Earth and Environmental Science Transactions of the Royal Society of Edinburgh, **98**, 85–99, 2007

Three islands and an archipelago: reciprocal interactions between humans and island ecosystems in Polynesia

Patrick V. Kirch

Departments of Anthropology and Integrative Biology, University of California at Berkeley,
California, CA 94720, USA.
E-mail: kirch@berkeley.edu

ABSTRACT: Oceanic islands offer outstanding 'model systems' for investigating long-term dynamics between human populations and their ecosystems. Whilst the state factors involved in human-environment dynamics on islands are often simpler than on continents, the same essential processes are involved. This paper applies a comparative approach to understanding the reciprocal interactions between a set of four Polynesian island cases (Tikopia, Mangaia, Mangareva, Hawaiian Islands), over time scales of between one and three thousand years (kyr). In all cases, the island ecosystems were colonised by Polynesian populations derived from the same ancestral culture, with similar socioeconomic patterns. However, the ecosystems vary significantly in scale, geologic age, and other characteristics. Comparing the historical trajectories of these human–environment dynamics, as revealed by archaeological and palaeoecological study, provides insights into the relative impact of humans on pristine island ecosystems, the influence of environment on ecosystem vulnerability, and the ways in which societies have modified their economies, sociopolitical structures, and other aspects of culture in response to long-term environmental changes.

KEY WORDS: socioecosystems, sustainability, biodiversity, agroecosystems, extinctions.

"Much progress in the observational sciences is due to . . . those who have discovered, critically evaluated, and compared natural experiments in fields where a laboratory experiment is highly impractical, if not impossible". Ernst Mayr (1997, p. 29)

As Ernst Mayr so aptly pointed out, in the historical sciences — and the present author would include archaeology and historical anthropology among these — controlled comparison of 'natural experiments' offers a productive approach to the discovery of fundamental processes. The comparative study of islands has a long history in evolutionary biology, the natural experiments exhibited by the Galapagos and Indonesian archipelagoes having provided evidence essential to Darwin and Wallace in their respective discoveries of the principles of natural selection and evolution. Islands likewise offer extraordinary opportunities for studying cultural change, including the complex, dynamic, and often non-linear interactions between human populations and the island ecosystems they discovered, colonised, and inhabited.

Over the past two to three decades, archaeologists working in concert with natural scientists have amassed significant empirical evidence for the anthropogenic transformation of oceanic ecosystems, and for the varied cultural adaptations and responses that such transformation have engendered (see Kirch & Hunt (eds) 1997; Kirch 2004). Indeed, the case of Easter Island (Rapa Nui) in particular has become a virtual 'poster child' for excessive anthropogenic disturbance, leading to societal collapse (Diamond 2005). The present paper reviews and synthesises the evidence from four Polynesian island cases: three smaller islands of varying sizes, and one larger archipelago. The aims are: (1) to examine the extent to which natural variation in island environments, such as substrate age, island size, and biodiversity, renders islands more or less vulnerable or resilient to human impact; (2) to assess whether the sequences of anthropogenic changes followed similar or divergent trajectories in different island ecosystems; (3) to compare the cultural and demographic responses that island populations invoked to deal with human-induced environmental changes; and (4) to pose the question of whether any of these island societies and their environmental management practices were sustainable over the long term.

1. Oceanic islands as model systems

Oceanic islands offer outstanding 'model systems' for investigating and understanding many kinds of ecological processes (Vitousek 1995, 2002, 2004). In a model system, fundamental variables can be readily identified, and the mechanisms of interaction among them tested. Whilst model systems are by definition relatively simple, they nonetheless contain all of the essential elements found in more complex systems, or in systems that operate on a larger scale; hence, their widespread application and utility. The diversity of Polynesian islands offers a set of contrastive model systems for ecosystem studies, due to the small number of well-defined 'state factors' that display especially clear properties: these include biogeochemical gradients as a function of *time* and development over the typically geological hot-spot progression of Polynesian island chains (the remnant Gondwanaland geology of New Zealand being a marked exception); strongly orthogonal variation in *climate* as expressed in moisture and temperature gradients; and natural *biotic components* that are typically depauperate at higher taxonomic levels yet amazingly variable at the species level as a consequence of adaptive radiation (Nunn 1994; Wagner & Funk (eds) 1995; Ziegler 2002).

doi:10.1017/S1755691007000011

Table 1 Environmental characteristics of the case studies

Island case	Size (km^2)	Geologic age	Maximum elevation	Geomorphology
Tikopia	4·6	<80 kyr	360 m	Volcanic cone with coastal plain, crater lake; no permanent streams; fringing reef.
Mangaia	52	16·6–18·9 ma	169 m	Weathered volcanic cone with radial stream drainage, surrounded by elevated reefal limestone (*makatea*); fringing reef.
Mangareva	24·5	5·6–6·3 ma	441 m	Small volcanic islets surrounded by extensive lagoon and barrier reef. Islets have small seeps and springs, no permanent streams.
Hawaiian Islands	16 698	0–0·6 ma (Hawai'i) to 5·55 ma (Ni'ihau)	390 m (Ni'ihau) to 4205 m (Hawai'i)	Highly varied landforms, ranging from young, undissected volcanic flowslopes to deeply weathered valley systems with permanent streams. Young islands lack developed reefs, older islands have extensive fringing reefs.

Islands also offer model systems for investigating and understanding human cultural evolution, including the complex interactions between human populations and the ecosystems they inhabit (Kirch 1984; Kirch & Green 1987; Vitousek 2002, p. 575). The same state factors that Vitousek has isolated for ecosystem studies combine with several other cultural factors to make the islands of Polynesia an outstanding arena for investigating 'human ecodynamics' (McGlade 1995). Among these cultural state factors are five of particular importance: (1) relatively late colonisation of a previously uninhabited set of islands by people with an advanced 'Neolithic' form of economy; (2) short, well-controlled time scales, ranging from ∼2900 to ∼1000 years in duration, for cultural evolution; (3) often considerable, if not total, isolation of the cultural group after an initial period of colonisation and two-way voyaging; (4) demographic transitions over time from small, low-density populations to large, high-density populations; and (5) in some larger islands or archipelagoes, significant transformation in the scale of sociopolitical complexity, as expressed in social hierarchy, economic control systems, material symbols of rank, monumentality, and similar indices (Kirch 1984). In addition, a further degree of cultural control stems from the fact that all Polynesian cultures can be traced back to a common Ancestral Polynesian culture which developed in the Western Polynesian homeland region (the area of Tonga, Samoa, Futuna, and 'Uvea) between ca. 500–0 BC (Kirch & Green 2001). Thus, using a phylogenetic model, it is possible to discern which features of any contact-period Polynesian group were retentions from the ancestral mode, or were innovations or adaptations arising after the breakup of Ancestral Polynesian culture.

The long-term evolution of landscapes involves complex, dynamically linked interactions between environmental and sociocultural phenomena (McGlade 1995; Balée (ed.) 1998; Redman *et al.* (eds) 2004). Human societies do not passively 'adapt' to their environments, they are actively engaged with those environments in a constant process of reciprocal feedback. Landscapes are socially constructed as well as physically modified. Thus it is useful to refer to Barton *et al.*'s (2004) concept of 'socioecosystems' for landscapes shaped by dynamically linked human-natural processes. As they observe, "the intertwined social and natural landscapes that are the context of human societies are contingent on socioecological history as well as the physical conditions under which this history took place" (Barton *et al.* 2004, p. 285). In attempting to unravel historical sequences of landscape change, one must therefore engage as much with evolving patterns of social and economic conditions, as with human impacts on and alteration of the physical and biotic environment.

The four distinct Polynesian socioecosystems examined here exhibit a significant range of variation in both natural environmental characteristics, such as island age and size, as well as in aspects of their traditional indigenous populations. All four cases have received substantial archaeological and palaeoecological study, with extensive empirical databases, much of which the present author participated in developing. These data are merely summarised in this paper, but references are provided to the published data sets.

2. Environmental variation

The four cases to be examined are: (1) Tikopia, a young volcanic island situated outside of the main Polynesian Triangle in the Eastern Solomon Islands, but occupied by a Polynesian-speaking population; (2) Mangaia, a relatively old volcanic and *makatea* island in the southern Cook Islands; (3) Mangareva, a small cluster of volcanic islets encompassed by an extensive barrier reef and lagoon system; and (4) the Hawaiian Islands, an extensive age progressive volcanic archipelago. Key aspects of their environmental variation are summarised in Table 1. Whilst all of these islands are in the first instance of volcanic origin, they vary considerably in details of geologic age and history, as well as in size. These geological differences result in varied biogeochemical properties, particularly soil nutrient status, and it will be argued that such variation had a profound influence on the degree of anthropogenic disturbance.

2.1. Island size

As is evident from Table 1, island size varies from the diminutive 4·6 km^2 of Tikopia, up to the aggregate land area of the eight main islands of the Hawaiian Archipelago at 16,698 km^2. Island size imposed constraints on human populations, most directly in terms of agricultural 'carrying capacity', and thus in the overall population (Table 2). However, the extent of arable land is not directly correlated to island size; the geologically youthful island of Hawai'i, for example, has vast areas covered in lava flowslopes <1 kyr in age that are unsuitable for Polynesian horticulture, and the heavily leached volcanic interior of Mangaia is also virtually worthless for cultivation. In contrast, almost the entire land surface of Tikopia supports tree or root crops. Whilst it is evident that smaller islands will be able to support relatively smaller populations, it is an open question as to whether smaller islands are most susceptible to anthropogenic impacts.

2.2. Geological age and biogeochemical constraints

Most Polynesian islands (again, with the significant exception of New Zealand) have 'hot spot' volcanic origins, derived from rapid extrusion of basalts from stationary magma plumes situated under the Pacific Plate (Nunn 1994). Due to the gradual tectonic movement of the plate, islands move off the hot spot within about 1–2 million years after initial shield building, although there is often secondary pyroclastic volcanic activity. Subsequently, as an island migrates in a generally northwesterly direction along its particular age progressive alignment (the Hawaiian Islands being a classic case), it undergoes subaerial erosion, development of topographic relief (including drainage systems), soil development, and formation of coral reefs. The island mass also subsides, so that eventually a young 'high' volcanic island will, over the course of several million years, be transformed into a 'near atoll' with only small volcanic islets surrounded by an extensive barrier reef and lagoon (Mangareva being a case in point) and, eventually, into a true atoll. This geomorphic evolution of Pacific plate islands was first described by Darwin, although the tectonic basis for the progressive subsidence was not recognised until fairly recently.

Whilst this geomorphic progression has long been recognised, and constrains certain kinds of landforms and resources available to human populations (such as the extent of reefs for fishing, or of streams which can be tapped for irrigation water), less widely appreciated is the way in which nutrient dynamics also change over geologic time, and their effect on ecosystem development. Building upon the soil model of Walker & Syers (1976), Vitousek and colleagues have demonstrated that island ecosystems situated on geological substrates of different ages (controlling for the same kind of basaltic parent rock) have radically different nutrient processes, and that nutrient limitation shifts in its characteristics from younger to older ecosystems (Vitousek *et al.* 1997; Chadwick *et al.* 1999; Chadwick & Chorover 2001; Vitousek 2004.). This is particularly the case for phosphorus (P), an essential element for plant growth, which derives from rock weathering, and is released as biologically available phosphate (PO_4). On young substrates the amount of P is almost exclusively primary mineral P, but over time the dominant fractions of P change, with the amount of plant-available P declining (Vitousek 2004, fig. 4.1). The work of Vitousek, Chadwick, and others in the Hawaiian ecosystem has amply demonstrated that ecosystems on old substrates are strongly P-limited. In contrast, young volcanic soils are likely to be N-limited, especially if N-fixers are absent or non-abundant. Recently, Vitousek *et al.* (2004) and Kirch *et al.* (2004a) have shown that prehistoric Hawaiian farming systems were heavily constrained by just such biogeochemical gradients expressed along varied substrate ages and elevations (elevation essentially correlating with rainfall and hence with the degree of nutrient loss through leaching).

In general terms, island age — and in particular, substrate age (as exposure of parent rock through mass wasting and erosion can rejuvenate nutrient cycles) — provide one key axis of environmental variation warranting close attention. In Figure 1, the four case study islands/archipelago are plotted on a graph whose x axis represents geologic age, with the y axis representing island area. Tikopia is a small island consisting of an andesitic cone which last erupted <80 kyr (Fryer 1974), and it should have almost no P-limitation. The islets of Mangareva are about 5–6 ma in age, based on K–Ar dating (Guillou *et al.* 1994), roughly the same age as Kaua'i in the Hawaiian chain, which has been shown by Vitousek (2004) to be strongly influenced by P-limitation. Older still is Mangaia, about 16–19 ma in age, with deeply weathered surfaces and virtually no surface rock exposure. Moreover, Mangaia is surrounded by a ring-like formation of elevated limestone of coral reef origin (called *makatea* in Polynesian), having been elevated due to point-loading of the oceanic crust by nearby Rarotonga (Stoddart *et al.* 1985). The old volcanic substrates of Mangaia are extremely limited in available P, and this is borne out by the island's vegetation patterns. Finally, the Hawaiian chain consists of eight main volcanic islands (with many smaller islets), ranging in age from recent (with literally 'hot rock' erupting from the Kilauea shield) to about 5·25–5·55 ma in the case of Kaua'i and Ni'ihau (Ziegler 2002).

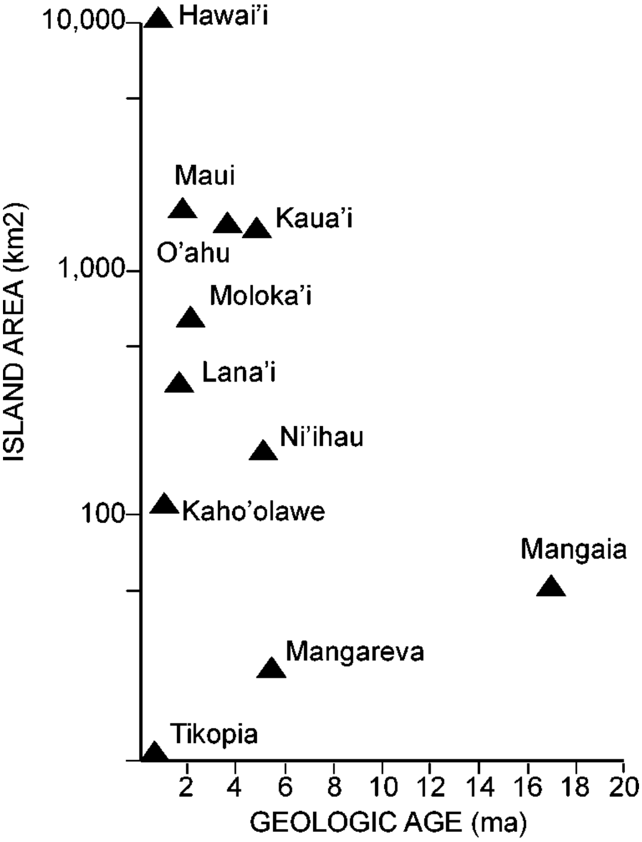

Figure 1 The islands considered in this comparative analysis plotted as a function of geological age (x axis) and size (y axis, log scale).

2.3. Biogeographic considerations

Fosberg (1963) pointed to a number of biogeographic features of islands that may make them vulnerable to human activities once their isolation has been breached. These features include: (1) limitation in biotic diversity, especially in the range of high-order taxa, often referred to as 'disharmony'; (2) a high degree of species-level endemism; (3) reduced inter-specific competition; and (4) 'protection from outside competition and consequent preservation of archaic, bizarre, or possibly ill-adapted forms' (Fosberg 1963, p. 5). Polynesian islands are depauperate in terms of their terrestrial biotas when viewed in comparison with those of continents, or even of the larger Melanesian islands. Prior to human arrival, they lacked vertebrates other than birds, bats, and (only in the Western Polynesian islands) a few reptiles. On the other hand, their plants and invertebrates had typically undergone remarkable sequences of adaptive radiation within certain groups, of which the pulmonate gastropods (e.g., the achatinellid snails), are a classic example (Solem 1976, 1983). Their avifaunas, including both land birds rich in species-level diversity and large resident populations of nesting seabirds, dominated island vertebrate faunas prior to human arrival, as abundant

Table 2 Cultural characteristics of the case studies

Island case	Maximum population	Population density (per km^2)	Economic system	Sociopolitical organisation
Tikopia	1500	250	Intensive orchard gardening; marine exploitation; no domestic animals.	Simple hereditary chiefdom; four clans. Little status differentiation.
Mangaia	3–5000	60	Taro irrigation in valleys, with shifting cultivation on lower slopes; limited fishing on narrow reef.	Chiefdom with succession by war. Developed priestly and warrior status groups.
Mangareva	1500–2000	60	Breadfruit and taro limited to small valleys and coastal plains. Extensive fishing in lagoon.	Competing chiefdoms with frequent warfare. Developed priestly and warrior status groups.
Hawaiian Islands	400 000+	25	Extensive dryland field systems on younger islands, taro irrigation in valleys on older islands. Pig and dog husbandry well developed.	Archaic states (four competing polities at contact), with divine kingship. Highly developed status differences; formal priesthood with distinct cults.

zooarchaeological and palaeontological evidence indicates (Steadman 1995, 1997). Lacking predators, these bird populations were probably naïve in the extreme and lacked predator responses, making them highly vulnerable to colonising humans (and to human-introduced rats).

From the point of view of the human resource base, Polynesian island biotas were deficient in terrestrial food resources, and their littoral and marine resources also varied considerably depending upon the degree of reef/lagoon development. To support their economies, the Polynesians introduced a significant array of both domestic animals (pig, dog, chicken) and crop plants (taro, yam, bananas, breadfruit, sugarcane, other cultigens; see Kirch 1991), along with a number of synanthropic taxa such as rats (*Rattus exulans*), snails (e.g., *Allopeas gracile*), weeds and the like. These biotic introductions constituted what Crosby (1986) likens to a ‘portmanteau’ biota, and enabled Polynesian groups to establish viable agroecosystems on a host of islands across the Pacific.

3. Aspects of cultural variation

Although all four cases considered here share common origins in the Ancestral Polynesian culture that developed out of its immediate Lapita predecessor in the first millennium B.C., their contact-period ethnographies display significant cultural variation, key aspects of which are summarised in Table 2, which briefly reviews a few aspects of cultural variation that influenced the reciprocal relationships between these island societies and their environments.

3.1. Population size and density

As would be predicted from differential island size, the maximum populations of the four cases under consideration ranged dramatically, from only about 1500 persons on Tikopia, to >400 000 throughout the Hawaiian archipelago at the time of initial contact with Europeans. However, of greater relevance to human–environment interactions is population density. Here we find Tikopia to have the maximum value, with about 250 persons/km^2, a figure that approaches the highest densities known anywhere in the tropics for pre-industrialised agroecosystems. Yet despite this high density, Tikopia is also known to have the most elaborated set of cultural controls on population growth and regulation (Firth 1936; Borrie *et al*. 1957), including abortion, infanticide, enforced celibacy of junior males, suicide voyaging, and warfare. The pre-contact population densities for Mangaia and Mangareva were somewhat lower, at ca. 60 persons/km^2. However, if their densities are considered as a function of *arable* land (rather than total land area), the values are much higher, probably approaching that of Tikopia. Likewise, the gross population density for Hawai‘i at ca. 25 persons/km^2, does not take into account the vast tracts of lava flows, or steep, mountainous, or even sub-alpine zones on the larger islands, all unsuited for Polynesian cultigens. Thus again, in the Hawaiian case, *local* population densities in the irrigated valleys or in areas of intensive dryland cultivation, were much higher than the averaged gross density for the archipelago, and in some localities certainly approached the density level of Tikopia.

In short, whilst total population and population densities vary among the cases under consideration, when density is considered as a function of *arable* land resource, all of these Polynesian agroecosystems were marked by relatively high density levels in late prehistory. Particularly in Hawai‘i, however, the much greater land area and vast extent of inland, mountainous zones, means that people were unevenly distributed, with pockets or zones of dense population concentration, and with other areas virtually uninhabited (Coulter 1931).

3.2. Economic systems

The fundamental dual horticultural–marine exploitation economic basis of Polynesian societies was well established by Ancestral Polynesian times, ca. 500 BC, as evidenced by both archaeological evidence and linguistic reconstructions (Kirch & Green 2001). The horticultural systems were based on a wide array of tropical root, tuber, and tree crops (especially taro (*Colocasia esculenta*) and yams (*Dioscorea alata* and other species), all of Southeast Asian and/or Papuan origins and introduced by oceanic peoples into the island ecosystems (Yen 1973). An additive element in Eastern Polynesia was the sweet potato (*Ipomoea batatas*), transferred prehistorically from South America, probably by Polynesian voyagers (Yen 1974; Hather & Kirch 1991); this crop became particularly important in the leeward, dryland field systems of the Hawaiian Islands. Pigs, dogs, and fowl were also all introduced. Polynesian marine exploitation included collecting and gathering of inshore and reef molluscs, crustacean, echinoderms, and algae, as well as a plethora of fishing methods (e.g., spearing, netting, trapping, angling, poisoning, trolling, etc.) targeting a full range of near-shore, benthic, and pelagic fishes.

Despite this common pattern of a dual horticultural–marine economic base, there were important differences (see Table 2), reflecting specific adaptations to local environmental conditions, as well as historical contingencies. Thus, for example, Tikopia exhibits the most elaborate form of arboriculture or ‘orchard gardening’, with only minor field cropping (Kirch &

Yen 1982). In Mangaia, pondfield irrigation of taro was the most important agricultural technique, and endemic warfare centred around control of the limited irrigation lands (Hiroa 1934). The limited water supplies of Mangareva restricted taro cultivation to small patches in the narrow valleys, and tree cropping of breadfruit assumed greater dominance (Hiroa 1938). The Hawaiian chain, with its varied topographic relief, exhibited the greatest variation in cropping systems, including shifting cultivation, intensive dryland field systems, and pondfield irrigation (Handy 1940).

Animal husbandry also varied in each case. In Tikopia, Mangaia, and Mangareva, pigs and dogs were absent at the time of European contact, although all three retained oral traditions of pigs having formerly been present, but eliminated at some point in the past (Kirch 2001). In Hawai'i, however, pigs and dogs were both raised in large numbers, and early European voyagers were impressed at the ability of the Hawaiian production systems to yield substantial quantities of pork.

3.3. Sociopolitical systems

As with their economies, the sociopolitical organisations of these four societies can all be traced back to a common pattern in the Ancestral Polynesian homeland (Kirch & Green 2001), but subsequent historical developments had led to considerable differences between them at their European contact endpoints. To use the tripartite classification system of Goldman, Tikopia represents a 'traditional' form of Polynesian society, with a 'religious system headed by a sacred chief and given stability by a religiously sanctioned gradation of worth' (Goldman 1970, p. 20). Both Mangaia and Mangareva are representative of the 'open' form of Polynesian societies, which are 'more strongly military and political than religious', and in which competing status rivalry between hereditary chiefs, priests, and warriors is evident. (Goldman himself put Mangareva in the 'stratified' category, but careful analysis of the ethnohistoric records indicates that it should be grouped with the 'open' societies.) Hawai'i exemplifies the 'stratified' system, where 'status differences are economic and political', and in which 'high ranks hold the rule and possess the land titles' while 'commoners are subjects and are landless' (Goldman 1970, p. 20). Indeed, a strong argument can be advanced that in the last two to three centuries prior to European contact, Hawaiian society crossed the boundary between chiefdom and archaic state, as these are typically defined (Kirch 2005).

4. Human–environment interactions: archaeological and palaeoecological evidence

This paper now turns to the archaeological and palaeoecological evidence for long-term historical trends in human-environment interactions in the four cases under consideration. Only a summary can be offered for each case, but references are given to the fully published data sets.

4.1. Tikopia

Having first been colonised ca. 900 BC by a Lapita-pottery making group (probably closely related to the Eastern Lapita population who formed the immediate ancestors of the Polynesians), Tikopia has the longest historical sequence of the four cases. The cultural sequence, reported in full by Kirch & Yen (1982), is complex, with multiple cultural inputs, the latest being an influx of several Polynesian-speaking groups, probably after A.D. 1200. Archaeological and palaeoenvironmental investigation of Tikopia was carried out in 1977–78, and the results are reported in Kirch & Yen (1982; see also Kirch 1986; Steadman *et al.* 1990).

4.1.1 Geomorphic changes. During the nearly three kyr that Tikopia was inhabited, a series of geomorphic changes significantly modified the island, precipitating changes in human settlement and land use. The most dramatic of these changes occurred in the coastal zone, including progradation of the calcareous beach ridges making up the western part of the island and, in late prehistory, the closure of a marine embayment to form a brackish water lake (Te Roto). These changes resulted in a net increase of about 40% in total land area, and a concomitant decrease of about 41% in the area of exploitable reef flat (as the beach ridges prograded over the reefs). This transformation of the coastal zone is correlated with a widespread mid-to-late Holocene drop in relative sea level in the southwestern Pacific of about 1 m (Dickinson 2003); whilst natural in origin, these changes nonetheless were correlated with important cultural adaptations. For example, extensive shellfish beds formerly lining the shores of the marine embayment were extirpated when the deposition of a tombolo cut off access to the sea and created a brackish lake, thus eliminating a major food source. Moreover, human land use resulted in some geomorphic changes, notably heightened erosion from the volcanic hillsides and deposition of coarse colluvium on the lower flanks. This was well attested in the investigations of the Rakisu agricultural zone (Kirch & Yen 1982, pp. 147–159). Because this colluvium consists of a mix of rock and finer particles of <80 kyr, it is highly fertile and not P-depleted, and thus enhanced horticultural possibilities on the lower flanks and adjacent coastal plain where volcaniclastic sediments became mixed with the reef-derived calcareous sediment.

4.1.2 The faunal record. The faunal sequence is documented by an aggregate assemblage of more than 35 000 bones (13 218 identified to some taxonomic level), and 1·03 metric tons of invertebrate remains. The early phase of human occupation was marked by high levels of exploitation of natural food resources, including molluscs, birds, and fish, with significant declines in the concentration of all of these categories over time. At least two land-bird (common megapode, banded rail) and four sea-bird species were extirpated within a few centuries after human arrival (Steadman *et al.* 1990). The middle and later phases of the sequence were then characterised by a major increase in quantities of pig (*Sus scrofa*), a domestic animal presumably husbanded and fed on vegetable produce (as it would have been impossible to let pigs forage at will on a small island such as Tikopia, without devastating effects on the horticultural system). Strikingly, however, pig is absent from archaeological deposits dating to the terminal prehistoric period, and pigs have not been kept on the island in historic times. A Tikopia oral tradition states that pigs were consciously eliminated due to their depredations on the gardens (Firth 1959, p. 34). Thus in the ethnographically documented subsistence system, protein was supplied almost exclusively by shellfish gathering and fishing (Firth 1939).

4.1.3 Fire, vegetation, and arboriculture. Although we lack a pollen record for Tikopia, general trends in the island's vegetation, and in the use of fire, were evident from changes in charcoal influxes in archaeological contexts. Charcoal is abundant in earlier deposits, but rare or lacking in later sediments (such as those at Rakisu), interpreted as reflecting a change from an initial pattern of shifting cultivation, to one of arboriculture. Ethnohistorically, the island's subsistence system is dominated by intensive tree cropping of coconut (*Cocos nucifera*), breadfruit (*Artocarpus altilis*), sago (*Metroxylon* spp.) and other trees (with understory of *Cyrtosperma* aroids and *Dioscorea* yams), in which fire is not used as an agronomic technique. Yen's study of the island's vegetation (in Kirch & Yen 1982) documented that more than 95% of the land surface is covered in a mosaic of intensively-managed tree crops and other cultigens, with only tiny patches of indigenous forest clinging to the steepest cliffs and windward slopes. Thus whilst the island gives the appearance of being entirely forested, it is an anthropogenic forest cover, continually managed and maintained through human land use activity. It is this level of intensive agro-forestry that permits Tikopia to maintain its high population density.

4.2. Mangaia

Mangaia lies within Eastern Polynesia, which did not begin to be settled until after the breakup of the initial Ancestral Polynesian culture and Proto-Polynesian speech community, and the onset of the final phase of exploration and colonisation of the central-eastern Pacific, sometime in the early first millennium A.D (Kirch & Green 2001). Some controversy surrounds the date of first human settlement of Mangaia (Kirch & Ellison 1994), with evidence from pollen cores suggesting a date as early as 1600–1800 BP, although the oldest directly dated cultural site has basal ^{14}C dates of ca. 900–1000 BP. Evidence for human–environment interaction was obtained during the interdisciplinary Mangaia Project co-directed by Kirch and Steadman (Steadman & Kirch 1990; Kirch *et al*., 1992, 1995; Kirch 1996, 1997a, b). The project methodology included extensive coring of lakes and valley alluvial sediments (Ellison 1994), as well as archaeological excavations in rockshelter and open sites.

4.2.1 Vegetation and geomorphic changes. The unique geomorphology of Mangaia, with a central volcanic core and radiating stream drainage pattern, surrounded by a ring of elevated limestone (*makatea*), resulted in significant sediment accumulations in the lower parts of the stream valleys, where alluvium was trapped against the *makatea* rampart. Twenty-five cores were taken from sites in seven drainage basins, and their sedimentary sequences dated by 26 ^{14}C samples (Kirch 1996, p. 5297); three cores were analysed for pollen content to reconstruct vegetation history.

The cores, up to 15 m deep in core TIR-1 in Veitatei Valley, exhibit a consistent stratigraphy, beginning with creation of brackish lakes and peat deposition around 7 kyr, correlating with Holocene sea level rise and drowning of a previously stable land surface. These small lakes reached a mid-Holocene maximum at $+1{\cdot}1$ m above modern sea level around 4 kyr. Sometime after 1·8 kyr, a rapid change in the depositional regime ensued, with peats being replaced by significant quantities of clayey alluvium, eroded from the weathered, 16–19 ma-old volcanic cone. Geochemical analysis of the TIR-1 core shows major increases in SiO_2 and Al_2O_3, along with free Fe, and a decrease in P_2O_5; these all signal the stripping off of a thin soil mantle formerly blanketing the volcanic hillsides, and exposing the deeply weathered laterite.

Correlated with this major shift in the depositional regime are dramatic changes in the pollen record, and in charcoal influx. Microscopic charcoal is essentially absent in the cores below samples dated earlier than 1·6–2·4 kyr, but increases dramatically above that level. Similarly, a major shift in the pollen spectra occurs at intervals dated between 2·4 and 1·6 kyr, with older levels containing significant quantities of indigenous forest taxa such as *Sophora*, *Erythrina*, *Weinmannia*, *Ficus* and other genera; these are replaced by a very limited suite of taxa dominated by the monocot tree *Pandanus tectorius*, along with two fern species (*Dicranopteris linearis* and *Cyclosorus interruptus*). These three species are fire-adapted, and dominate the volcanic hillslope vegetation today. The major changes in erosion and deposition, advent of extensive burning and charcoal influx, and replacement of native forest with a restricted suite of pyrophytic vegetation are all interpreted as resulting from the arrival of Polynesians on the island, and the use of shifting cultivation on the volcanic cone.

4.2.2 The faunal record. An extensive faunal assemblage was excavated from the Tangatatau (MAN-44) rockshelter in Veitatei Valley, comprising 35 157 bones, and significant quantities of marine invertebrates (Kirch *et al*. 1995; Butler 2001). Whilst the majority of fauna consists of fishbone, 795 identified bird bones document a sequence of avifaunal extinctions and extirpations. Basal deposits in the rockshelter include six species of seabirds and 14 species of native land birds (including rails, pigeons, doves and parrots). Species diversity declines rapidly in the mid to upper levels of the site. Of the 17 native land bird species represented in the sequence, 13 are historically extinct or extirpated, and of the 13 seabird species, three are extirpated while only two are not directly endangered. Similarly, there is a significant reduction in the quantities of an indigenous fruit bat (*Pteropus tonganus*) from lower to upper levels.

The MAN-44 faunal record also documents the introduction of the Pacific rat (*Rattus exulans*), pigs (*Sus scrofa*) and jungle fowl (*Gallus gallus*). Rats rapidly proliferated, and may have contributed to forest decline (through predation on seedlings and seeds) and to avifaunal extinctions (through predation on eggs or nestlings). Pigs are present in the early to mid levels of the site, but decline in the upper levels and were absent from the island at the time of missionary contact in the early 19th century; the elimination of pigs from the economic system may be explained by trophic competition with humans under conditions of high population density and resource stress (Kirch 2001).

The marine and brackish water faunal assemblages also exhibit significant changes throughout the MAN-44 sequence. Butler (2001) has demonstrated that changes in the frequencies of fish, as well as changes in fish size, are consistent with a model of resource depression resulting from high levels of human predation. Similarly, the marine molluscs (especially *Turbo setosus*) display size reductions over time consistent with sustained collecting pressure.

4.2.3 Land use and settlement. Archaeological investigations of both rockshelter and open sites in several valleys indicate that in the later period of Mangaian prehistory (ca. AD 1400–1800) a distinctive settlement pattern emerged centred around intensive terraced, pondfield irrigation of the valley bottoms (Kirch 1997a; Endicott 2000; Taomia 2000). The interior volcanic slopes had by this time been thoroughly denuded and their old, P-exhausted soils could not sustain horticulture. Residential sites and temples (*marae*) were situated on valley slopes immediately above the irrigation systems. The ethnohistoric record, including extensive Mangaian oral traditions, document a late period phase of endemic warfare and raiding, with control of the irrigation systems as the primary objective (Hiroa 1934). Even the religious system had been modified to reflect the economic dominance of irrigation (Kirch 1997a). Moreover, archaeological evidence from a rockshelter site (MAN-84) in Keia Valley documents the reality of personal violence; a late period assemblage of 1864 human bones represents at least 41 individuals whose bodies were ritually dismembered and cooked in earth ovens (Steadman *et al*. 2000).

4.3. Mangareva

The historical ethnography of Mangareva is presented by Hiroa (1938), whilst Emory (1939) pioneered archaeological reconnaissance. Green (Green & Weisler 2000, 2002, 2004; Weisler & Green 2001) carried out the first stratigraphic excavations in 1959, and an international team has recently renewed archaeological and palaeoecological study (Conte & Kirch (eds) 2004). Dates from several rockshelters, from the Onemea dune site, and from subsurface deposits in Rikitea Village all suggest initial Polynesian colonisation at around AD 900.

4.3.1 Deforestation and erosion. Mangareva is among the most severely deforested of all Polynesian islands, lacking a single endemic plant species (Huguenin 1974); the botanist of the 1934 Bishop Museum's Mangarevan Expedition lamented that the islands "are desolated; their natural flora is more completely exterminated than that of any other part of the world I have seen" (St. John 1935, p. 57). Whilst the coastal plains and small valleys are planted in a mix of Polynesian introduced tree crops (especially breadfruit and coconut), the hillslopes are dominated by fire-adapted *Miscanthus* grassland and *Dicranopteris* ferns. Unfortunately, the Mangareva islets lack suitable sites for pollen coring; reconstruction of the islands vegetation and the sequence of deforestation must await identification and analysis of charcoal from archaeological contexts, currently in progress. Given the ubiquitous presence of a number of genera and species of endemic terrestrial snails (Solem 1976, 1983; Bouchet & Abdou 2001, 2003), all now extinct and known from subfossil and archaeological contexts, it is almost certain that the islets were originally covered in natural forest prior to human colonisation.

Geomorphic evidence for erosion and deposition of colluvium in the late prehistoric and early historic periods is abundant, reflecting the near total removal of forest cover during the course of human occupation. One example is the GAT-3 site in Gatavake Valley on Mangareva Island, where 1·2 m of colluvial sediment caps an older land surface; charcoal at the base of the colluvium dates to the late 17th century A.D. (Conte & Kirch (eds) 2004, pp. 69–70).

4.3.2 The faunal record. A terrestrial and marine faunal record for Mangareva is now emerging through re-analysis of rockshelter assemblages excavated by Green in 1959 (Steadman and Justice 1998; Green & Weisler 2004), along with recently excavated open site and rockshelter assemblages (Howard & Kirch 2004; Worthy & Tennyson 2004). The earliest site, Onemea, with dates ca. AD 1000–1200 and thought to fall within the initial colonisation phase, yielded a rich array of bird bones, dominated by seabirds (especially a *Pseudobulweria* petrel now extirpated on Mangareva), but with an extinct *Ducula* pigeon also represented. The Nenega-Iti rockshelter, dating to ca. AD 1300–1500, has a much lower frequency of bird bones, indicating a rapid decline in the avifauna of the islands following human arrival. We now know that Mangareva had at least 20 bird species when humans first arrived, of which at least seven species are extirpated or extinct. The species remaining historically are only present in low or endangered populations confined to the smallest, uninhabited islands.

Also indicative of the natural terrestrial biota prior to human arrival are endemic landsnails in the families Torntellinidae, Endodontidae, Punctidae, and Assimineidae, recovered from archaeological contexts (Howard & Kirch 2004, pp. 112–116). These snails are globally extinct today, but were evidently ubiquitous across the Mangarevan landscape prior to deforestation.

At the time of European contact, the Pacific rat was the only mammal present in Mangareva, although oral traditions state that pigs had formerly been present (Hiroa 1938, pp. 194–195). This was confirmed by Green's 1959 excavations, yielding small numbers of pig (11 NISP) as well as dog (5 NISP) bones; recent excavation at Nenega-Iti also produced a pig premolar, as well as small fragments of medium mammal post-cranial bones that are probably from pigs (Howard & Kirch 2004, p. 117). As on both Tikopia and Mangaia, pigs were formerly part of the economic system, but were eliminated prior to European arrival (see Kirch 2001).

Mangareva's reef-lagoon ecosystem vastly exceeds the total area of its small islets. Not surprisingly, the ethnographic record (Hiroa 1938, pp. 197–198) indicates that marine resources were the main source of protein, and consequently fishermen enjoyed high social status and power. Fish bones dominate the vertebrate faunal assemblages from Mangarevan sites, and marine molluscs and crustaceans are also plentiful in these deposits (Howard & Kirch 2004). In striking contrast with Mangaia, however, there is no indication of resource depression in the marine faunal assemblages studied to date. The Mangarevan marine ecosystem appears to have been sufficiently extensive and resilient to sustain continued harvesting pressure from the relatively small human population without suffering measurable impacts to its invertebrate or vertebrate resources.

4.3.3 Land use and settlement. Archaeological surveys, such as those at Tokani Bay (Green & Weisler 2000, fig. 2; Weisler 1996), Atituiti-Ruga, and Atiaoa Valley (Conte & Kirch (eds) 2004, figs. 3.12, 3.30), document a late prehistoric settlement pattern with densely concentrated habitation and horticultural sites along the coastal plains and in the narrow valleys. In contrast, the denuded steeper hillslopes, covered in pyrophytic *Miscanthus* and *Dicranopteris*, are largely devoid of sites. Intensive taro production was undertaken in small systems of irrigated pondfields wherever there were springs or seeps providing permanent water supply, as at Atituiti-Ruga (Conte & Kirch (eds) 2004, fig. 3.13). The endemic warfare between competing chiefdoms on Mangareva Island is reflected in the presence of fortified habitation sites to protect chiefly offspring (the so-called 'royal nurseries'), situated on the flanks of Mt Auorotini (Emory 1939).

4.4. Hawaiian Islands

The largest archipelago within tropical-subtropical Polynesia, the Hawaiian Island chain has been more extensively investigated than the other cases, with decades of sustained archaeological study (see Kirch 1985, 2000 for overviews). Nonetheless, as for Mangaia and Mangareva, there has been continuing debate and evolving consensus regarding the timing of initial Polynesian discovery and settlement of the archipelago. Most researchers now accept a date of ca. AD 800 for initial human presence in the islands.

4.4.1 Vegetation and geomorphic changes. Individual islands of the archipelago vary as to the availability of sites with well stratified wetland sediments amenable to coring and pollen analysis, with good sites being found largely on the older islands with more developed landforms including swamps and ponds. On both O‘ahu and Kaua‘i islands, palynological studies have shown that human activities — including the use of fire — began to result in significant changes to the indigenous lowland vegetation by around AD 800–1000 (Athens *et al.* 1992; Athens & Ward 1993; Athens 1997; Burney *et al.* 2001; Burney & Burney 2003). The importance of fire in these vegetation changes is evident in elevated microscopic charcoal influxes. On O‘ahu, a number of cores show major declines in the frequency of an indigenous palm (*Pritchardia* sp.), which today is a rare species but which appears to have dominated lowland vegetation at the time of human arrival. The lowland *Pritchardia* forests seem to have been completely replaced by a mosaic of managed agroecosystems and second growth by around AD 1200. However, higher mountainous regions (above about 500 m elevation) on these islands retained extensive tracts of native *Acacia–Metrosideros* forest into historic times. Thus while Polynesian land use practices resulted in extensive modification to the lowland vegetation, these did not extend to higher zones.

Sequences of vegetation change on the younger islands such as Maui and Hawai‘i have been determined through analysis of charcoal assemblages from archaeological contexts. In Kahikinui on East Maui, an arid region not permanently inhabited until ca. AD 1400, a native dryland forest and scrub landscape was gradually modified by increasingly intensive cultivation of sweet potato and other crops (Coil 2004; Coil & Kirch 2005). Similarly, on the geologically rejuvenated peninsula of Kalaupapa, Moloka‘i Island, charcoal from the Kaupikiawa Rockshelter site (Kirch *et al.* 2004b) documents the transformation of a taxonomically diverse dryland forest (with taxa such as *Diospyros*, *Acacia*, *Antidesma*, *Flueggea*, *Psycotrax*, *Chenopodium*, *Osteomeles*, *Senna*, and *Wikstroemia*) to a dryland agricultural field system with short fallow dominated by a limited suite of shrubs and herbs.

Human land use and anthropogenic removal of native forests in the Hawaiian lowlands also resulted in increased erosion, and concomitant deposition of alluvial and colluvial sediments in various parts of the islands. For example, the large windward valley of Kahana on O‘ahu was far more deeply embayed 2 kyr BP than in the early historic period, and whilst some of the coastal progradation probably resulted from late Holocene sea level changes, the in-filling of the valley's floor with alluvium seems largely to have resulted from forest clearance and shifting cultivation in the valley interior (Mueller-Dombois & Wirawan 2005). Likewise, in the Halawa Valley, Moloka‘i, destabilisation of hillslopes, erosion, and colluvial deposition are dated to as early as AD 1200 (Kirch 1975, 1982).

4.4.2 The faunal record. At the time of Polynesian arrival in the archipelago, non-marine vertebrates included about 100 species of birds (and one bat species), with both flightless and volant species. The flightless birds included an endemic genus of ibis (*Apteribis* spp.), at least four genera of geese or anatids (*Geochen*, *Thambetochen*, *Ptaiochen* and *Chelychelynechen*), and a number of rails (*Porzana* spp.). The anatids, as large bodied and presumably naïve flightless birds, offered excellent food sources for colonising humans. Olson and James (Olson & James 1982, 1984; James *et al.* 1987) have presented the palaeontological and zooarchaeological evidence for the extirpation and in many cases extinction of the Hawaiian avifauna following human colonisation. The large flightless taxa disappeared rapidly, and rarely appear in later archaeological contexts. There are also indications that formerly extensive populations of nesting or roosting seabirds on the main islands were greatly reduced in numbers (Kirch 1982, table 1).

Whilst direct predation undoubtedly contributed to the extinction of the large anatids, indirect factors probably played a significant role as well. In recent investigations of sinkholes on the ‘Ewa Plain, O‘ahu Island, Athens *et al.* (2002) directly dated the abundant bones of human-introduced Polynesian rats (*Rattus exulans*), showing that these rats were present as early as cal AD 850–1289. A major episode of forest decline on the ‘Ewa Plain was probably a direct effect of an explosion of the *R. exulans* population and its predation on vulnerable native plants. "The rats could have produced their damage through seed and fruit predation, consumption of seedlings and new leaf production, and girding of soft-barked trees, as well as consumption of invertebrates critical to plant pollination and the nutrient cycle" (Athens *et al.* 2002, p. 74). Ecological shifts following Polynesian colonisation of O‘ahu are also indicated by changing frequencies of land snails in the sinkholes (Christensen & Kirch 1986), which also contain dense deposits of bird bones in their upper levels. In this case, the reductions in populations of both birds and snails is linked to collapse of their shared habitat, the native dryland forest, as a consequence of human introduction of the rat.

Along with their crop plants, the colonising Polynesians introduced the domestic pig, dog, and jungle fowl to the Hawaiian Islands. In contrast to the cases of Tikopia, Mangaia, or Mangareva, in Hawai‘i the populations of these domestic animals flourished. Indeed, when Captain James Cook and other early European explorers and voyagers arrived in the islands in the late 18th and early 19th centuries, they were impressed by the ability of the Hawaiian production systems to produce large quantities of hogs (these being prized for the salt pork so essential to supply European ships' stores). Moreover, pigs and dogs played important and highly structured roles in the social and religious systems; pigs were an exclusively male food, and the primary item of ritual sacrifice at war temples, while dogs were the preferred food of female chiefs.

4.4.3 Intensive agroecosystems and aquaculture. By the time of European contact, the lowland landscapes of the Hawaiian archipelago had been converted to a vast canvas of agroecosystems of two fundamental types, corresponding to two differing trajectories of agricultural intensification (Kirch 1994, pp. 251–268). Systems of terraced, flooded pondfields watered by canals tapping permanent streams, or in some cases springs, were used for the irrigated monoculture of taro (*Colocasia esculenta*). This kind of agroecosystem was focused on the colluvial slopes and alluvial floodplains of the windward and some leeward valleys, and to a lesser degree on coastal plains (as along the southern shore of Moloka‘i Island). These irrigation systems constitute what Brookfield (Blaikie & Brookfield (eds) 1987; Brookfield 1972, 1984) called "landesque capital intensification", in which landscapes are permanently modified by agronomic infrastructure. Although they were distributed throughout the length of the archipelago, the irrigation systems were principally concentrated on the geologically older, westerly islands, from West Maui to Kaua‘i, with their greatest extent on O‘ahu and Kaua‘i (Handy 1940; Earle 1980). This uneven distribution reflects the dearth of suitable valley landscapes and surface watercourses on the younger islands, especially Hawai‘i and East Maui (Fig. 2).

The second major agroecosystems consisted of the dryland field systems, which were confined to the geologically younger, easterly islands, especially Hawai‘i and East Maui (and the Kalaupapa Peninsula on Moloka‘i). The dominant crops within the dryland systems were sweet potato (*Ipomoea batatas*) and dryland taro, augmented by secondary crops such as yams (*Dioscorea* spp.), sugarcane, and other cultivars. These dryland agroecosystems depended almost exclusively on rainfall (in some localities augmented by fog-drip, or by minor seasonal irrigation), making them susceptible to seasonal variation and higher risk (Lee and Tuljapurkar 2006). They exemplify a distinct trajectory of intensification, originally defined by Boserup (1965), which may be termed "cropping cycle intensification" (Kirch 1994, p. 19; fig. 5). In their final configurations, with a reticulate grid of field boundaries intersected by trails, these systems left permanent traces on the Hawaiian landscape, and in that respect resemble the landesque capital intensive systems. However, in the greater labour inputs required for their continued maintenance, and in their significantly lower yields (as well as higher risk), the key processes of intensification of the dryland systems were distinct from those of the irrigated pondfields.

As shown in Figure 2, the geographical distribution of these two types of agroecosystems mirrors the geological age progression and biogeochemical gradients of the Hawaiian archipelago. Whilst minor areas of irrigation were present on Hawai‘i and East Maui, these large island areas were primarily

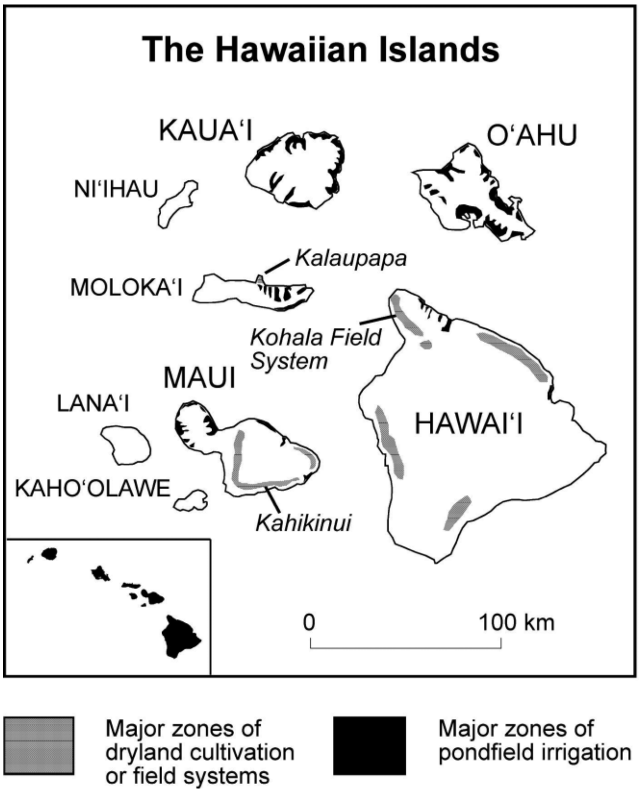

Figure 2 The Hawaiian Islands, showing major zones of irrigated pondfield cultivation, and of dryland field systems. Inset map shows the islands in their proper geographic configuration. Note that the dryland field systems are largely confined to the younger volcanic islands of Maui and Hawai‘i. (Figure adapted from Vitousek *et al.* 2004).

dependent upon labour intensive rain-fed crop production for their economic base. In contrast, from West Maui to Kaua‘i, local populations based their economies on the higher yielding, and less risk-prone, irrigation systems. Recent work on soils and agriculture in Hawai‘i has shown that “low soil fertility precluded the development of large-scale intensive dryland agricultural systems on stable upland surfaces on the older islands of the archipelago” (Vitousek *et al.* 2004, p. 1668). The intensive rain-fed dryland agricultural systems of the younger, eastern islands had targeted zones of relatively fertile soils (accompanied by adequate precipitation), where leaching had not yet deprived soils of rock-derived phosphorus and other essential plant nutrients. On the older islands, similar landscapes (old volcanic shield surfaces) with adequate rainfall have insufficient base cation saturation to develop intensive agriculture. On these older islands, only in valley topography where mass wasting and streamflow tap unweathered rock and release new nutrient sources, could intensive agriculture be practiced; this, of course, is precisely where the irrigation systems were developed.

The marine resources of the older, westerly Hawaiian islands were substantially richer than those of the younger islands. In particular, the construction of yet another form of landesque capital intensification — stone walled fishponds for the husbandry of mullet (*Mugil cephalis*) and milkfish (*Chanos chanos*) (Kikuchi 1976) — was limited to older and geomorphologically stable coastlines. Thus, the western half of the archipelago not only enjoyed better prospects for development of irrigation and aquaculture, but also the richest and largest stocks of marine resources. The eastern half of the island chain, despite comprising more land area overall (12 345 km^2 amounting to 74% of the total area of the main islands), had greatly restricted possibilities for irrigation or aquaculture, limited marine resources, required greater labour inputs necessitated by the dryland systems, and suffered the highest levels of risk (due to dependence upon stochastically variable rainfall).

The temporal development of these Hawaiian agroecosystems has begun to be demonstrated through archaeological research. On windward O‘ahu, one of the largest continuous zones of wet valley cultivation, radiocarbon dates from several sites document initial construction of irrigation systems by at least AD 1000 (Allen 1991, 1992). Allen concludes that by AD 1400 “agricultural system construction and production in areas along major streams were coordinated at a supralocal level”, resulting in “production of taro surpluses” (Allen 1991, p. 129). In the Waikolu Valley of windward Moloka‘i, irrigation system construction has been dated to AD 1240–1280 (Kirch (ed.) 2002, p. 46). Whilst valley irrigation systems continued to be extended and enlarged after AD 1400, an initial phase of investment in these landesque capital agroecosystems was temporally coincident with the major phase of population increase between roughly AD 1000 and 1450.

In contrast, the vast dryland field systems of Hawai‘i Island and East Maui did not begin to be developed until after ca. AD 1400. In Kahikinui, situated within what Handy (1940, p. 161) called “the greatest continuous dry planting area in the Hawaiian islands”, a suite of 160 ^{14}C dates documents the earliest phase of permanent habitation and dryland cultivation commencing in the 15th century, and intensifying thereafter (Kirch, unpublished data). In leeward Kohala, the earliest ^{14}C dates from the Kohala field system also date to the 15th century, and the progression of field system intensification thereafter is indicated through analysis of the grid of field boundary walls (Ladefoged *et al.* 2003). For the vast Kona field system, a series of ^{14}C dates also indicates construction of the formal field boundaries beginning in the 15th century (M. Allen (ed.) 2001, fig. 11.1). And, on Moloka‘i, the Kalaupapa field system again confirms this temporal pattern, with its field system developing from the 15th century onwards (Kirch (ed.) 2002; McCoy 2006).

5. Comparative analysis

Having summarised the evidence for long-term evolution of each of the four Polynesian socioecosystems under consideration, the similarities and/or differences between these cases can now be assessed, and what these may reveal concerning fundamental processes of human–environment interactions on oceanic islands.

5.1. Anthropogenic impacts

In all four cases, initial colonising groups of Polynesians arrived on previously uninhabited islands, seeking to establish viable, permanent communities based on a common economic pattern that combined root and tree-crop horticulture with exploitation of wild terrestrial foods (primarily birds) and marine resources. However, as can be seen in Table 3, the outcomes in each of the four cases were not identical. Particularly striking are differences in the impact of human land use on the native vegetation, and the degree of deforestation. Tikopia, although the smallest island, had its native forest cover largely removed, but rather than being deforested the island was converted to an intensively managed agro-forest. The Hawaiian Islands also had extensive modifications to their lowland and mesic forests, but retained significant areas of indigenous forest cover, largely in the higher mountainous zones. In the case of Tikopia, the young geologic age and consequent high nutrient status encouraged regrowth of

Table 3 Anthropogenic impacts on island environments

Category	Tikopia	Mangaia	Mangareva	Hawaiian Islands
Avifauna	Limited extinctions, extirpation	Extensive extinction and extirpation	Extensive extinction and extirpation	Extinction of larger and flightless taxa
Marine fauna	Reduction in overall quantity over time	Severe resource depression	No evidence for resource depression	No evidence for resource depression
Vegetation	Native forest replaced with managed agro-forest	Severe deforestation of volcanic interior	Severe deforestation of hillsides	Extensive modification of lowland forests, replacement with managed agroecosystems
Biotic introductions	Pigs, dogs, fowl, rats, crops; pigs later eliminated	Pigs, dogs, fowl, rats, crops; pigs later eliminated	Pigs, dogs, fowl, rats, crops; pigs later eliminated	Pigs, dogs, fowl, rats, crops; pigs and dogs became major food items
Geomorphic changes	Natural coastal progradation; anthropogenic deposition of colluvium	Extensive erosion of volcanic interior and deposition of alluvium in valleys	Significant erosion of hillsides	Some anthropogenic erosion and valley in-filling, colluvial deposition

secondary and economic forest, whilst in Hawai‘i the sheer size of the islands was a key factor and the extent of lowland deforestation in some degree was influenced by island age up the east-to-west age gradient of the archipelago. In contrast, the two mid-sized islands, Mangaia and Mangareva, suffered severe deforestation of their volcanic surfaces, without replacement of forest cover with managed economic plants (except on colluvial or alluvial zones). The more severe deforestation in these cases correlates with their relatively older geologic ages, and their consequent reduced nutrient status, especially P-limitation. In the case of the older Hawaiian Islands (such as O‘ahu and Kaua‘i), there is some evidence for the creation of extensive pyrophytic grasslands on the older and nutrient depleted shield surfaces, but in these cases the sheer size of the islands served to preclude total deforestation. Moreover, rejuvenation of colluvium in valley systems on the older Hawaiian islands (Vitousek *et al.* 2003) allowed for the development of intensive agroecosystems based on taro irrigation.

In all cases, the pre-human vertebrate faunas were essentially limited to birds (with a bat species in the case of Hawai‘i), and in every instance we have zooarchaeological evidence for extirpations and extinctions of both seabirds and landbirds, although the degree of impact again varies, and is most extreme on the heavily deforested islands of Mangaia and Mangareva. As Steadman (1995, 1997) and others (e.g., Athens *et al.* 2002) have discussed, human colonisation of oceanic islands impacted bird populations in a number of ways, including direct predation for food and feathers, but also indirect effects brought on by Pacific rats, reduction in native vegetation and habitats, repeated firing of habitats, and so on. On Tikopia, the replacement of indigenous forest with an agro-forest system continues to provide habitats for a number of indigenous or endemic birds (such as the coconut lorry (*Trichoglossus haematodus*) which flourishes in substantial flocks), and is an example of the complex causal linkages between human land use and ecosystem maintenance. In the Hawaiian Islands, the large flightless anatids disappeared quite rapidly, as their bones rarely appear in archaeological deposits, but significant populations of forest birds such as the endemic honeycreepers (Drepanidiane) continued to populate the higher mountain forest habitats on the main islands into the early post-European contact period (Ziegler 2002).

On the geologically older and P-limited islands where nesting seabird populations were eliminated or greatly reduced (Mangaia and Mangareva), this probably had a reciprocal negative feedback effect on terrestrial ecosystem function. As marine predators, the seabirds consumed significant quantities of fish and then deposited P, N, and other nutrients through their guano droppings onto the terrestrial land surface. As studies have shown for the Channel Islands of California (Anderson & Polis 1999; Sanchez-Pinero & Polis 2000), such nutrient inputs through seabird guano can elevate terrestrial nutrient levels by as much as six times. Indeed, it is likely that on Mangaia and Mangareva, the nutrient inputs provided by seabirds were essential to the long-term maintenance of indigenous vegetation cover in pre-human times. When these inputs were eliminated through anthropogenic impacts on the nesting seabird populations, the deposition of marine-derived nutrients also ceased. Thus the extirpation of seabirds on older oceanic islands may have played a crucial role in deforestation of these islands, and in some cases, declines in their agricultural productivity as well.

5.2. Relative vulnerability and resilience to human impacts

The four cases permit us to examine two key factors that might bear on the vulnerability or resilience of oceanic environments to anthropogenic effects: island size and geologic age. Size clearly has some effect, since larger islands such as those of the Hawaiian chain simply have more area and more varied topography, and hence have some elasticity with respect to human intrusion. On the other hand, small size alone need not render an island highly vulnerable, as the case of Tikopia demonstrates. Here geologic age, weathering, and the state of local biogeochemical gradients become critical.

The resilience of particular components of the terrestrial or marine biota are likewise affected by such factors as island size and diversity of habitats, as well as the utility of those habitats for human land use purposes. On Mangaia, the interior volcanic hillsides were wholly denuded of native vegetation after human colonisation, through the use of fire and forest clearance, which is interpreted as attempted cultivation of these old land surfaces in shifting cultivation; an effort that ended in failure and denudation of these surfaces. But on the karstic *makatea*, much of which is wholly unsuited for plant cropping, patches of native forest remained intact, providing refugia that continue to support small populations of nesting seabirds. Similarly, in Hawai‘i, the large tracts of mountainous interior, including areas in steep cliffs or ridges largely impassable by humans, also provided extensive habitats for native land birds, thus ensuring their survival until the introduction of avian malaria and other diseases after European contact.

In the cases considered here, however, it is clearly geologic age — and more importantly, its corollary of nutrient status as a function of weathering and leaching — that had the greatest importance in determining whether islands were more or less vulnerable to Polynesian land use practices. On a small and young island such as Tikopia, P is in abundant supply, and N is presumably also supplied in aerosol form from sea spray continually blown up onto the hillslopes from the surrounding reefs. Tikopia's remarkable ability to maintain its intensive agro-forest system no doubt owes much to this particular set of environmental characteristics. On Mangareva, and especially on 16–19 ma-old Mangaia, P is severely depleted, and in the pre-human ecosystems, it was almost certainly the extensive nesting populations of seabirds that continued to supply sufficient levels of both P and N to maintain native forest cover. When human actions simultaneously destroyed the bird populations and removed the indigenous forest cover, the exposed deeply weathered lateritic soils were incapable of supporting forest regrowth, or even intermittent cultivation. Horticultural activities on these islands had to be confined to the limited zones where colluvial and alluvial soils had accumulated. The Hawaiian archipelago exhibits a 'sliding scale' of vulnerability along its age-progression, with the older islands of O'ahu and Kaua'i being most susceptible to deforestation on their older volcanic shield surfaces (Vitousek 2004). However, these islands also have significant areas of valley development, where mass wasting of cliffs and steep hillsides results in rejuvenation of nutrient status through exposure of unweathered rock (Vitousek *et al.* 2003). This enabled Polynesian populations on these islands to develop intensive systems of irrigation on alluvium and mixed gardening on colluvial slopes (Kirch 1977), even though the older, weathered shield surfaces were largely unused for cultivation.

5.3. Demographic and cultural responses

Although they all derived from a shared Ancestral Polynesian pattern, the socioecosystems that evolved in Tikopia, Mangaia, Mangareva, and Hawai'i reflect both the specific ecological circumstances of each island environment, and the historical pathways in which each society responded to the possibilities and constraints that it faced. As briefly summarised in sections 2–3 of this paper (see also Table 2), these socioecosystems varied greatly in their demographic, economic, social, political, and even religious structures, all of which were influenced or shaped to some extent by the long-term sequence of human–environment interactions. A comprehensive discussion of these is beyond the scope of the present paper, but some trends deserve comment.

In all four cases, population density levels at the time of European contact were relatively high, at least when considered in terms of population density per area of arable land. However, cultural controls on population varied widely between these societies. Tikopia was the one society in which a culturally explicit model of population regulation ('zero population growth') had developed, and was continually reinforced by the chiefly authorities, as Firth (1936) so well described in his ethnography. Using a number of methods (*coitus interruptus*, abortion, infanticide, enforced celibacy of junior males, and suicide voyaging), the Tikopia continually strove to keep their population at a level that matched the productive capacity of their intensive agro-forest production system. That their efforts were not always successful is indicated by oral traditions of inter-tribal warfare in the past (Firth 1961), yet the society-wide goal was that of demographic regulation. Mangaia and Mangareva lacked such a conscious, socially-mandated policy of population control, yet population clearly had to be regulated in some manner; in these societies this seems to have been accomplished through endemic inter-tribal warfare and violence (Hiroa 1934, 1938). The differences between Tikopia on the one hand, and Mangaia and Mangareva on the other, may partly reflect the *scale* of these societies, as has been suggested elsewhere (Kirch 1997b). Tikopia is small enough to have a *collective* social sense, encapsulated by their phase *matou nga Tikopia*, "we, the Tikopia". Thus it is possible for the Tikopia to view their socioecosystems as a 'commons', and to make collective decisions for the common social good.

Mangaia and Mangareva, with slightly larger overall populations distributed over larger land areas or on separate small islands (in the case of Mangareva), lacked such a collectivity, being socially and politically fragmented into competing groups that viewed each other with scorn and derision. Unable to achieve a collective perspective on resources and population, they failed to develop effective population regulation, or collective means of resource control and sharing. Moreover, due to the vulnerability of their islands (see above), their respective abilities to develop productive agricultural systems were severely limited, and in Mangaia terrestrial and marine resources also suffered resource depression due to overexploitation. In Mangareva, the vast reef-lagoon ecosystem lent a degree of relief, and the high social status of fishermen reflects this (by withholding the gift of fish, a Mangarevan fisherman could bring down a chief; Hiroa 1938). In many respects, then, Mangaia and Mangareva represent classic cases of the "tragedy of the commons" (Hardin 1968; McCay & Acheson (eds) 1987).

Hawai'i presents an altogether different case from either the collective 'commons' of Tikopia, or the tragic cases of Mangaia and Mangareva, where in the face of deforestation and resource depression, a lack of social collectivity expressed itself in repetitive cycles of social violence and rampant competition for control of limited resources. The Hawaiian archipelago is of such a vaster scale — both geographically and demographically − that the historical trajectory of its socioecosystems evolved towards something not seen elsewhere in Polynesia. By late prehistory (ca. AD 1650–1800) the populations of several independent Hawaiian polities reached levels of between 50 000 to 100 000 persons, without evidently exceeding 'carrying capacity' (although the dryland field systems had been increasingly pushed to their limits of intensification). Moreover, these populations were organised in a strongly hierarchical, 'top down' manner, as Hawaiian elites had managed to transform the ideological structures of their society to one in which high chiefs had become 'divine kings'. With these changes came a complete transformation of the land tenure and tribute system, in which land rights no longer went with ascent groups, but were held as hierarchical territorial units corresponding to the hierarchy of king and chiefs (Kirch & Sahlins 1992; Kirch 2005). This new sociopolitical structure — and a new religious system to legitimate it — was admirably suited to undertake further intensification of the now vast dryland field systems, irrigation complexes, and fishponds that formed the backbone of the Hawaiian staple economy.

Yet the Hawaiian socioecosystems also had their limits, especially on the younger islands where the dryland field systems provided the greatest amount of production, and which by late prehistory had already begun to push to the margins of several zones where the combination of soils and rainfall were suited to intensive cropping of sweet potato and dryland taro (Kirch *et al.* 2004a; Vitousek *et al.* 2004). As these systems were required to support still expanding populations, at the same time that they were expected to meet the substantial demands of the elite for surpluses of various kinds (foodstuffs, pigs, craft goods), they became increasingly susceptible to environmental perturbations, especially drought. In spite of various bet-hedging strategies (Allen 2004), the dryland systems were risky, and if Hawaiian oral traditions are taken at face value, they failed more than once, resulting in widespread famine and social unrest. Indeed, the present author has argued that it was precisely this set of conditions that underlay the major political developments at the onset of European contact, namely the inter-island wars of attempted conquest, especially promulgated by the Hawai‘i and Maui island kings, whose polities were so dependent upon the dryland field systems (Kirch 1984; 2007).

6. Conclusions: long-term sustainability of island socioecosystems

Under the contemporary onslaught of such threats as unchecked population growth in developing countries, the biodiversity crisis (heavily driven by deforestation of tropical lowlands), and anthropogenic global warming, there is mounting interest in the concept of *sustainability* (National Research Council 1999). Exactly what is meant by the term, or by the linked concept of ‘sustainable development’ varies according to author, but fundamentally incorporates a notion of meeting contemporary needs without compromising the ability of future generations to meet their own needs. Key aspects of sustainable systems therefore are typically seen to include preservation of resource stocks and biodiversity, as well as maintenance of ‘ecosystem services’ (Daily (ed.) 1997). In light of such concepts, what might the long-term histories of Polynesian ‘model systems’ tell us about the sustainability of these socioecosystems?

Of the four cases reviewed here, Tikopia seems the clearest example of a socioecosystem that has been capable of sustaining itself over a time span of several millennia. Although the island suffered some reductions in its natural resource base after initial human colonisation, it nonetheless continues to support considerable biodiversity, in part because its agroforest mimics the multi-storey structure of tropical rainforests, thus providing diverse microhabitats (Kirch & Yen 1982, pp. 38–46). Moreover, the island’s society has developed a strong collective sense of the ‘commons’, including a deeply ingrained concept of population regulation. Some, of course, would find the traditional Tikopia methods of population control unacceptable, as did Anglican missionaries in the 20th century (Firth 1936). Their efforts to stop Tikopian demographic controls through the use of celibacy, abortion, infanticide and so forth led to rapid population growth that culminated in over-population and disaster following two cyclones in the 1950s (Borrie *et al*. 1957; Firth 1959). Only the enforced outmigration of Tikopians to other parts of the Solomon Islands has managed to resolve this problem. Thus, the Tikopia socioecosystem is sustainable, as long as culturally ingrained methods of population control are applied.

At face value, the Hawaiian case also seems to represent a sustainable trajectory, one that was being highly managed in a top-down hierarchical fashion, rather than through the social collectivity of Tikopia. Certainly, the Hawaiian agroecosystems were models of intensive land management, and indeed there is much interest in Hawai‘i today in applying the ‘*ahupua‘a* model’ of land management to contemporary landscapes (Minerbi 1999). Hawai‘i also lost some of its natural biodiversity during the early phase of Polynesian settlement, but its ecosystem services were largely intact and well-functioning in late prehistory. What might give us pause, however, is to reflect on the differentials in the quality of daily life in varied sectors of traditional Hawaiian society. Access to resources had become distinctly unequal in late prehistoric Hawai‘i, as had the amount of time and energy expended in subsistence production by different sectors of society. As an incipient ‘archaic state’, Hawaiian society had developed a degree of what Tilly (1998) labels ‘durable inequality’, evident along axes of both rank and gender (Kirch 2005). All indications from the archaeological record, for example, are that daily life for commoners in the drier, leeward, risk-prone regions of such islands as Maui, Lana‘i, or Hawai‘i was one of endless labour to support a subsistence existence in which any modicum of surplus was immediately siphoned off up the social hierarchy. Certainly, Hawaiian traditions of oppressive chiefs and commoner revolts (Sahlins 1972, pp. 144–147) speak to the extent to which inequality had become pervasive in late Hawaiian society. That the Hawaiian agroecosystems were efficiently managed cannot be doubted; that they equally benefited all sectors of society is a myth rather dangerously promulgated by revisionist history.

Finally, the historical trajectories of both Mangaia and Mangareva must give us much pause, for these are unmistakable cases of unsustainable socioecosystems, societies in which resources had been severely depleted, ecosystem services impaired, and social existence itself ruled by overt competition, if not too often also by fear and sheer terror. The rise of warrior classes in both these societies is telling, as the historical ethnographies of Hiroa (1934, 1938) bring out in great detail, typically through these societies’ own oral traditions of endless wars and social upheavals. To be sure, these island ecosystems were without doubt the most vulnerable and fragile of the cases we have examined, owing to their geological ages and consequent nutrient limitations, as well as to their small size and, in the case of Mangaia, to limited marine resources. It is to be doubted whether the initial Polynesian colonists who arrived on these shores could have had any expectations that these islands would be infinitely more susceptible to deforestation, or that the elimination of their seabird populations would sever a key link in ecosystem functioning. To read the history of Mangaia or Mangareva as one in which the actions of prior generations set up devastating consequences for their descendants is not to suggest that these were wilful acts of ‘eco-vandalism’. But in the contexts and constraints of their unique island environments, human actions did have inevitable consequences, to be suffered by future generations. In this regard, at least, the model systems of Polynesia do hold lessons for humanity today.

7. References

Allen, J. 1991. The role of agriculture in the evolution of the pre-contact Hawaiian state. *Asian Perspectives* **30**, 117–32.

Allen, J. 1992. Farming in Hawai‘i from colonization to contact: Radiocarbon chronology and implications for cultural change. *New Zealand Journal of Archaeology* **14**, 45–66.

Allen, M. S. (ed.) 2001. *Gardens of Lono: Archaeological Investigations at the Amy B. H. Greenwell Ethnobotanical Garden, Kealakekua, Hawai‘i*. Honolulu: Bishop Museum Press.

Allen, M. S. 2004. Bet-hedging strategies, agricultural change, and unpredictable environments: Historical development of dryland agriculture in Kona, Hawai‘i. *Journal of Anthropological Archaeology* **23**, 196–224.

Anderson, W. B. & Polis, G. A. 1999. Nutrient fluxes from water to land: Seabirds affect plant nutrient status on Gulf of California islands. *Oecologia* **118**, 324–32.

Athens, J. S. 1997. Hawaiian native lowland vegetation in prehistory. *In* Kirch, P. V. and Hunt, T. L. (eds) *Historical Ecology in the Pacific Islands: Prehistoric Environmental and Landscape Change*, 248–70. New Haven, Connecticut: Yale University Press.

Athens, S., Ward, J. V. & Wickler, S. 1992. Late Holocene lowland vegetation, O‘ahu, Hawai‘i. *New Zealand Journal of Archaeology* **14**, 9–34.

Athens, J. S., Tuggle, H. D., Ward, J. V. & Welch, D. J. 2002. Avifaunal extinctions, vegetation change, and Polynesian impacts in prehistoric Hawai‘i. *Archaeology in Oceania* **37**, 57–78.

Athens, S. & Ward, J. V. 1993. Environmental change and prehistoric Polynesian settlement in Hawai‘i. *Asian Perspectives* **32**, 205–23.

Balée, W. (ed.) 1998. *Advances in Historical Ecology*. New York: Columbia University Press.

Barton, C. M., Bernabeu, J., Aura, J. E., Garcia, O., Schmich, S. & Molina, L. 2004. Long-term socioecology and contingent landscapes. *Journal of Archaeological Method and Theory* **11**, 253–95.

Blaikie, P. & Brookfield, H. C. (eds) 1987. *Land Degradation and Society*. London: Methuen.

Borrie, W. D., Firth, R. & Spillius, J. 1957. The population of Tikopia, 1929 and 1952. *Population Studies* **10**, 229–52.

Boserup, E. 1965. *The Conditions of Agricultural Growth: The Economics of Agrarian Change under Population Pressure*. Chicago: Aldine.

Bouchet, P. & Abdou, A. 2001. Recent extinct land snails (Euconulidae) from the Gambier Islands with remarkable apertural barriers. *Pacific Science* **55**, 121–7.

Bouchet, P. & Abdou, A. 2003. Endemic land snails from the Pacific Islands and the museum record: documenting and dating the extinction of the terrestrial Assimineidae of the Gambier Islands. *Journal of Molluscan Studies* **69**, 165–70.

Brookfield, H. C. 1972. Intensification and disintensification in Pacific agriculture: A theoretical approach. *Pacific Viewpoint* **13**, 30–48.

Brookfield, H. C. 1984. Intensification revisited. *Pacific Viewpoint* **25**, 15–44.

Burney, D. A., James, H. F., Burney, L. P., Olson, S. L., Kikuchi, W., Wagner, W. L., Burney, M., McCloskey, D., Kikuchi, D., Grady, F. V., Gage II, R. & Nishek, R. 2001. Fossil evidence for a diverse biota from Kaua‘i and its transformation since human arrival. *Ecological Monographs* **71**, 615–41.

Burney, L. P. & Burney, D. A. 2003. Charcoal stratigraphies for Kaua‘i and the timing of human arrival. *Pacific Science* **57**, 211–26.

Butler, V. L. 2001. Changing fish use on Mangaia, Southern Cook Islands: Resource depression and the prey choice model. *International Journal of Osteoarchaeology* **11**, 88–100.

Chadwick, O. A., Derry, L. A., Vitousek, P. M., Huebert, B. J. & Hedin, L. O. 1999. Changing sources of nutrients during four million years of ecosystem development. *Nature* **397**, 491–7.

Chadwick, O. A. & Chorover, J. 2001. The chemistry of pedogenic thresholds. *Geoderma* **100**, 321–53.

Christensen, C. C. & Kirch, P. V. 1986. Non-marine molluscs and ecological change at Barbers Point, O‘ahu, Hawai‘i. *Bishop Museum Occasional Papers* **26**, 52–80.

Coil, J. 2004. *'The Beauty that Was': Archaeological Investigations of Ancient Hawaiian Agriculture and Environmental Change in Kahikinui, Maui*. Unpublished PhD.

Dissertation, Department of Anthropology, University of California, Berkeley.

Coil, J. & Kirch, P. V. 2005. Ipomoean landscapes: Archaeology and the sweet potato in Kahikinui, Maui, Hawaiian Islands. *In* Ballard, C., Brown, P. and Bourke, M. (eds) *Sweet Potato in the Pacific*, 71–84. Sydney: Oceania Monographs.

Conte, E. & Kirch, P. V. (eds) 2004. *Archaeological Investigations in the Mangareva Islands* (*Gambier Archipelago*), *French Polynesia*. Archaeological Research Facility Contribution **No. 62**. Berkeley, California: University of California.

Coulter, J. W. 1931. *Population and Utilization of Land and Sea in Hawaii, 1853. Bernice P. Bishop Museum Bulletin* **88**. Honolulu.

Crosby, A. 1986. *Ecological Imperialism: The Biological Expansion of Europe, AD 900–1900*. Cambridge: Cambridge University Press.

Daily, G. (ed.) 1997. *Nature's Services: Societal Dependence on Natural Ecosystems*. Washington, DC: Island Press.

Diamond, J. 2005. *Collapse: How Societies Choose to Fail or Succeed.* Viking, New York.

Dickinson, W. R. 2003. Impact of Mid-Holocene hydro-isostatic highstand in regional sea level on habitability of islands in Pacific Oceania. *Journal of Coastal Research* **19**, 489–502.

Earle, T. K. 1980. Prehistoric irrigation in the Hawaiian Islands: An evaluation of evolutionary significance. *Archaeology and Physical Anthropology in Oceania* **15**, 1–28.

Ellison, J. 1994. Palaeo-lake and swamp stratigraphic records of Holocene vegetation and sea-level changes, Mangaia, Cook Islands. *Pacific Science* **48**, 1–15.

Emory, K. P. 1939. *Archaeology of Mangareva and Neighboring Atolls. Bernice P. Bishop Museum Bulletin* **163**. Honolulu.

Endicott, J. 2000. *Archaeological and ethnohistoric evidence for protohistoric social relations on Mangaia Island, Cook Islands*. Unpublished PhD Dissertation, Department of Anthropology, University of California, Berkeley.

Firth, R. 1936. *We, The Tikopia*. London: George Allen & Unwin.

Firth, R. 1939. *Primitive Polynesian Economy*. London: George Routledge and Sons.

Firth, R. 1959. *Social Change in Tikopia*. New York: Macmillan Co.

Firth, R. 1961. *History and Traditions of Tikopia*. *Polynesian Society Memoir* **No. 33**. Wellington, New Zealand: The Polynesian Society.

Fosberg, F. R. 1963. The island ecosystem. *In* Fosberg, F. R. (ed.) *Man's Place in the Island Ecosystem: A Symposium*, 1–7. Honolulu: Bishop Museum Press.

Fryer, P. 1974. Petrology of some volcanic rocks from the northern Fiji Plateau. *Geological Society of America Bulletin* **85**, 1717–20.

Goldman, I. 1970. *Ancient Polynesian Society*. Chicago, Illinois: University of Chicago Press.

Green, R. C. & Weisler, M. I. 2000. *Mangarevan Archaeology: Interpretations Using New Data and 40 Year Old Excavations to Establish a Sequence from 1200 to 1900 AD. University of Otago Studies in Prehistoric Archaeology* **No. 19**. Dunedin: University of Otago.

Green, R. C. & Weisler, M. I. 2002. The Mangarevan sequence and the dating of geographic expansion into southeast Polynesia. *Asian Perspectives* **41**, 213–41.

Green, R. C. & Weisler, M. I. 2004. Prehistoric introduction and extinction of animals in Mangareva, Southeast Pacific. *Archaeology in Oceania* **39**, 34–41.

Guillou, H., Gillot, P. Y. & Guille, G. 1994. Age (K/Ar) et position des îles Gambier dans l'alignement volcanique du point chaud de Pitcairn (Pacifique sud). *Comptes Rendues Académie Sciences* **318**, 635–41. Paris.

Handy, E. S. C. 1940. *The Hawaiian Planter*, Vol. 1. *Bernice P. Bishop Museum Bulletin* **161**. Honolulu.

Hardin, G. 1968. The tragedy of the commons. *Science* **162**, 1243–8.

Hather, J. & Kirch, P. V. 1991. Prehistoric sweet potato (*Ipomoea batatas*) from Mangaia Island, Central Polynesia. *Antiquity* **65**, 887–93.

Hiroa, Te Rangi (P. H. Buck), 1934. *Mangaian Society. Bernice P. Bishop Museum Bulletin* **122**. Honolulu.

Hiroa, Te Rangi (P. H. Buck), 1938. *Ethnology of Mangareva. Bernice P. Bishop Museum Bulletin* **157**. Honolulu.

Howard, N. M. & Kirch, P. V. 2004. Zooarchaeological analysis of faunal assemblages. *In* Conte, E. & Kirch, P. V. (eds) *Archaeological Investigations in the Mangareva Islands* (*Gambier Archipelago*). *French Polynesia*, 106–21. *Archaeological Research Facility Contribution* **No. 62**. Berkeley, California: University of California.

Huguenin, B. 1974. La végétation des îles Gambier – relevé botanique des espèces introduites. *Cahiers du Pacifique* **18(2)**, 459–72.

James, H., J. Stafford, T.W., Steadman, D., Olson, S., Martin, P., Jull, A. & McCoy, P. 1987. Radiocarbon dates on bones of extinct birds from Hawaii. *Proceedings of the National Academy of Science, USA* **84**, 2350–4.

Kikuchi, W. 1976. Prehistoric Hawaiian fishponds. *Science* **193**, 295–9.

Kirch, P. V. 1975. Excavations at Sites A1–3 and A1–4: Early settlement and ecology in Halawa Valley. *In* Kirch, P. V. & Kelly, M. (eds) *Prehistory and ecology in a windward Hawaiian valley: Halawa Valley, Molokai*, 17–70. *Pacific Anthropological Records* **24**. Honolulu: Bishop Museum.

Kirch, P. V. 1977. Valley agricultural systems in prehistoric Hawaii: An archaeological consideration. *Asian Perspectives* **20**, 246–80.

Kirch, P. V. 1982. The impact of the prehistoric Polynesians on the Hawaiian ecosystem. *Pacific Science* **36**, 1–14.

Kirch, P. V. 1984. *The Evolution of the Polynesian Chiefdoms*. Cambridge: Cambridge University Press.

Kirch, P. V. 1985. *Feathered Gods and Fishhooks: An Introduction to Hawaiian Archaeology and Prehistory*. Honolulu: University of Hawaii Press.

Kirch, P. V. 1986. Exchange systems and inter-island contact in the transformation of an island society: The Tikopia case. *In* Kirch, P. V. (ed.) *Island Societies: Archaeological Approaches to Evolution and Transformation*, 33–41. Cambridge: Cambridge University Press.

Kirch, P. V. 1991. Polynesian agricultural systems. *In* Cox, P. A. & Banack, S. A. (eds) *Islands, Plants, and Polynesians: An Introduction of Polynesian Ethnobotany*, 113–33. Portland, Oregon: Dioscorides Press.

Kirch, P. V. 1994. *The Wet and the Dry: Irrigation and Agricultural Intensification in Polynesia*. Chicago: University of Chicago Press.

Kirch, P. V. 1996. Late Holocene human-induced modifications to a central Polynesian island ecosystem. *Proceedings of the National Academy of Sciences, USA* **93**, 5296–300.

Kirch, P. V. 1997a. Changing landscapes and sociopolitical evolution in Mangaia, Central Polynesia. *In* Kirch, P. V. & Hunt, T. L. (eds) *Historical Ecology in the Pacific Islands: Prehistoric Environmental and Landscape Change*, 147–65. New Haven, Connecticut: Yale University Press.

Kirch, P. V. 1997b. Microcosmic histories: Island perspectives on 'global' change. *American Anthropologist* **99**, 30–42.

Kirch, P. V. 2000. *On the Road of the Winds: An Archaeological History of the Pacific Islands before European Contact*. Berkeley, California: University of California Press.

Kirch, P. V. 2001. Pigs, humans, and tropic competition on small Oceanic islands. *In* Anderson, A. and Murray, T. (eds) *Australian Archaeologist: Collected Papers in Honour of Jim Allen*, 427–39. Canberra: Australian National University, Centre for Archaeological Research and Department of Archaeology and Natural History.

Kirch, P. V. (ed.) 2002. *From the 'Cliffs of Keolewa' to the 'Sea of Papaloa': An Archaeological Reconnaissance of Portions of the Kalaupapa National Historical Park, Moloka'i, Hawaiian Islands. Oceanic Archaeology Laboratory, Special Publication* **No. 2**. Berkeley, California: Archaeological Research Facility.

Kirch, P. V. 2004. Oceanic islands: Microcosms of 'global change'. *In* Redman, C. L., James, S. R., Fish, P. R. & Rogers, J. D. (eds) *The Archaeology of Global Change*, 13–27. Washington, D.C: Smithsonian Books.

Kirch, P. V. 2005. *From Chiefdom to Archaic State: Social Evolution in Hawaii*. Grace Elizabeth Shallit Lecture Series. Provo, Utah: Department of Anthropology, Brigham Young University.

Kirch, P. V. 2007. Hawaii as a model system for human ecodynamics. *American Anthropologist* **109**, 8–26.

Kirch, P. V., Flenley, J., Steadman, D., Lamont, F. & Dawson, S. 1992. Ancient environmental degradation. *National Geographic Research & Exploration* **8**, 166–79.

Kirch, P. V., Steadman, D. W., Butler, V. L., Hather, J. & Weisler, M. I. 1995. Prehistory and human ecology in Eastern Polynesia: Excavations at Tangatatau rockshelter, Mangaia, Cook Islands. *Archaeology in Oceania* **30**, 47–65.

Kirch, P. V., Hartshorn, A. S., Chadwick, O. A., Vitousek, P.M., Sherrod, D. R., Coil, J., Holm, L. & Sharp, W. D. 2004a. Environment, agriculture, and settlement patterns in a marginal Polynesian landscape. *Proceedings of the National Academy of Sciences USA* **101**, 9936–41.

Kirch, P. V., O'Day, S., Coil, J., Morgenstein, M., Kawelu, K. & Millerstrom, S. 2004b. The Kaupikiawa Rockshelter, Kalaupapa Peninsula, Moloka'i: New investigations and reinterpretation of its significance for Hawaiian prehistory. *People and Culture in Oceania* **19**, 1–27.

Kirch, P. V. and Ellison, J. 1994. Palaeoenvironmental evidence for human colonization of remote Oceanic islands. *Antiquity* **68**, 310–21.

Kirch, P. V. & Green, R. C. 1987. History, phylogeny, and evolution in Polynesia. *Current Anthropology* **28**, 431–43, 452–6.

Kirch, P. V. & Green, R. C. 2001. *Hawaiki, Ancestral Polynesia: An Essay in Historical Anthropology*. Cambridge: Cambridge University Press.

Kirch, P. V. & Hunt, T. L. (eds) 1997. *Historical Ecology in the Pacific Islands: Prehistoric Environmental and Landscape Change*. New Haven, Connecticut: Yale University Press.

Kirch, P. V. & Sahlins, M. D. 1992. *Anahulu: The Anthropology of History in the Kingdom of Hawaii*. 2 vols. Chicago, Illinois: University of Chicago Press.

Kirch, P. V. & Yen, D. E. 1982. *Tikopia: The Prehistory and Ecology of a Polynesian Outlier. Bernice P. Bishop Museum Bulletin* **238**. Honolulu.

Ladefoged, T. N., Graves, M. W. & McCoy, M. D. 2003. Archaeological evidence for agricultural development in Kohala, Island of Hawai'i. *Journal of Archaeological Science* **30**, 923–40.

Lee, C. & Tuljapurkar, S. 2006. Risky business: Temporal and spatial variation in preindustrial dryland agriculture. *Human Ecology* **34**, 739–63.

Mayr, E. 1997. *This is Biology: The Science of the Living World*. Cambridge, Massachusetts: Harvard University Press.

McCay, B. J. & Acheson, J. M., (eds) 1987. *The Question of the Commons: The Culture and Ecology of Communal Resources*. Tucson, Arizona: University of Arizona Press.

McCoy, M. 2006. *Landscape, Social Memory, and Society: An Ethnohistoric–Archaeological Study of Three Hawaiian Communities*. Unpublished PhD Dissertation, University of California, Berkeley.

McGlade, J. 1995. Archaeology and the ecodynamics of human-modified landscapes. *Antiquity* **69**, 113–32.

Minerbi, L. 1999. Indigenous management models and protection of the ahupua'a. *Social Process in Hawai'i* **29**, 208–25.

Mueller-Dombois, D. & Wirawan, N. 2005. The Kahana Valley ahupua'a, a PABITRA study site on O'ahu, Hawaiian Islands. *Pacific Science* **59**, 283–92.

National Research Council 1999. *Our Common Journey: A Transition Toward Sustainability*. Washington, DC: National Academy Press.

Nunn, P. D. 1994. *Oceanic Islands*. Oxford: Blackwell Publishers.

Olson, S. L. & James, H. F. 1982. Fossil birds from the Hawaiian Islands: Evidence for wholesale extinction by man before Western contact. *Science* **217**, 633–5.

Olson, S. L. & James, H. F. 1984. The role of Polynesians in the extinction of the avifauna of the Hawaiian Islands. *In* Martin, P. S. and Klein, R. L. (eds) *Quaternary Extinctions: A Prehistoric Revolution*, 768–80. Tucson, Arizona: University of Arizona Press.

Redman, C. L, James, S. R., Fish, P. R. & Rogers, J. D. (eds) 2004. *The Archaeology of Global Change: The Impact of Humans on Their Environment*. Washington, DC: Smithsonian Books.

Sahlins, M. 1972. *Stone Age Economics*. Chicago: Aldine.

Sanchez-Pinero, F. & Polis, G. A. 2000. Bottom-up dynamics of allochthonous input: Direct and indirect effects of seabirds on islands. *Ecology* **81**, 3117.

Solem, A. 1976. *Endodontoid Land Snails from Pacific Islands* (*Mollusca: Pulmonata: Sigmurethra*). Part I. *Family Endodontidae*. Chicago, Illinois: Field Museum of Natural History.

Solem, A. 1983. *Endodontoid Land Snails from Pacific Islands* (*Mollusca: Pulmonata: Sigmurethra*). Part 2. *Families Punctidae and Charopidae*. Chicago, Illinois: Field Museum of Natural History.

Steadman, D. W. 1995. Prehistoric extinctions of Pacific island birds: Biodiversity meets zooarchaeology. *Science* **267**, 1123–30.

Steadman, D. W. 1997. Extinctions of Polynesian birds: Reciprocal impacts of birds and people. *In* Kirch, P. V. & Hunt, T. L. (eds) *Historical Ecology in the Pacific Islands: Prehistoric Environmental and Landscape Change*, 51–79. New Haven, Connecticut: Yale University Press.

Steadman, D. W., Pahlavan, D. S. & Kirch, P. V. 1990. Extinction, biogeography, and human exploitation of birds on Anuta and Tikopia, Solomon Islands. *Occasional Papers of the Bishop Museum* **30**, 118–53.

Steadman, D. W., Antón, S. & Kirch, P. V. 2000. Ana Manuka: A prehistoric ritualistic site on Mangaia, Cook Islands. *Antiquity* **74**, 873–83.

Steadman, D. W. & Justice, L. J. 1998. Prehistoric exploitation of birds on Mangareva, Gambier Islands, French Polynesia. *Man and Culture in Oceania* **14**, 81–98.

Steadman, D. W. & Kirch, P. V. 1990. Prehistoric extinction of birds on Mangaia, Cook Islands, Polynesia. *Proceedings of the National Academy of Science USA* **87**, 9605–9.

St. John, H. 1935. Report of Harold St. John, Botanist. *In* Gregory, H. E. *Report of the Director for 1934. Bernice P. Bishop Museum Bulletin* **133**. Honolulu.

Stoddart, D. R., Spencer, T. & Scoffin, T. P. 1985. Reef growth and karst erosion on Mangaia, Cook Islands: A reinterpretation. *Zeitschrift für Geomorphologie* **57**, 121–40.

Taomia, J. M. E. 2000. Household units in the analysis of prehistoric social complexity, Cook Islands. *Asian Perspectives* **39**, 139–64.

Tilly, C. 1998. *Durable Inequality*. Berkeley, California: University of California Press.

Vitousek, P. M. 1995. The Hawaiian Islands as a model system for ecosystem studies. *Pacific Science* **49**, 2–16.

Vitousek, P. M. 2002. Oceanic islands as model systems for ecological studies. *Journal of Biogeography* **29**, 573–82.

Vitousek, P. M. 2004. *Nutrient Cycling and Limitation: Hawai'i as a Model System*. Princeton, New Jersey: Princeton University Press.

Vitousek, P. M., Chadwick, O. A., Crews, T., Fownes, J., Hendricks, D. & Herbert, D. 1997. Soil and ecosystem development across the Hawaiian Islands. *GSA Today* **7(9)**, 1–8.

Vitousek, P. M., Chadwick, O. A., Matson, P. A., Allison, S., Derry, L. A., Kettley, L., Luers, A., Mecking, E., Monastra, V. & Porder, S. 2003. Erosion and the rejuvenation of weathering-derived nutrient supply in an old tropical landscape. *Ecosystems* **6**, 762–72.

Vitousek, P. M., Ladefoged, T. N., Kirch, P. V., Hartshorn, A. S., Graves, M. W., Hotchkiss, S. C., Tuljapurkar, S. & Chadwick, O. A. 2004. Soils, agriculture, and society in precontact Hawai'i. *Science* **304**, 1665–9.

Wagner, W. L. & Funk, V. A. (eds) 1995. *Hawaiian Biogeography: Evolution on a Hot Spot Archipelago*. Washington DC: Smithsonian Institution.

Walker, T. W. & Syers, J. K. 1976. The fate of phosphorus during pedogenesis. *Geoderma* **15**, 1–19.

Weisler, M. I. 1996. An archaeological survey of Mangareva: Implications for regional settlement models and interaction studies. *Man and Culture in Oceania* **12**, 61–85.

Weisler, M. I. & Green, R. C. 2001. Holistic approaches to interaction studies: A Polynesian example. *In* Jones, M. & Sheppard, P. (eds) *Australasian Connections and New Directions: Proceedings of the 7th Australasian Archaeometry Conference*, 413–47. *Research Papers in Anthropology and Linguistics* **No. 5**. Auckland, New Zealand: University of Auckland.

Worthy, T. W. & Tennyson, A. J. D. 2004. Avifaunal assemblages from Nenega-Iti and Onemea. *In* Conte, E. & Kirch, P. V. (eds) *Archaeological Investigations in the Mangareva Islands (Gambier Archipelago), French Polynesia*, 122–7. *Archaeological Research Facility Contribution* **No. 62**. Berkeley, California: University of California.

Yen, D. E. 1973. The origins of Oceanic agriculture. *Archaeology and Physical Anthropology in Oceania* **8**, 68–85.

Yen, D. E. 1974. *The Sweet Potato and Oceania. Bernice P. Bishop Museum Bulletin* **236**. Honolulu.

Ziegler, A. C. 2002. *Hawaiian Natural History, Ecology, and Evolution*. Honolulu: University of Hawai'i Press.

MS received 23 December 2005. Accepted for publication 24 July 2006.