards, and other matters will be fully defined. Years 1-2 Fieldwork: The first two years will focus on fieldwork in both Kahikinui and Kohala, involving integrated teams that include the investigators and graduate students. In Kahikinui, archaeological survey will be expanded onto lands of the geologically older Kula Volcanic Series, while in Kohala we will expand our survey work into upland and windward areas not previously investigated. Fieldwork will be concentrated in the summer, while laboratory analysis of samples can proceed throughout the year. Year 3, Synthesis and Modeling: Our third year will be devoted to synthesis of data obtained in years 1 and 2, and to refining the quantitative models essential for testing specific hypotheses. As we are dealing with complex, non-linear and hence not necessarily intuitive relationships between cultural and natural systems, we anticipate one outcome of these analyses will be the need to acquire additional primary data. Year 4 will be devoted to such additional fieldwork as necessary to fill in gaps in our understanding, as well as producing an integrated synthesis of our interdisciplinary results.

3. Education and Other Contributions to Infrastructure. Because the project integrates diverse fields that rarely interact so fundamentally, the research will contribute to the unification of disciplines, over and above research results obtained. Graduate students trained at Berkeley, Stanford, Hawaii, Wisconsin, and Santa Barbara will benefit most directly from these interactions. In addition, several of the co-PIs have established records of incorporating undergraduates, graduate students, the lay public, resource managers, and policy makers into their on-going Hawaiian research, and will continue these activities in this project. Kirch has experience conducting fieldwork as a high-level undergrad/graduate field school, and three dissertations are already forthcoming the Kahikinui Project. Graves has involvement with the Kohala Historic Preservation Committee, and Kirch with Ka 'Ohana o Kahikinui, both local Native Hawaiian groups with strong involvement in resource use. Vitousek co-directs the Hawaii Ecosystem Project, a consortium of agencies and research universities that facilitates

ecological research and education in Hawaii - including >20 PhD theses at 8 universities, and supporting internships for Hawaiian students - and Chadwick interacts with the Kohala Center, a community-based program to expand higher education in the North Hawaii region. The local Maui and Hawaii communities will be drawn into the research proposed here, and the results will thereby shape how people perceive land and culture locally as well as globally.

E. SIGNIFICANCE OF PROPOSED RESEARCH

This research is focused on the Hawaiian Islands, but the issues we address are global. The cultural and biological processes that developed and interacted in Hawaii, from population growth to the increasing centralization of political power and economic control, have happened everywhere and indeed are taking place globally today. The Hawaiian Islands are unique in the precision with which we can define the arena in which these processes play out, from the biogeochemical matrix underlying agricultural development to the nature and isolation of the founding culture. Molecular biologists describing a particular model organism (C. elegans) characterize it as possessing "the ideal compromise between complexity and tractability" (www.biotech.missouri.edu/Dauer.World/wormintro.html). For our questions, we believe that the same can be said of the Hawaiian Islands. The approaches, concepts, and models developed here can contribute to basic understanding of how ecosystems, agriculture, and social structure interacted in a constrained, isolated world - and that understanding can illuminate how we view the world today.