Journal of Anthropological Archaeology 51 (2018) 173–186

Contents lists available at ScienceDirect

Journal of Anthropological Archaeology

journal homepage: www.elsevier.com/locate/jaa

The prevalence and importance of niche construction in agricultural development in Polynesia

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ARTICLE INFO

Keywords:
Agriculture
Niche construction
Adaptation
Polynesia

ABSTRACT

The practice of cultivation has an immediate and long-lasting effect on the environment. Often, we tend to think of these effects in terms of immediate production outcomes, notably increased plant production. However, such modification of the environment has the potential to directly influence of rate and trajectory of agricultural development more generally. Using niche construction, a concept that has proven effective to understand subsistence change elsewhere, we examine pathways of agricultural change in Polynesia. We highlight the prevalence of niche construction in agricultural trajectories in the region, using both a summary of evidence through Polynesia as well as a targeted case study, and illustrate a framework for organizing those trajectories. In doing so, we build on previous attempts at examining the relationship between cultivation and adaptation in the region, which, given that Polynesia is thought of as a model system for investigating human-environmental relationships, can be used as a more general model of agricultural change globally.

1. Introduction

No concept has been more important to the study of agricultural change, both past and present, than intensification. Defined as increased labor or capital inputs per unit of land (Brookfield, 1972), intensification provided Boserup (1965:13) a general framework for the study of agricultural change. The concept of intensification spurred the development of an archaeology of agriculture (see Morrison, 1994), creating a research environment where general patterns of agricultural change in different areas were increasingly compared. While intensification has been undoubtedly useful in archaeology, important critiques have been made of both the fundamental assumptions of the original intensification model (Morrison, 1994) and the general usefulness of the concept in archaeology itself (Leach, 1999). Intensification is often part of a typological scheme (after Morrison, 1996) used for broad comparative purposes, but frequently lacking a clear definition (Leach, 1999). Such a typological approach often views variation between intensive and non-intensive agriculture in transformational or essentialist terms (cf. Hart, 1999). These critiques have led to calls to identity alternative ways to conceptualize agricultural change (Brookfield, 2001), especially those alternatives that integrate process and history (Kirch, 1994).

Niche Construction Theory (NCT) (Odling-Smee et al., 2003) provides a useful alternative to intensification for the investigation of archaeologically identifiable agricultural behaviors. Niche construction concerns the ways in which the actions of organisms impact the selective environment of themselves and other organisms. Since cultivation is simply the manipulation of the environment to create conditions for another organism to survive, niche construction is a logical perspective to underpin the archaeological investigation of changing cultivation practices. The premises and potential applications of this framework have been thoroughly examined in the discipline (e.g., Brock et al., 2016; Broughton et al., 2010; Laland and O'Brien, 2010, 2011) and several researchers have begun to investigate agricultural change and other subsistence activities as niche construction (e.g., Collard et al., 2011; O'Brien and Laland, 2012; Rowley-Conwy and Layton, 2011; Scarborough, 2015; Smith, 2007, 2009; Terrell et al., 2003; Wilkinson et al., 2012, 2015; Zeder, 2012). These researchers have highlighted the long-lasting impacts of subsistence activities on environments, other biota, and the environmental and social context within which activities are practiced (e.g., political systems, soil nutrients, previous infrastructural development).

The power of humans to construct niches is exemplified by the ancient colonizers of the Pacific who transported their landscapes (Kirch, 1982), bringing with them plants, animals, and ideas that would transform their new island homes. Cultivation practices in Polynesia (Fig. 1) are variable, reflecting colonization histories, environmental variation, and changing social and cultural practices within related

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https://doi.org/10.1016/j.jaa.2018.06.007
Received 9 February 2018; Received in revised form 23 June 2018
Available online 27 July 2018

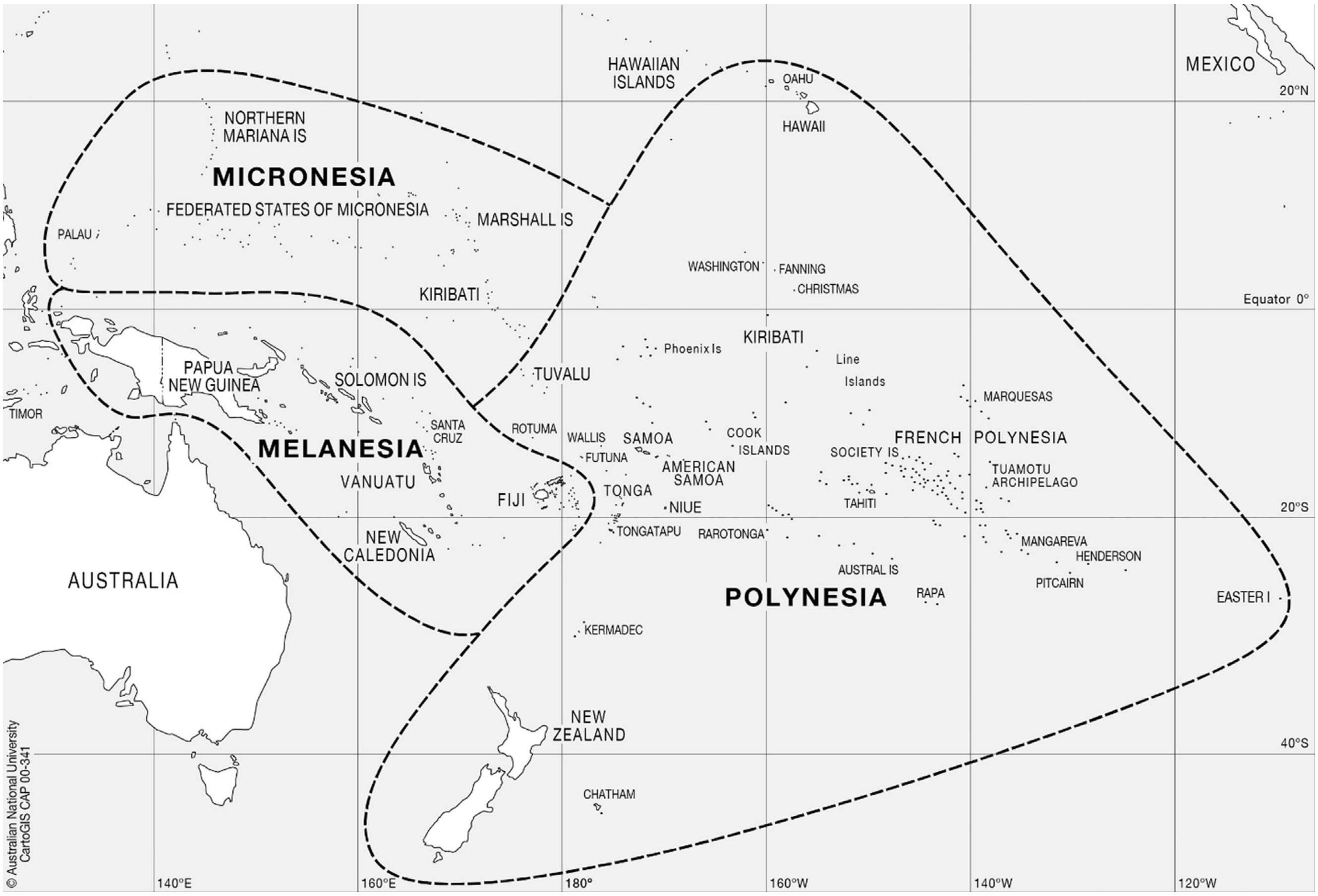

Fig. 1. Oceania with Polynesia defined and island groups identified.
Source: CartoGIS services, College of Asia and the Pacific, The National University of Australia

populations inhabiting relatively bounded island ecosystems. Because of this, agricultural practices in Polynesia are a potentially important example of how niche constructing activities have affected the evolution of subsistence systems and socio-ecosystems more generally. Polynesia is not the only region of Oceania where niche construction occurred, as similar practices and sequences also developed in Melanesia and Micronesia. However, here we are using Polynesia as a case study to illustrate these region-wide patterns. In the following section we summarize NCT, paying particular attention to aspects relevant to agriculture. In subsequent sections, we review agricultural change in Polynesia highlighting the fit with niche construction expectations and provide a detailed example from Tikopia to highlight the importance of niche construction in sequences of agricultural change. We conclude by suggesting ways to improve our understanding of the constructed landscapes created through agricultural economies in Polynesia by integrating process and history through the conceptual framework of NCT.

2. Niche construction

Lewontin (1982) has long argued that the organism and environment co-evolve. Notably the organism has the ability to modify the environment, actively creating its own selective pressures, which then feedback on future generations. Defined by Laland et al. (2015:4), "niche construction refers to the process whereby the metabolism, activities, and choices of organisms modify or stabilize environmental states, and thereby affect selection acting on themselves and other species." In general, niche construction relates to the evolution of the context of development. Tenets of niche construction acknowledge the influence of past actions in shaping the physical and cultural environments that affect behavioral change by modifying the relative benefits of one path of development or another (Laland et al., 2014). This ability to influence the direction and rate of evolution through behavior is not a restricted process, but, rather, nearly universal (Odling-Smee et al., 2003:18).

Niche construction works in two ways: relocation and perturbation (Odling-Smee et al., 2003; see also discussion in Laland and O'Brien, 2010:306–307). Relocation is simply the movement of a group of organisms to a new habitat. The new habitat, with different environmental characteristics, often exhibits new selective pressures. In reference to humans, a hypothetical scenario may involve a coastal to inland population movement: a move that includes responses to new niches, defined as the sum of the habitat requirements and behaviors allowing a species to persist, and potential hazards. With respect to cultivation, these new environments might feature hazards, topography, or soils that favor certain cultivation techniques or strategies[1] over others. Alongside relocation, perturbation relates to the ecosystem engineering capacity of organisms, humans especially. Ecosystem engineering is the ability of organisms to control the availability and abundance of resources in their ecosystem (Jones et al., 1994), which then affects other organisms. The environment can be manipulated to suit the organism and this modified environment is then inherited by

[1] Terms such as strategy and technique have no generally accepted archaeological definition. Here we use technique to mean a single behavioural class that has a definitive archaeological signature, such as lithic mulch or pondfield. Strategies refer to groups of behaviors, such as those that increase labor inputs or expand areas under cultivation, undertaken for a desired outcome (e.g., increased production, decreased variance). Strategies might have unknown or undesired consequences in conjunction with or absent of the desired outcomes.

future generations (Sterelny, 2005). However, outcomes also might negatively affect populations and human intentions can be decoupled from selective pressures. Such long-term and unforeseen consequences are typical of complex human systems (van der Leeuw, 2013), under which agriculture would fall.

The human niche is made up of both ecological and cultural elements (Laland and O'Brien, 2010:307–310, 2011), and the changing cultural context of a human population may impact the diversity and rate of change of behaviors (e.g., Fuentes, 2014, 2016; Sterelny and Watkins, 2015). The human cultural context might, for example, include changed socio-political relations (Shennan, 2011). The concept of niche construction is centered on inheritance, as it is inheritance that allows for the accumulation of the consequences of cultural and environmental change. The inheritance of both cultural variants and modified environments augment the selective pressures or general socio-environmental context under which future behaviors occur. This is in addition to the environmental changes that take place absent of human involvement. Moreover, populations inherit cultural variants that are filtered or edited through generations (Jablonka and Lamb, 2005).

What makes long-term agricultural practice a particularly useful example of niche construction is the fact that forms of cultivation, and other types of human activity, create legacy effects that influence how, when, and where cultivation is practiced (Arroyo-Kalin, 2016; Lansing, 2007; Morrison, 2006; Spriggs, 1986). This is a byproduct of human attempts to create conditions suitable for plant growth (Terrell et al., 2003:330–331) and is especially true of landesque capital investments. Defined as investment in permanent landscape modifications that enhance production, through increased yield or long-term stability (Blaikie and Brookfield, 1987; see also Håkansson and Widgren, 2014), landesque capital investments exhibit high front-end labor costs but the continued costs of maintenance are less. Recent research on landesque capital modifications, both in the form of large scale earthworks such as terraces and more modest changes in soils, have shown that these are resources for future use (Morrison, 2014:57), which become historically entangled in lineages of agricultural change. In this sense, the consequences of changing cultivation techniques in the past may become part of the cause of future changes in cultivation techniques. Such landesque capital is often the result of short-term labor investments in infrastructure, but these modifications can also accumulate at a landscape scale across longer time ranges as well. As model systems for the investigation of human-environmental relationships and agricultural development (e.g., DiNapoli et al., 2018; Kirch, 2007; Vitousek et al., 2004, 2014), Polynesian islands present a useful case study of the use of niche construction concepts to explain agriculture and associated subsistence change (Allen, 2013). We begin by discussing the behaviors indicative of niche construction and then highlight both the importance of recognizing niche construction through a case study, and the novel expectations that are generated.

3. Describing agricultural variation in Polynesia with niche construction concepts

Cultivation practices in Polynesia most likely arose through descent with modification from ancestral populations in the west: Tonga, Sāmoa, Fiji and others (Yen, 1973). Kirch (1982) proposed some time ago that many of these modifications to ancestral agricultural techniques in particular island environments are explained by adaptation, in the sense of populations responding to new environmental and social pressures. Given the emphasis on adaptation in explanations of agricultural variation in Polynesia (Kirch, 1980, 1982), it is logical to consider agricultural adaptation in the region from a niche construction perspective (see Day et al., 2003). This review is not exhaustive, but it demonstrates the applicability of niche construction concepts.

3.1. Construction and accretion of an agricultural niche

The environment of Polynesia, particularly terrestrial biodiversity, is influenced by island isolation and size (MacArthur and Wilson, 1967), with few naturally occurring edible plants and a limited range of birds and bats (Dye and Steadman, 1990). However, colonists to all Polynesian islands brought with them animals and plants, some domesticated and some not. Perhaps more importantly, though, these same colonists brought with them ideas related to cultivation techniques and strategies, among other things. The *relocation* of this collection of ideas and crops is referred to as a transported landscape (Kirch, 1982). In addition to primary cultivars, settlers to these islands also brought with them medicinal, building, and decorative plants (Whistler, 2009). These transported and constructed landscapes were the baseline from which agriculture developed on each island or in each archipelago.

Island landscapes began to be manipulated and modified as soon as they were colonized by human populations. Much of this change resulted from the clearing and burning of vegetation to create garden and habitation spaces but that also resulted in erosion, sedimentation, and vegetation change (e.g., Athens and Ward, 1993; Kahn et al., 2015b; Kirch, 1994; Kirch and Yen, 1982; Lepofsky et al., 1996). Erosion and deposition of sediments resulted in modification of existing soils, both on the hillslopes where cultivation was originally practiced, and along coastlines where eroded sediments were deposited as alluvial and colluvial soils. This process was of such influence that folk soil taxonomies included reference to the results. On Niuatoputapu, for instance, the *fasifasi'ifeo* soils were created by the mixture of eroded terrigenous sediments, calcareous sands already present on the beach, and organic refuse from past occupation on the coastal beach ridge (Kirch, 1988). This soil was highly arable and one of the most productive environments on the island.

Burning and other clearing of vegetation led to deforestation on some islands (Atkinson et al., 2016; Rolett and Diamond, 2004), while on others the structure of the forest changed dramatically, with native species being replaced with economic introductions (Kirch, 2007). On most islands, economic species of trees replaced portions of native forests (Dotte-Sarout and Kahn, 2017; Huebert, 2014; Huebert and Allen, 2016; Kirch, 1994; Kirch et al., 2015; Lincoln and Ladefoged, 2014), and agroforestry techniques have been documented to extend across almost the entirety of small islands (Kirch, 2007:90). Arboriculture takes advantage of the arboreal niche (Latinis, 2000), counteracting the effects of limited land area. These practices might sometimes be conceptualized as landesque capital, part of a constructed environment that persists for future generations and explicable in terms of large, but delayed, returns (see discussion regarding arboriculture in Terrell et al., 2003).

The translocation of plants and animals to islands was far from uniform, a situation that Yen (1973:76) describes as involving both reassortment and resegregation. Of particular impact was the introduction and eventual prehistoric distribution of sweet potato (*Ipomoea batatas*) in Eastern Polynesia. Whereas colonizers from the west brought with them tropical plants of Near Oceanic origins, the introduction of sweet potato into Eastern Polynesia from South America around 800–600 years ago (Kirch, 2017; Ladefoged et al., 2005; Roullier et al., 2013), offered an opportunity to cultivate in a drier and cooler environment. This is best illustrated by the importance of the crop in subtropical-to-temperate New Zealand where tropical plants, such as the otherwise ubiquitous taro (*Colocasia esculenta*), had a restricted distribution and were not as productive as elsewhere in Polynesia (Furey, 2006:13). In fact, even the cultivation of sweet potato is limited south of the Banks Peninsula on South Island (Bassett et al., 2004; Furey, 2006:10–11). Without the introduction of sweet potato, it is unlikely that New Zealand population densities seen in prehistoric times, especially in the North Island, could have been realized. The introduction of sweet potato had similar impacts in Hawaiʻi and Rapa

Nui. Given water requirements, taro is difficult to cultivate in leeward areas of young volcanic islands in Hawai'i and throughout much of the island of Rapa Nui. The lower water requirements of sweet potato opened up new areas of cultivation, promoting the expansion and increase of human populations as well as surplus production (McCoy, 2006:312–313; Wallin et al., 2005). In the Hawaiian case, it is clear that this expansion of agricultural productivity created the context for the development of large-scale political economies in late pre-contact times (Kirch, 2010), at least after some level of initial experimentation and uncertainty (Ladefoged and Graves, 2000:441).

No commensal species had more of an impact on oceanic islands than rats (*Rattus exulans*). Rats have been variously linked to island deforestation and bird extinctions on a range of islands (Athens, 2009; Athens et al., 2002; Hunt, 2007; Kirch, 2007; Leppard, 2018; Swift et al., 2017). Not only does this modify the local ecosystems of these islands, it changes the context within which human populations lived by contributing to the loss of a protein source (birds) and contributing to the decline of raw materials (wood). It is not a stretch to infer that these changes unintentionally modified the cultural trajectory of island societies, notably Rapa Nui (Hunt and Lipo, 2009). Destruction of forest would have opened additional lands for agricultural production, though the loss of raw materials would have been detrimental and the loss of forests would have changed the water balance of the island as effects accumulated through time. In addition to loss of a protein resource, reductions of seabirds would have placed a constraint on nutrients available for intensive agriculture (Kirch, 2007:94; Swift et al., 2017:12), as bird guano is an important source of phosphorus and nitrogen on old, nutrient-depleted geological substrates.

While the introduction of exotic species has modified island agricultural niches, nothing speaks to the niche construction capabilities of human groups in the Pacific more than infrastructural developments in these different environmental settings. To some extent, these infrastructural developments allowed agriculture to be practiced in more "marginal" lands, thereby increasing productive capacity (McCoy and Graves, 2010). In several places, populations constructed agricultural lands through the manipulation of water flow (Kirch and Lepofsky, 1993), both within and outside stream systems, using a variety of techniques such as the diversion of streamflow into canals and the construction of pondfield terraces (Clark, 1986; Kirch, 1977; Lepofsky, 1994). In these cases, construction was geared toward the creation or expansion of land suitable for the growth of taro and other crops. Few areas of Polynesia are more marginal in a terrestrial environment sense than coral atolls. There, cultivation focused on more saline tolerant crops (e.g., *Cyrtosperma* sp.) and required that farmers tap into the small fresh water lens by digging pits (Chazine, 2012). Because sediments on these atolls are calcareous, cultivation required the creation of suitable soils through organic mulching (Barrau, 1961, 1965).

Construction was not restricted to perpetually wet landscapes, however, and dryland or mixed zone infrastructure has been noted to serve important functions to counteract environmental pressures encountered in newly cultivated environments. Intermittent irrigation systems are known from Waimea in Hawai'i (Clark, 1986), which use similar technologies as other irrigation systems but take advantage of the unique ecology of Waimea that includes intermittent streams to increase the area of production (McIvor and Ladefoged, 2018). Barrage systems in intermittent streams that channel or trap periodic water to extend cultivation are known for the Society Islands as well as Hawai'i (Kahn et al., 2015a; Kirch, 1977; Lepofsky, 1994). In contrast, more dryland oriented drainage systems are known from Sāmoa and New Zealand (e.g., Barber, 2004; Ishizuki, 1974; Quintus, 2015), where the cultivation of dryland taro necessitated the use of ditches to protect crops from excess surface runoff. It is hypothesized that cross-slope ditches that limited the amount of water running across the surface of steep gardens increased the build-up of soils and reduced erosion (Quintus et al., 2016) (Fig. 2).

Many of these dryland systems, especially on high islands, made use

Fig. 2. A cross-slope ditch on the island of Ofu. The ditch would trap and move water and sediment around the cultivated plot reducing erosion.

of terraces to stabilize slopes and retain moisture (Allen, 2004). Kurashima and Kirch (2011) have noted the importance that these terraces might have played in Hawai'i to take advantage of rejuvenated, nutrient-rich colluvial soils in windward regions. Beyond their ability to improve growing conditions, these terraces also created marked landscapes that probably made management more efficient or at least easier (Yen, 1973:124). In this respect, dryland terraces might have served as gardens tied to particular families or groups in the Society Islands (Lepofsky and Kahn, 2011).

The use of low walls or embankments in dryland systems has been noted in several locations (Barber, 2004; Kirch, 1994; Leach, 1976; Sullivan, 1985), though they are best documented in Hawai'i (Fig. 3). Hawaiian dryland farming techniques were constrained by a set of ecological factors, notably the intersection of substrate geology and precipitation (Kirch, 2011; Lincoln et al., 2014; Vitousek et al., 2004, 2014). These conditions created sweet-spot zones where agriculture was possible and productive, which are today predictable (Ladefoged et al., 2009). While finding these sweet spots was essential for farming, and certainly structured the development of these techniques, the manipulation of the environment was also critical for cultivation. Here, populations invested in low stone and earthen embankments or linear mounds that, with the added height created by the planting of sugarcane (*Saccharum officinarum*) counteracted the effects of persistent winds in places such as the Kohala peninsula (Ladefoged et al., 2003:927). These techniques were largely geared toward the production of sweet potato and some dryland taro, with more minor crops also

Fig. 3. The Leeward Kohala Field System (LKFS). The visible field ridges acted to modify wind movement in such a way to increase soil moisture on the inland side of the field ridged. The site extends across an area as large as 60 km^2 (photograph courtesy of Noa Lincoln).

Fig. 4. A sunken pit cultivation technique on Rapu Nui. The sunken nature of the feature would limit evapotranspiration (from Morrison, 2012; courtesy of Alex Morrison).

planted. Since sweet potatoes grow low to the ground, even low embankments grown with sugarcane help mitigate the effects of wind damage and maintain soil moisture by reducing evapotranspiration. The incorporation of sugarcane likely played an additional role as a soil additive, as mulching with decomposing sugarcane leaves was an important source of nitrogen (Lincon and Vitousek, 2016).

Agronomic techniques on the island of Rapa Nui, notably lithic mulches, boulder gardens, and pits (Fig. 4), acted in a similar way to reduce variability in soil moisture and temperature (Morrison, 2012; Stevenson et al., 2002; Wozniak, 1999). These techniques possibly also acted to accelerate nutrient transfer from rock additions to the soils (Ladefoged et al., 2010; Vitousek et al., 2014), as production on Rapa Nui, too, was spatially restricted by ecological constraints similar to those in Hawai'i (Ladefoged et al., 2013). Additives to soils, either lithics or shell, were made in New Zealand (Barber, 2004, 2010, 2013; McFadgen, 1980). Both shell and stone additives likely maintained soil structure and soil moisture, and may have warmed plants and suppressed weeds (Barber, 2013:38). The warming of soils and plants might have created conditions for longer growing seasons, which would have been particularly important in the southern North Island and northern South Island of New Zealand.

3.2. Ecological inheritance

At times agricultural techniques were structured by historical contingencies (e.g., crop relocations) and relatively stable ecological conditions (e.g., soil phosphorus), but limiting factors to agriculture were also mitigated by creating environments that mimicked naturally productive settings. The ability of artificial environments to influence productivity has been demonstrated through agricultural productivity modelling (e.g., Puleston and Tuljapurkar, 2008; Puleston et al., 2017). Combining productivity modelling with agricultural infrastructure chronologies, Ladefoged et al. (2008) determined that the construction of agricultural plots in one section of the Kohala Field System on Hawai'i Island developed to maximize surplus agricultural production, at the expense of lowered life expectancy for farmers. This and other agricultural strategies produced new social and environmental contexts for the subsequent development of agricultural techniques. As Morrison (2007:238) relates, changes to cultivation practices often “immediately ramify and create new conditions for production.” These possible changes in selective pressures are the result of past activities and possible changes in the use of pre-existing cultivation techniques (i.e., exaptation, after Gould and Vrba, 1982).

The pattern of erosion and sedimentary deposition caused by initial shifting cultivation is one such past development that influenced agricultural change on many islands, often in conjunction with natural landscape evolution (Spriggs, 1997:100). On Ofu Island in the Samoan archipelago, the mixing of terrigenous sediments with organic refuse and calcareous sands created a new arable environment used for root and tree crop production by at least the end of the 1st millennium AD (Kirch and Hunt, 1993; Quintus, 2018). A similar, and more apparent, process played out on Niuatoputapu and Futuna where these anthropogenic soils allowed for additional land to be put under cultivation (Kirch, 1988, 1994). The pattern of erosion and deposition acted to replenish important nutrients on old geological substrates in other places, resulting in a cultivation technique centered on colluvial slopes, as on Moloka'i Island in Hawai'i (Kurashima and Kirch, 2011). While we have focused on the positive effects of human construction, it is important to note that some forms of intensive cultivation resulted in nutrient depletion (Meyer et al., 2007). These outcomes were inherited by subsequent generations as well, with potential results including the need to increase labor inputs, as in conventional cropping cycle intensification (after Kirch, 1994).

Some of these historical sequences also created conditions for investments in landesque capital. Notably, deposition of sediments created fertile alluvial plains conducive to the construction of irrigation networks on several tropical Pacific islands, both in and outside of Polynesia (Kirch, 1994:227; Spriggs, 1981, 1997). In this way, the deposition of sediment probably modified the selective environment to favor the construction of landesque capital, typically in the form of irrigated terraces. Key to this is that sediment deposition, brought about by human-induced environmental perturbation, changed the evolutionary costs and benefits of corporate-built irrigation systems.

These investments in infrastructure have the capacity to bring about fundamental changes in the social relations of production. Often, infrastructure inscribes the land and lends greater visibility and permanence to land boundaries, at least to some extent. In relation to capital investment in the Andes, Erickson (1993:411) argues:

> What raised fields and other landscape capital systems did was to tie farmers to the land, making them relatively immobile and subject to labor taxes and tribute. Such a situation is beneficial to the state in that such farmers can easily be controlled and labor and goods can easily be expropriated for the elite's purposes.

This seems to be a general process in Polynesia as well. In several archipelagos and on several islands, emergent elites took advantage of previously developed techniques that incorporated agricultural infrastructure (Ladefoged et al., 2008; Lepofsky and Kahn, 2011). On Ofu, Sāmoa, variation in the location of storm drain structures changes from a principal association with singular households to an increasing association with what appears to be supra-household lands in socially prominent positions likely under the control of elites (Quintus et al., 2016). Concurrent with variation in spatial patterning is increased variation in the scale of the complexes themselves, from predominantly single ditches with a single cultivated parcel to a network of ditches and multiple parcels. In short, cultivation techniques that developed within a particular environmental and social context also created conditions that might favor changes in the social relations of production, further technique changes, and an increase in different production strategies.

Studies of agricultural change in recent years have increasingly drawn attention to the relationships between different strategies that are important for the functioning and persistence of agricultural systems (Bruno, 2014). The proliferation of a cultivation technique may be tied to the performance of other techniques, a point that is not well considered in discussions of intensification. Often different cultivation techniques have different constraints, and the presence of multiple, integrated techniques spread across different environments may create emergent benefits not realized by the techniques individually. The changing temporal and spatial distributions of some techniques can also alter the selective environment for others. Addison (2008) has discussed the changing role of wet taro production in the Marquesas, hypothesizing an agricultural trajectory that was influenced by the relationship between tree cropping and root crop cultivation. An initial focus on wet taro provided a quick return for Marquesan colonists, but over time arboriculture, with its intrinsically delayed returns, increased in frequency and provided substantial subsistence output. A relationship between the development of arboriculture and other forms of cultivation is hinted at in Hawai'i as well. Allen (2004:216) argued that the expansion of breadfruit in Kona, Hawai'i took advantage of an open agricultural niche, thereby increasing productive capacity and providing a source of diversification. The breadfruit zone of Kona provided a microenvironment for the cultivation of understory crops, largely sweet potato and paper mulberry, and was likely able to produce a larger surplus relative to labor inputs compared to dryland production (Lincoln and Ladefoged, 2014:200).

Pathways of agricultural change did not stop at European contact. While new crops and techniques were introduced after European and Asian populations entered the Pacific, remnants of past cultivation strategies continue to structure modern production, largely because of the environmental impacts brought about by cultivation. Modern populations still make use of the modified forests of their ancestors (e.g., Kirch and Yen, 1982), and are able to do so more efficiently than previously given the effects of cumulative labor in the past. Similar to the situation in precontact times, fertile back beach areas play a significant role in modern production, especially in wetlands areas (e.g., Tikopia, Niuatoputapu, Ofu). Infrastructure created by past generations continues to be used as part of high yielding strategies (Jones et al., 2015), and labor requirements to continue these strategies are relatively minimal. Techniques and strategies are subject to reimagining in some ways, but past infrastructure has provided the template for later use.

4. Niche construction and agricultural pathways in Polynesia

It is clear from the above that human populations in Polynesia modified their ecologies and those modified ecologies had an effect on future populations through the creation of novel selective environments. Within these sequences, broad patterns are apparent that are important for promoting comparison as well as deeper understanding. Kirch (1982, 1984) originally developed an evolutionary understanding of agricultural development in Polynesia comprising processes of adaptation, expansion, and intensification. The latter two components, intensification[2] and expansion, are strategies that incorporate or operationalize techniques. These strategies are goal directed, with both intended and unintended consequences. Intensification, expansion, and other agricultural strategies modify niches, the archaeologically visible results of behaviors associated with manipulating planting environments. Because these strategies and techniques are niche constructing activities that may influence selection processes, they can be conceptualized using components of NCT. Because of this, we build on Kirch's original division and, based on the framework of NCT and the last several decades of empirical work on Polynesian agriculture, propose that relocation, perturbation, and feedback may be more effective ways to conceptualize and order trajectories of agricultural change in the region. These can, and often do, occur in non-linear relationship and there is no inherent unilineal pathway that follows from relocation, perturbation, and inheritance. These characteristics of niche construction lead to the multi-linear pathways that agricultural systems in Polynesia follow (see Kirch, 1994).

[2] We do not view intensification as an explanatory process in its own right. Intensification is better described as an agricultural strategy or outcome since it is goal directed and involves a plan of action to achieve that goal. Intensification can be part of pathways of agricultural development, but does not explain them.

4.1. Relocation: responding to novel context

Relocation through colonization was a fundamental factor in the creation of agricultural variation in Polynesia by exposing populations to new environments and pressures. In line with expectations of NCT (Laland and O'Brien, 2010), such relocation created marked variation early in cultural sequences. As has been noted by several researchers (e.g., Kirch, 1982; Yen, 1973), the movement of peoples across the Pacific influenced cultivation techniques and strategies. Not only are stochastic processes important in the evolution of these techniques and strategies, as some crops, animals, or techniques did not always get transferred to different colonized islands, but each crop, animal, and technique was placed within a new environment and consequently subject to potentially different selective pressures of that new environment. The same impacts of relocation were realized in each subsequent relocation on individual islands. Importantly, variation in the practice of cultivation developed when populations began to live in markedly different ecological zones on single islands. This process is typified by the expansion of tropical agricultural practices into temperate New Zealand (Kirch, 1982:2). Additionally, movement from coastal to inland areas exposed groups to new environmental pressures, resulting in novel cultivation strategies (e.g., Quintus et al., 2016), that built on or from known strategies (e.g., wet land ditching).

A key evolutionary process of organisms is the ability to use previously generated traits or characteristics in novel ways, termed exaptation (Gould and Vrba, 1982). This is apparent in the case of agricultural infrastructure, where the same infrastructure was used in markedly different ways in different contexts. Hawaiian linear mounds highlight this potential (see Lincoln and Vitousek, 2017:19). In the Leeward Kohala Field System, these linear mounds trap mist and provide a windbreak, enhancing soil moisture. In contrast, in Kona, similar infrastructure might have been built to manage solar radiation. Such functional flexibility is important to niche constructing organisms given the fact that it can translate into rapid variation, enabling "fit" with their new environmental context (see Laland et al., 2015).

This calls attention to a rethinking of the definition of innovation in technological systems as the majority of such innovations were dependent on the inheritance of previous systems of cultivation, though some exceptions to this might be present (e.g., genetic changes to plants (Kirch, 2006)). In the majority of cases, innovation involved the retooling of previous technologies in order to meet the challenges of a new selective environment, which created variation. This is well illustrated by variation in wetland, irrigated, or barrage systems. All systems in the region make use of similar underlying technologies and infrastructure in order to function in new ecologies. Kirch (1977) and Clark (1986) detail such variation in Hawai'i, explicitly linking these to local ecological conditions. While McCoy and Graves (2010) argue that at least some of these techniques should be thought of as innovations, their prevalence in East Polynesia (see Kahn et al., 2015a:372–374) is better understood as adaptive radiation of an inherited technological system into new selective environments (Cochrane and Jordan, 2017). Such sequences result in the accumulation of novel variants that are transmitted to subsequent generations. Certainly, technological elements are added to this repertoire, such as new ditch types or new terrace types, but those build on and are dependent upon previously inherited techniques and newly experienced selective environments.

All plants have ranges of environmental attributes within which they can grow, often associated with where those plants were first domesticated. The goal of a producer when relocated is to re-create that range of environmental attributes that result in desired yields. This is often the point of the construction of infrastructure and cultivatable surfaces. Constructed soils are well known throughout the region as the sum result of terrigenous deposition on coastal plains, *in situ* calcareous sediments, and organic debris from previous land use (Kirch, 1988, 1994; Kirch and Yen, 1982). Other types of anthrosols with lithic or shell additives have been identified on several islands, most notably

Rapa Nui and New Zealand (Barber, 2010; McFadgen, 1980; Stevenson et al., 2002; Wozniak, 1999). As Barber (2010:85) notes, such construction of anthrosols can be seen as experimentation from a diverse range of techniques translocated to new environments. Such experimental construction was true for a variety of techniques and continued through cultural sequences. Experimental construction is also evident in the relationship between relatively static environmental conditions and micro-scale variations in Hawai‘i. Within the broad ecological characteristics of the wet and dry, biogeochemical gradients affected the ability to practice certain cultivation strategies in some locations (Kirch, 2011; Ladefoged et al., 2009; Vitousek et al., 2004, 2014). While the biogeochemical gradients were clearly influential in Hawai‘i, long-term cultivation was made feasible by the modification of these biogeochemical gradients at the microscale through soil additives (Lincoln and Vitousek, 2017). Most telling, farmers in Hawai‘i are recorded to have mulched pits within lava flow fields to create conditions of increased fertility (Handy et al., 1972), a practice that is markedly similar, though in a completely different environment and for a different reason, to pit cultivation on low-lying islands.

Niche construction changes agricultural pathways after relocation by extending or enhancing areas suitable for plant growth. In doing so, populations modify the long-term potential of these environments in such a way to enhance population fitness, if measured as growth and survival. The long-term growth and survival of populations involved adaptive radiation (Kirch, 1982), as the diversity of agricultural techniques and strategies in Polynesia owes much to the environmental variation in the region. Nevertheless, the sequence must also be understood as the radiation of the agricultural niche carried with and executed by populations moving through the region.

4.2. Perturbation: creating novel context

These transformed landscapes that allowed for the growth and survival of human populations were inherited by subsequent generations of producers, creating additional opportunities, constraints, and path dependency, which is the increased probability of one trajectory over another. In other words, the engineering of the ecosystem practiced through sequences of agricultural adaptation in Polynesia resulted in novel selective pressures that necessitated further response. As noted by Day et al. (2003:86–87), niche construction activities often lead to the elaboration of niche construction activities. This is true of cultivation systems in Polynesia, where niche construction activity was met with particular agricultural paths that took advantage and sought to regulate or maintain previously constructed niches.

The role of landscape change in constraining and enabling production is now well documented throughout Polynesia (e.g., Kirch, 1994, 2007; Spriggs, 1981, 1997). This process of landscape transformation was a product of human perturbation and resulted in the reconfiguration of the costs and benefits of cultivating areas of an island. On Futuna, for instance, shifting cultivation on steep hillsides early in the sequence led to erosion and sediment deposition that influenced formation of alluvial plains, making irrigated cultivation both feasible and productive (see Kirch, 1994:219–225). The benefits of irrigated cultivation relative to dryland production, namely higher productivity and lower labor inputs, reverberated throughout the social system and led, in part, to the development of a unique political economy. It was the inheritance of the transformed or perturbed environment that fed back to influence the formation of this social system.

The presence of past infrastructure biased the sequence of agricultural change. All landesque capital investments (e.g., infrastructure, long-lived economic plant species) save labor for future generations by preserving the effects of that labor on the landscape. The past investments can then be modified and built upon over subsequent generations, allowing the creation of more complex and productive agricultural landscapes through time. This is certainly the case of the largescale agricultural landscapes of Hawai‘i, where infrastructure was built upon and elaborated over generations to create their present configuration (Ladefoged and Graves, 2008; McCoy et al., 2017). In this case, the type of infrastructure built in previous times structured the long-term trajectory agriculture in that place. Tree crops are another form of such investment, which are transmitted to subsequent generations. Over generations, these economic or domesticated landscapes are modified and built upon, sometimes for the primary purpose of creating a landscape that is more useful for future generations (see Terrell et al., 2003).

The presence of infrastructure in some places would reduce labor costs of subsequent generations cultivating in that location, which would contrast in places where previous infrastructure had not yet been built. Competition for or control of these places should be greater relative to where investments had not been made, thereby biasing not only the direction of agricultural change but also political change. Such a prediction is empirically met in other parts of the world where previously built infrastructure was coopted by suprahousehold authorities (e.g., Erickson, 2006:353; Morehart, 2010:89), and is preliminarily supported by cases in Sāmoa (Quintus et al., 2016), Rapa Iti (DiNapoli et al., 2018), and Hawai’i (Ladefoged and Graves, 2008:784–785). For Hawai‘i, it was the previous construction of infrastructure that enabled the construction of additional infrastructure, facilitating a particular agricultural strategy (increased production) associated with a re-definition of social relations (surplus extraction) (Ladefoged and Graves, 2008:784). If this is accurate, we should see evidence of sporadic investments in infrastructure followed by evidence of increased cooperation, as a manifestation of increased suprahousehold coordination. Cooperation is important for expanding and scaling up infrastructural investments, which may also set the stage for competition between groups for control of the means of production. The rise of political economies might not be related to controlling labor in some circumstances; it might relate to controlling the product of past labor.

The social system itself can be thought of as a perturbation in some circumstances. No matter the cause of the formation of certain social forms, those social forms structure cultural practices (e.g., by biasing cultural transmission). These legacy cultural forms have partly influenced the manifestation of chiefly power in the region (Allen, 2010; Kirch, 1984; Quintus et al., 2016). Furthermore, these social institutions themselves create the context for the practice of certain techniques, often because group cooperation and redistribution spreads risk (Kirch, 1984: 260). As Ladefoged and Graves (2008) note, some agricultural developments were not potentially fitness enhancing until after the formation of larger political units and social networks. What these social forms provided in some cases was the opportunity for expansion. For Hawai‘i, many strategies of production were spread across large expanses of land (Allen, 2004:217–218). A strategy of expansion into more marginal lands became feasible as regional coordination counteracted selective pressures associated with a temporally variable environment (see Ladefoged and Graves, 2000:443).

4.3. Investigating feedback and inheritance

The empirical results of agricultural behaviors (e.g., eroded environments) and the agricultural behaviors themselves (e.g., shifting cultivation) are passed on by ecological and cultural inheritance, respectively (Laland et al., 2000), to subsequent generations of producers. The frequency with which the *results* (iterum e.g., eroded environments) are inherited is a function of demography, such as the distribution of individuals across space, and contingent environmental characteristics (e.g., high-slope environments). The frequency with which *behaviors* are inherited is, in part, also influenced by the culturally influenced environmental characteristics of constructed niches. Within this light, the primary deficiency of an intensification-focused model of agricultural change is the lack of explicit recognition of the importance of mechanisms of inheritance.

Cultural and ecological inheritance are important characteristics of causes of diversification through perturbation and relocation at the regional scale of Polynesia. Inheritance allows variants to feedback and affect future production. As has been noted by other researchers, a significant number of biological traits and components of technical systems begin as something different (Andriani and Cohen, 2013:8) and are augmented or exapted in present circumstances. This is true also of knowledge systems that depend on transmission to build upon previous developments (e.g., the adage of standing on the shoulders of giants; Mesoudi and O'Brien, 2008; Tehrani and Riede, 2008). The feedback that arises from behavioral modification to environments is visible in the accretionary characteristics of agricultural activities that has been increasingly recognized (e.g., Erickson, 2008; Lansing and Fox, 2011; Morrison, 2006, 2014). The results of agricultural practices are stored in palimpsest landscapes. These palimpsest landscapes, the product of both relocation and perturbation, are inherited by subsequent generations of producers.

Inherited behavioral variants, in this case cultivation techniques, interact with each other and further constructed niches (Laland et al., 2015:10). Consider, for example, the changing fitness differences between culturally inherited techniques of shifting cultivation and raised-field farming after many swidden farming cycles in an environment increasingly characterized by high erosion and low soil deposition (Fig. 5). The frequency of these behaviors in successive cultural and biological generations is caused by changing selection pressures associated with the constructed niche. The frequency by which behaviors are inherited will also be influenced by population demography (Premo and Scholnick, 2011; Grove, 2016) and transmission processes (Boyd and Richerson, 1985). Taken together, the causes of agricultural change in human constructed niches include the ecological inheritance of a continuously changing niche, cultural inheritance of agricultural behaviors, and selection of different behaviors. The strength of selection will vary as a product of feedback between previous behaviors and the results of these behaviors in the ecological niche (see Fig. 5).

The differential outcome of agricultural strategies may be summed up in the difference between cropping cycle intensification and landesque capital modification. These techniques, one environmentally extractive (e.g., depleting nutrients) and one environmentally additive (e.g., creating more land suitable for cultivation), have significant implications for future land-use practices. Landesque capital investments accumulate labor over multiple generations, with the possibility of *reduced* labor investment in that technique. The extractive nature of cropping cycle intensification depletes soil nutrients such that increased labor directed at fertilization, weeding, mulching, and other techniques of soil preparation is necessary. In these ways, the use of one of these two "modes of intensification" have fundamentally different repercussions for descendent farmers, which can have ramifications for social relations of production as well (e.g., food for more or less labor over the long-term). Focusing on the variable ecological impacts inherent in these strategies provides a foundation for understanding how each functions within a selective environment and the future consequences of that functionality.

Perhaps most importantly, NCT has significant implications for how we understand contemporary cultivation practices. Given the long developmental sequences embodied by these agricultural landscapes, it is becoming increasingly recognized that these techniques and strategies provide important sources of stored ecological knowledge that can be mined to increase modern resiliency and sustainability (Erickson, 2003; Lansing, 2007 for examples from outside of the Pacific). Investigations of niche construction provide an opportunity to understand the functionality of these systems in counteracting certain selective pressures as well as the consequences of different kinds of strategies and techniques. Both these elements are important to take into consideration while developing plans for future use of traditional agricultural techniques. Specifically, the use of these techniques today will be subject to a novel selective environment. In this context, it is unlikely they will function in the same capacity as they did in the past and their use may create additional consequences not previously recognized. This is true of all technological systems (van der Leeuw, 2013). Instead of replicating past techniques, this framework suggests that it will be important to recognize the inevitability of retooling in order to counteract the socio-ecological pressures present in modern times.

4.4. Case study: the role of niche construction on Tikopia

The cultural sequence of Tikopia provides a useful example. We think this is so for several reasons, notably given the island's small size

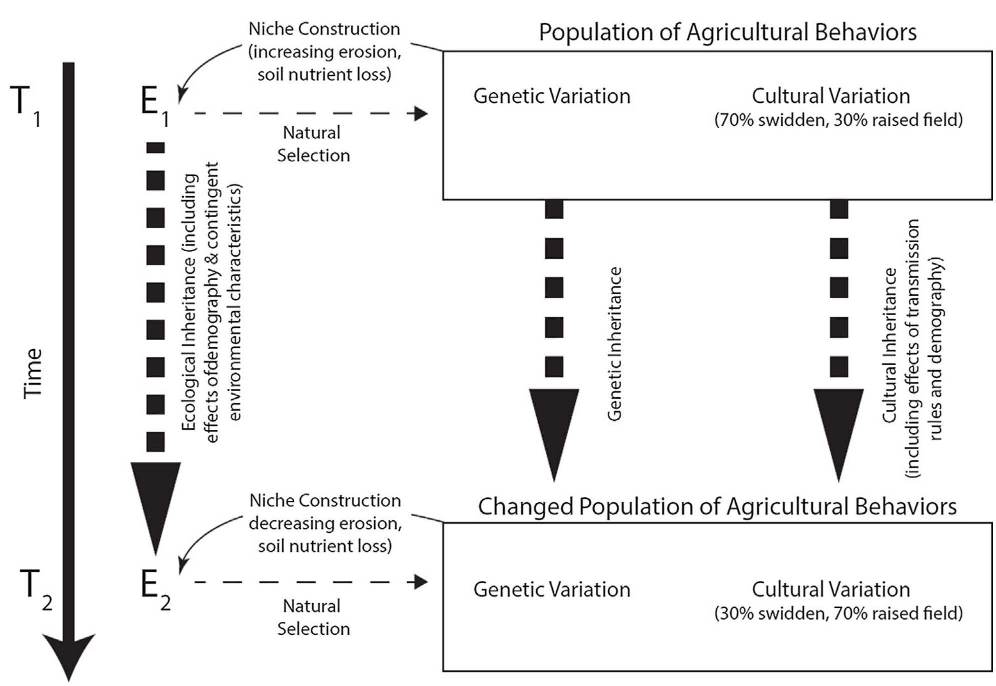

Fig. 5. Hypothetical schematic illustrating the role of inheritance in agricultural niche construction. E_1 and E_2 are environments at different points in time (figure modified after Laland and O'Brien, 2011).

and exceedingly well documented archaeological and ethnographic record (Firth, 1936; Kirch, 2007; Kirch and Yen, 1982). Further, and in general, the effects of niche construction are more apparent on a small island where even small scale changes to the environment are likely to ramify over space and time (Quintus, 2018) and sustaining habitation may have required substantial niche construction (Allen, 2013). Finally, Tikopia lacks general markers of intensification, such as irrigation systems, even though production on the island supported one of the highest population densities in the Pacific. The long-term development of the Tikopia food production system has been well-established (Kirch, 1994, 2007; Kirch and Yen, 1982). We build on this foundation by explicitly articulating the behavioral strategies that modified the selective context of future generations in the same location. By doing so, we demonstrate not just the feedback loops present in the sequence, which have been documented, but also why and how those feedback loops were created and what long-term effect those feedback loops had and continue to have on the island.

Tikopia was settled early in the 1st millennium BC by a Lapita pottery carrying or producing population (Kirch, 2007:89; Kirch and Swift, 2017). These people presumably were carrying at least some crops, though the exact roster of introductions is unknown (Kirch, 1994:296–297). Evidence of initial cultivation, in the form of sedimentation records, suggests of use of extensive shifting cultivation, involving fire (evidenced by charcoal in eroded sediments) that cleared slopes of mature vegetation. This clearance resulted in the significant erosion and deposition of volcanic sediments onto calcareous beach flats during the mid to late-1st millennium AD (Kirch and Yen, 1982:329), extending productive potential on the costal flats (Kirch, 2007:89; Kirch and Yen, 1982:348). Interestingly, these colluvial flats were not the product of a single event and were themselves constructed by erosion and deposition over a substantial period of time (Kirch and Yen, 1982:153–154). This pattern would have resulted in the continual replenishment of fertile soil onto previously cultivated spaces through a process of colluvial rejuvenation (see Vitousek et al., 2010). The end result of this process, whether intentional or not, was the expansion of agricultural activities. This simple sequence set the stage for future production-related activities on the island, as it was this modified environment that was inherited by future generations. A human created resource fundamentally augmented the selective environment of Tikopia in such a way to change the costs and benefits of cultivation and marine exploitation for future generations.

Natural geomorphological processes were affecting the island at the same time. Sea-level drawdown appears to have resulted in the expansion of the coastal flats and the decrease in reef area (Kirch, 2007:89). The effect, in conjunction with exploitation by human populations, was the decreased density or complete extirpation of several wild resources during the 1st millennium BC and 1st millennium AD (Kirch, 2007:284, 285, 297). This was true of both terrestrial and marine wild resources, with some bird species being extirpated (Steadman et al., 1990). Human response to these “natural” processes can only be understood by examining the intersection of these changes within the context of human construction activity and inherited production strategies. An obvious outcome of these circumstances was a lower reliance on wild marine and terrestrial resources by the human population. However, the novel ecosystems constructed on Tikopia created conditions for the practice of variable subsistence strategies that offset the pressures associated with the intersection of natural process, such as alteration of marine habitats, and cultural activities. The newly created colluvial flats formed by human-induced landscape change provided an area for agriculture that offset losses of productive shallow marine environments (Kirch, 1994), along with an increased reliance on domesticated pigs (Kirch and Yen, 1982:281). In other words, human niche construction made it advantageous to invest in terrestrial food production at this time.

Further perturbations of the environment occurred in the 2nd millennium AD, associated with the intrusion of populations from Polynesia along with associated material culture and techniques (Kirch and Swift, 2017). These people inherited landscapes that had been constructed by humans in the previous 2000 years or so. This resulted in the population encountering novel selective pressures that were the result of previous land use in conjunction with geomorphological change. This is in addition to not being subject to selective pressures to which the original inhabitants were exposed. An important aspect of this was that terrestrial landscapes were larger relative to previous times (Kirch and Yen, 1982:332), likely the result of continued human-induced erosion as well as natural sea-level fluctuations, creating additional land suitable for cultivation on the coastal plains. The new population introduced historically inherited techniques of production, perhaps from some region of West Polynesia, including pit fermentation technology for the storage of banana and breadfruit (Kirch and Yen, 1982:333). Building on the beginning of arboricultural development in the 1st millennium AD, the natural forest was almost completely replaced by economic trees and understory cultigens in the 2nd millennium AD (Kirch, 2007:90). It is this environmental modification that created conditions for increased population densities, and the arboricultural system of Tikopia has stood out as an example of a low-labor input system that produces high yields supporting a dense population (Firth, 1965; Kirch, 2007). While it is unclear whether the original erosion that resulted in the expansion of cultivatable lands was intentional, the process of intentional land reclamation in the historic period is well documented. Trees stabilize landscapes and Kirch and Yen (1982:40–41) note that the planting of tress to stabilize coastal landscapes was an important step in creating arable land. Notably, after vegetation is grown to aid stabilization, organic refuse can be thrown in among the trees to increase the fertility of that stabilized land. A similar process occurred on the lake edge. The persistence of novel forests on the island through ecological inheritance and their associated ecological functionality through time have resulted in the agroforestry strategy becoming an evolutionary stable strategy (definition after Orzack and Sober, 1994:365–366). In this case, such a stable strategy is the outcome of long-term human niche construction, including the erosion of hillslopes and the reduction in exploitable shallow marine environments, and not simply external selective pressures.

These contexts continue to be inherited, albeit in a slightly modified form, by generations of modern producers in the region. Importantly, this breaks down the division between cultivation practiced in the past and that practiced in the same location in the present. For Tikopia today, cultivation is structured by the counteracting and creation of selective contexts with origins in the past. To understand modern cultivation practices and their performance within a historically constructed environment, as well as ecosystem structure more generally, the sequence and outcomes of human niche construction must be documented. Discussion surrounding intensification do not often consider this point. In a specific sense, inherited landscapes of Tikopia, the sum result of indigenous developments over 2800 years and the introduction of some European crops, created the context for the Tikopia response to hazards in the 1950s. The dependence on the inherited arboricultural system, important to support a high population density, and the periodicity of cyclones in the region created a vulnerability in the production system. These vulnerabilities were not just apparent in the historic period, though, and the elimination of pigs (Kirch, 2007:89) and the onset of conflict late in the pre-contact sequence (Firth, 1961:159) might be related to these vulnerabilities. What this example does illustrate, though, is how niche construction activities can reduce the flexibility of production systems by creating a type of path dependency, not well documented in previous examinations of agricultural trajectories in Polynesia. Ecological and cultural inheritance are cumulative processes that can constrict opportunities for future development just as much as they allow them.

Tikopia illustrates well the impact of relocation, perturbation (ecosystem engineering), and inheritance. Relocation through the act of island settlement resulted in behavioral strategies that began the

Table 1
The link between production techniques, selective contexts, and outcomes on Tikopia.

Cultural Practice	Selective Context	Link to Previous Cultural Practices	Impact on Potential Selective Pressures	Potential Long-term Outcome
Shifting cultivation	Lack of native economic terrestrial resources	Island settlement	Alleviation of land limitations, increased terrestrial productivity,	Increased population, decreased reliance on wild resources; erosion
Agroforestry	High population density, declining terrestrial and marine productivity	Erosion and nutrient reduction caused by shifting cultivation, higher population, reduction in marine productivity	Increased terrestrial productivity, counteracts nutrient reductions, maintains soil structure and stability, offset losses of marine productivity; development of agroforestry "landesque capital"	Increased population, increased reliance on agroforestry, decreased reliance on wild resources
Wetland cultivation	Reduced marine ecosystem, prograded coastal plain	Erosion of sediments from hillslopes caused by shifting cultivation, potential replenishment of nutrients through colluvial rejuvenation	Increased terrestrial productivity, offset losses of marine productivity	Increased population, decreased reliance on wild resources
Pit Fermentation	Increased reliance on agroforests, periodic cyclones	Increased reliance on agroforestry, higher population, population intrusion	Augmentation of resource availability; potential for political economy of surplus	Reduction in rate and degree of famine

sequence of agricultural change. Notably, this relocation was met with the exploitation of wild resources as well as the initial clearance of vegetation for both shifting cultivation and habitation. It was relocation that also created the pressures leading to the introduction of exotic plants and animals, largely to counteract the lack of economic terrestrial resource available in remote island landscapes. This initial relocation provided the baseline from which the production system on Tikopia would evolve, but subsequent mechanisms of relocation also modified the trajectory of agricultural change. Of note was the intrusion of migrants and material culture from the east. Just as earlier populations were subject to the pressures of a new environment, so were the new migrants in the 2nd millennium AD. Pressures, which included a higher population density and a less productive marine environment inherited from previous populations that lived on the island, were counteracted by the introduction of tree crops and pit fermentation techniques allowing the storage of some starches. The latter was important for the success of the former given the frequency and strength of tropical storms within the region.

The effects of strategies associated with counteracting pressures imparted by relocation had lasting impacts on the landscape. Shifting cultivation practiced in the beginning of the Tikopian cultural sequence was in part responsible for the enrichment of coastal plains that are now important agroecosystems for the cultivation of tubers. It was the expansion of this technique that resulted in the degree of landscape evolution visible on the modern island. This occurred at the same time that sea-level changes reduced the area of exploitable shallow marine environments. Over time, and especially after intrusion of additional human populations in the 2nd millennium AD, the island was constructed into an economic landscape with a focus on high density tree crops. This was a long-term strategy that had the consequence of creating enhanced vulnerability to certain kinds of environmental perturbations, especially periodic cyclones.

Inheritance of the results of relocation and perturbation led to the specific pathway of production on Tikopia. The inherited techniques held by the original settlers of Tikopia constrained the potential strategies used to counteract the pressures of a new environment, namely the transported landscapes and the ability to exploit wild marine resources. The inherited technique of shifting cultivation, which was part of the response to pressures of relocation, changed the environment. Both the agricultural technique and the initial modified landscape were inherited by the subsequent generation of producers and it was the selective context of the inherited cultural and environmental niche that led to changes. In response to these modified selective pressures, cultivation was expanded, offsetting the decrease in available wild resources, and resulting in additional erosion as well as the use of constructed landscapes. The increased reliance on terrestrial production was a novel behavioral trait in this environment, one that would also be subject to transmission to subsequent generations. The fact that "new" colluvium is recognized as important cultivation space historically (see Kirch and Yen, 1982:43) hints that knowledge regarding past experience with these ecosystems was part of inheritance. In conjunction with the effects of natural sea-level fluctuations, these techniques and modified landscapes were transmitted. In this case, the transmission occurred at the same time new techniques, and, probably, people were being integrated on the island. Agroforestry appears to have expanded at this point. Agroforests allow groups to produce a high quantity of goods per unit of land area (see Kirch, 1994; Kirch and Yen, 1982), especially when those agroforests include breadfruit. These agroforests also retain soils on steep hillslopes, enabling understory cultivation, and mimic the natural tropical rainforest to maintain biodiversity (Kirch and Yen, 1982). In this way, the formation of agroforests counteracted the pressures associated with a higher population density and an inherited landscape with decreased marine resources relative to earlier times. New techniques often create new pressures, however, and agroforestry is susceptible to wind damage. To some extent, this is offset by the use of pit fermentation storage, but whether the use of the storage device was brought with tree cropping or was a response to destruction of tree crops after the formation of the economic landscape is unclear. What is clear is that several forms of risk management, including the Tikopia collective social sense (Kirch, 2007) and the continued cultivation of minor crops less likely to be damaged by storms, developed out of or in concert with this situation

While this case study is not exhaustive, it does illustrate the strength of understanding developed from the use of NCT and an investigation of the evolution of selective environments. We are not the first to recognize these feedback loops on Tikopia (see e.g., Kirch, 1994:295–305, 2007). Still, feedback loops are created through the impacts of cultivation on selective pressures (Table 1), a point not highlighted in previous investigations. The reciprocal interplay between changing environments and cultivation strategies can only be understood through evaluation of changing selective pressures brought about by human perturbation and relocation, and the intersection of these activities with "natural" environmental processes. The Tikopia constructed their environment in concert with ongoing climatically-driven environmental change. These different activities, both culturally and naturally defined, became historically entangled through inheritance to have cascading effects through time and create variation relative to other production systems in the region. Following Allen (2013) for the Cook Islands, the construction of the environment was likely necessary for long term habitation on Tikopia. In doing so, they responded to the outcomes of that construction, which were the creation and elimination of selective pressures and contexts. Such a sequence created path dependency as even opportunities for development were constrained by the product of responses to previous selective contexts.

Without an understanding of how human strategies and techniques modify the selective context of human behavior and how those consequences cascade through time, explanations of agricultural change are incomplete as this is key for the development of variation. Holding a selective environment constant, the outcome of not recognizing principles of inheritance and feedback, creates a likely inaccurate image of why agricultural sequences follow one particular pathway and not another. It is within this context that we believe niche construction provides an answer to the call of Kirch (1994:321–323) for a conceptual framework to investigate sequences of cultivation that integrates history and process.

4.5. Novel expectations

We also believe NCT offers additional perspectives and expectations to guide future research. Such novel expectations or lines of inquiry add to the usefulness of the NCT perspective. These are adapted from general predictions of NCT (see Laland et al., 2015:10).

First, we expect that high rates of innovation/reinvention of agricultural techniques will occur after either relocation (see Yen, 1973; Cochrane and Jordan, 2017) or environmental perturbation to counteract the effects of these two historical contingencies. Previous research has associated increased innovation with risk (Fitzhugh, 2001), which is an important component of novel environments. Innovation between perturbation and relocation should be less frequent. However, the adoption and spread of the innovation may be more gradual as the performance of the new technique becomes known. Agricultural productivity modelling (e.g., Ladefoged et al., 2008) has a role to play in estimating the effects of agricultural technique innovation on selection and technique feedback loops within a constructed niche.

Second, we would expect that other organisms have had an influence on the use of certain techniques, as illustrated in the example of rats on Rapa Nui above and the importance of sea birds for the fertility of soils on old volcanic substrates (Kirch, 2007). A central tenet of NCT is that some organism can modify the selective pressures within which another organism lives. For example, earthworms and other organisms create or maintain areas suitable for cultivation in other areas of the world (McKey et al., 2010), but they are also known to deplete soil inorganic nutrients (Resner et al., 2015). Pig, and other domesticated animal, management has the potential to modify agricultural infrastructure, as well as the spatial configuration of cultivation. Further, the need to feed these domesticates is likely to translate into archaeologically identifiable signatures as it would be necessary to construct an environment for feeding a managed herd of pigs. In this sense, a viable object of future research is the role of behaviors of other organisms in affecting agriculture sequences in Polynesia.

Third, we expect agricultural practices to influence the rate and trajectory of the evolution of other organisms (e.g., landsnails, birds, etc.). This has already been demonstrated to some extent in the Pacific in that anthropogenic landscape change associated with agricultural practices have been shown to create habitat for some varieties of landsnails (i.e., *Lamellaxis gracilis*; Christensen and Kirch, 1981:85), planthoppers (Matthews, 2003), and various weeds (Leach, 2005).

Finally, changes in agricultural practice are not necessarily progressive and characterized by long-term increases in productivity or resilience to stress, though these states may be experienced at different points in any sequence. Instead, temporal and spatial feedback loops will be a key component to explain the manifestation of any particular trajectory of agricultural change. This view of reciprocal causation (after Laland, 2015) limits the role played by singular factors (e.g., population growth, environmental change, political development), as demonstrated by several examples provided in previous sections (i.e., Hawaiʻi, Sāmoa, Tikopia). The synchronic and diachronic relationships between these different factors cannot be disentangled in the creation of the context of agricultural development.

5. Conclusions

The complex agricultural landscapes of Polynesia are the result of long-term cultural and ecological developments at work at several scales, a point that has been made about agricultural landscapes throughout the world (Ford and Nigh, 2015). What we advocate is the investigation of agricultural development that proposes historical explanations based within well-documented evolutionary processes (i.e., niche construction, selection). Process and history, important components of explanations of agricultural trajectories (Kirch, 1994), are brought together in NCT through non-genetic mechanisms of cultural and ecological inheritance. The mechanisms of inheritance allow the accumulation of products of history, which then feed back to affect future production systems by creating the context of cultural practice. This reciprocal and recursive model of causation necessitates a focus on the historical foundation of agricultural change, identified as a primary component of such landscape scale cultural practice as production (Erickson, 2008; Morrison, 2006, 2014). By identifying the long-term patterns and ramifications of niche construction, as the context within which agricultural strategies and techniques are used, explanations of the persistence or abandonment of techniques and strategies can be created and compared.

Thus, recognition of niche construction contributes in several ways. The use of niche construction centers investigations on the processes of actual long-term trajectories of agricultural change, as it is in these that explanations for variation are found (see Morrison, 2006). This enables reciprocal causation to be recognized. Populations do not often respond to singular factors. Instead, they respond to the perceived collection of factors within the confines of historical constraints and cultural knowledge. This is further enabled by understanding the relationship between contemporary agricultural techniques and strategies. The integration of various techniques and strategies often signifies that these systems are complementary in some way. This is important because a change in one cultivation strategy might bring about a change in another, as each strategy or technique modifies the selective context of the other. In many respects, the complementary nature of cultivation strategies maintains resiliency of systems and the recognition of the importance of niche construction offers an opportunity for archaeologists to contribute to discussions surrounding such themes in modern times. Archaeologists have the requisite knowledge to identify legacy effects of past land use practices that continue to have an effect on how people produce food today.

Conflict of interest

The authors have no conflicts of interest.

Acknowledgments

We thank Patrick Kirch, John Terrell, Robert DiNapoli, Tim Rieth, Julie Field, and an anonymous reviewer for providing critical comments on previous drafts of this manuscript.

Funding sources

Part of this research was funded by the Royal Society Te Apārangi Marsden Fund (17-UOA-010, contract UOA1709).

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.jaa.2018.06.007.

References

Addison, D.J., 2008. The changing role of irrigated *Colocasia esculenta* (taro) on Nuku Hiva, Marquesas Islands: from an essential element of colonization to an important risk-reduction strategy. Asian Perspect. 47, 139–155.
Allen, M.S., 2004. Bet-hedging strategies, agricultural change, and unpredictable environments: historical development of dryland agriculture in Kona, Hawaii. J. Anthropol. Archaeol. 23, 196–224.
Allen, M.S., 2010. Oscillating climate and socio-political process: the case of the Marquesan chiefdom, Polynesia. Antiquity 84, 86–102.
Allen, M.S., 2013. 'Buying into' niche construction? A case study from the Cook Islands. Abstr. Proc. Austral. Soc. Human Biol. HOMO: J. Comparative Human Biol. 64, 142.
Andriani, P., Cohen, J., 2013. From exaptation to radical niche construction in biological and technological complex systems. Complexity 18, 7–14.
Arroyo-Kalin, M., 2016. Landscaping, landscape legacies, and landesque capital in Pre-Columbian Amazonia. In: Isendaul, C., Stump, D. (Eds.), The Oxford Handbook of Historical Ecology and Applied Archaeology. Oxford University Press, New York. https://doi.org/10.1093/oxfordhb/9780199672691.013.16.
Athens, J.S., 2009. *Rattus exulans* and the catastrophic disappearance of Hawai'i's native lowland forest. Biol. Invasions 11, 1489. https://doi.org/10.1007/s10530-008-9402-3.
Athens, J.S., Ward, J.V., 1993. Environmental change and prehistoric Polynesian settlement in Hawai'i. Asian Perspect. 32, 205–223.
Athens, J.S., Tuggle, H.D., Ward, J.V., Welch, D.J., 2002. Avifaunal extinctions, vegetation change, and Polynesian impacts in prehistoric Hawai'i. Archaeol. Oceania 37, 57–78.
Atkinson, Q.D., Coomber, T., Passmore, S., Greenhill, S.J., Kushnick, G., 2016. Cultural and environmental predictors of Pre-European deforestation on Pacific Islands. PLOS ONE 11 (5), e0156340. https://doi.org/10.1371/journal.pone.0156340.
Barber, I., 2004. Crops on the border: the growth of archaeological knowledge of Polynesian cultivation in New Zealand. In: Furey, L., Holdaway, S. (Eds.), Change Through Time: 50 years of New Zealand Archaeology. New Zealand Archaeological Association Monograph, pp. 169–192.
Barber, I., 2010. Diffusion or innovation? Explaining lithic agronomy on the southern Polynesian margins. World Archaeol. 42, 74–89.
Barber, I., 2013. Molluscan mulching at the margins: investigating the development of a South Island Māori variation on Polynesian hard mulch agronomy. Archaeol. Oceania 48, 40–52.
Barrau, J., 1961. Subsistence Agriculture in Polynesia and Micronesia. B.P. Bishop Museum Bulletin 223, Honolulu.
Barrau, J., 1965. L'humide et le sec: an essay on ethnobiological adaptation to contrastive environments in the Indo-Pacific area. J. Polynesian Soc. 74, 329–346.
Bassett, K.N., Gordon, H.W., Nobes, D.C., Jacomb, C., 2004. Gardening at the edge: documenting the limits of tropical Polynesian kumara horticulture in Southern New Zealand. Geoarchaeology 19, 185–218.
Blaikie, P., Brookfield, H.C., 1987. Land Degradation and Society. Methuen, London.
Boserup, E., 1965. The Conditions of Agricultural Growth; The Economics of Agrarian Change Under Population Pressure. G. Allen & Unwin, London.
Boyd, R., Richerson, R.J., 1985. Culture and the Evolutionary Process. University of Chicago Press, Chicago.
Brock, W.A., O'Brien, M.J., Bentley, R.A., 2016. Validating niche-construction theory through path analysis. Archaeol. Anthropol. Sci. 8, 819–837.
Brookfield, H.C., 1972. Intensification and disintensification in Pacific agriculture: a theoretical approach. Pacific Viewpoint 13, 30–48.
Brookfield, H.C., 2001. Intensification, and alternative approaches to agricultural change. Asia Pacific Viewpoint 42, 181–192.
Broughton, J.M., Cannon, M.D., Bartelink, E.J., 2010. Evolutionary ecology, resource depression, and niche construction theory: applications to central California hunter-gatherers and Mimbres-Mogollon agriculturalists. J. Archaeol. Method Theory 17, 371–421.
Bruno, M.C., 2014. Beyond raised fields: exploring farming practices and processes of agricultural change in the ancient Lake Titicaca Basin in the Andes. Am. Anthropol. 116, 130–145.
Chazine, J.M., 2012. Wet taro cultivation on atolls: a techno-cultural paradox? In: Spriggs, M., Addison, D., Matthew, P.J. (Eds.), Irrigated Taro (*Colocasia esculenta*) in the Indo-Pacific. Senri Ethnological Studies 78, Osaka, pp. 83–93.
Christensen, C.C., Kirch, P.V., 1981. Nonmarine mollusks from archaeological sites on Tikopia, Southeastern Solomon Islands. Pac. Sci. 35, 75–88.
Clark, J.T., 1986. Waimea-Kawaihae, A Leeward Hawaii Settlement System (Unpublished PhD Dissertation). Department of Anthropology, University of Illinois at Urbana-Champaign.
Cochrane, E.E., Jordan, F., 2017. Adaptive radiation of agricultural techniques in Oceania. Paper presented at the 1st Cultural Evolution Society conference, Jena, Germany.
Collard, M., Buchanan, B., Ruttle, A., O'Brien, M.J., 2011. Niche construction and the toolkits of hunter-gatherers and food producers. Biol. Theory 6, 251–259.
Day, R.L., Laland, K.N., Odling-Smee, J., 2003. Rethinking adaptation: the niche construction perspective. Perspect. Biol. Nat. 46, 80–95.
DiNapoli, R.J., Morrison, A.E., Lipo, C.P., Hunt, T.L., Lane, B.G., 2018. East Polynesian islands as models of cultural divergence: the case of Rapa Nui and Rapa Iti. J. Island Costal Archaeol. 13, 206–223.
Dotte-Sarout, E., Kahn, J.G., 2017. Ancient woodlands of Polynesia: a pilot anthracological study of Maupiti Island, French Polynesia. Quat. Int. 457, 6–28.
Dye, T., Steadman, D.W., 1990. Polynesian ancestors and their animal world. Am. Sci. 78, 207–215.
Erickson, C.L., 1993. The social organization of Prehispanic raised field agriculture in the Lake Titicaca Basin. In: Scarborough, V., Isaac, B. (Eds.), Economic Aspects of Water Management in the Prehispanic New World. JAI Press, Greenwich, pp. 369–426.
Erickson, C.L., 2003. Historical ecology and future explorations. In: Lehmann, J., Kern, D.C., Glaser, B., Woods, W.I. (Eds.), Amazonian Dark Earth: Origin, Properties, Management. Kluwer Academic Publishers, Dordrecht, pp. 455–500.
Erickson, C.L., 2006. Intensification, political economy, and the farming community: in defense of a bottom-up perspective of the past. In: Marcus, J., Stanish, C. (Eds.), Agricultural Strategies. Cotsen Institute, Los Angeles, pp. 233–265.
Erickson, C.L., 2008. Amazonia: the historical ecology of a domesticated landscape. In: Silverman, H., Isbell, W.H. (Eds.), Handbook of South American Archaeology. Springer, New York, pp. 157–183.
Firth, R., 1936. We, the Tikopia. Beacon, Boston.
Firth, R., 1961. History and Traditions of Tikopia. Polynesian Society Memoir No. 33, Wellington.
Firth, R., 1965. Primitive Polynesian Economy. Routledge & K. Paul, London.
Fitzhugh, B., 2001. Risk and invention in human technological evolution. J. Anthropol. Anthropol. 20, 125–167.
Ford, A., Nigh, R., 2015. The Maya Forest Garden: Eight Millennia of Sustainable Cultivation of the Tropical Woodlands. Left Coast Press, Walnut Creek, California.
Fuentes, A., 2014. Human evolution, niche complexity, and the emergence of a distinctively human imagination. Time Mind 7, 214–257.
Fuentes, A., 2016. The extended evolutionary synthesis, ethnographic, and the human niche: toward an integrated anthropology. Curr. Anthropol. 57, S12–S26.
Furey, L., 2006. Maori Gardening: An Archaeological Perspective. New Zealand Department of Commerce, Wellington.
Gould, S.J., Vrba, E.S., 1982. Exaptation – a missing term in the science of form. Paleobiology 8, 4–15.
Grove, M., 2016. Population density, mobility, and cultural transmission. J. Archaeol. Sci. 74, 75–84.
Håkansson, N.T., Widgren, M. (Eds.), 2014. Landesque Capital: The Historical Ecology of Enduring Landscape Modifications. Left Coast Press, Walnut Creek.
Handy, E.S., Handy, E.G., Pukui, M.K., 1972. Native Planters in Old Hawai'i Their Life, Lore, and Environment. B.P. Bishop Museum Bulletin 233, Honolulu.
Hart, J.P., 1999. Maize agriculture evolution in the Eastern Woodlands of North America: a Darwinian perspective. J. Archaeol. Method Theory 6, 137–180.
Huebert, J., 2014. The Role of Arboriculture in Landscape Domestication and Agronomic Development: A Case Study from the Marquesas Islands, East Polynesia (Unpublished PhD Thesis). Department of Anthropology, University of Auckland.
Huebert, J.M., Allen, M.S., 2016. Six centuries of anthropogenic forest change on a Polynesian high island: archaeological charcoal records from the Marquesas Islands. Quat. Sci. Rev. 137, 79–96.
Hunt, T.L., 2007. Rethinking Easter Island's ecological catastrophe. J. Archaeol. Sci. 34, 485–502.
Hunt, T.L., Lipo, C.P., 2009. Revisiting Rapa Nui (Easter Island) "Ecocide". Pac. Sci. 63, 601–616.
Ishizuki, K., 1974. Excavation of site SU-Fo-1 at Folasa-a-Lalo. In: Green, R.C., Davidson, J.M. (Eds.), Archaeology in Western Samoa. Auckland Institute and Museum Bulletin 6, Auckland, pp. 36–57.
Jablonka, E., Lamb, M., 2005. Evolution in Four Dimensions: Genetic, Epigenetic, Behavioral, and Symbolic Variation in the History of Life. MIT Press, Cambridge.
Jones, B.D., Ladefoged, T.N., Asner, G., 2015. Tracing the resilience and revitalization of historic taro production in Waipi'o valley, Hawai'i. J. Polynesian Soc. 124, 83–109.

Jones, C.G., Lawton, J.H., Shachak, M., 1994. Organisms as ecosystem engineers. Oikos 69, 373–386.
Kahn, J.G., Dotte-Sarout, E., Molle, G., Conte, E., 2015a. Mid- to late prehistoric landscape change, settlement histories, and agricultural practices on Maupiti, Society Islands (Central East Polynesia). J. Island Coastal Archaeol. 10, 363–391.
Kahn, J.G., Nickelsen, C., Stevenson, J., Porch, N., Dotte-Sarout, E., Christensen, C.C., May, L., Athens, J.S., Kirch, P.V., 2015b. Mid- to late Holocene landscape change and anthropogenic transformations on Mo'orea, Society Islands: a multi-proxy approach. Holocene 25, 333–347.
Kirch, P.V., 1977. Valley agricultural systems in prehistoric Hawaii: an archaeological consideration. Asian Perspect. 20, 246–280.
Kirch, P.V., 1980. The archaeological study of adaptation: theoretical and methodological issues. Adv. Archaeol. Method Theory 3, 101–156.
Kirch, P.V., 1982. Ecology and the adaptation of Polynesia agricultural systems. Archaeol. Oceania 17, 1–6.
Kirch, P.V., 1984. The Evolution of Polynesian Chiefdoms. Cambridge University Press, Cambridge.
Kirch, P.V., 1988. Niuatoputapu: The Prehistory of a Polynesian Chiefdom. Thomas Burke Memorial Washington State Museum Monograph No. 5, Seattle.
Kirch, P.V., 1994. The Wet and the Dry: Irrigation and Agricultural Intensification in Polynesia. University of Chicago Press, Chicago.
Kirch, P.V., 2006. Agricultural intensification: a Polynesian perspective. In: Marcus, J., Stanish, C. (Eds.), Agricultural Strategies. Cotsen Institute, Los Angeles, pp. 191–217.
Kirch, P.V., 2007. Three islands and an archipelago: reciprocal interactions between humans and island ecosystems in Polynesia. Earth Environ. Trans. Roy. Soc. Edin. 98, 85–99.
Kirch, P.V., 2010. How Chiefs Became Kings: Divine Kingship and the Rise of Archaic States in Ancient Hawai'i. University of California Press, Berkeley.
Kirch, P.V. (Ed.), 2011. Roots of Conflict: Soils, Agriculture, and Sociopolitical Complexity in Ancient Hawai'i. SAR Press, Santa Fe.
Kirch, P.V. (Ed.), 2017. Tangatatau Rockshelter: The Evolution of an Easter Polynesian Socio-Ecosystem. Cotsen Institute of Archaeology, Los Angeles.
Kirch, P.V., Lepofsky, D., 1993. Polynesian irrigation: archaeological and linguistic evidence of origins and development. Asian Perspect. 32, 183–204.
Kirch, P.V., Swift, J.A., 2017. New AMS radiocarbon dates and re-evaluation of the cultural sequence of Tikopia Island, Southeast Solomon Islands. J. Polynesian Soc. 126, 313–336.
Kirch, P.V., Hunt, T.L., 1993. Excavations at the To'aga Site (AS-13-1). In: Kirch, P.V., Hunt, T.L. (Eds.), The To'aga Site: Three Millennia of Polynesian Occupation in the Manu'a Islands, American Samoa. Contributions of the University of California Archaeological Research Facility No. 51, Berkeley, pp. 43–83.
Kirch, P.V., Yen, D.E., 1982. The Prehistory and Ecology of a Polynesian Outlier. B.P. Bishop Museum Bulletin No. 238, Honolulu.
Kirch, P.V., Molle, G., Nickelsen, C., Mills, P., Dotte-Sarout, E., Swift, J., Wolfe, A., Horrocks, M., 2015. Human ecodynamics in the Mangareva Islands: a stratified sequence from Nenega-Iti rock Shelter (site AGA-3, Agakauitai Island). Archaeol. Oceania 50, 23–42.
Kurashima, N., Kirch, P.V., 2011. Geospatial modeling of pre-contact Hawaiian production systems on Moloka'i Island, Hawaiian Islands. J. Archaeol. Sci. 38, 3662–3674.
Ladefoged, T.N., Graves, M.W., 2000. Evolutionary theory and the historical development of dry-land agriculture in north Kohala, Hawai'i. Am. Antiq. 65, 423–448.
Ladefoged, T.N., Graves, M.W., 2008. Variable development of dryland agriculture in Hawai'i: a fine-grained chronology from the Kohala Field System, Hawai'i Island. Curr. Anthropol. 49, 771–802.
Ladefoged, T.N., Lee, C.T., Graves, M.W., 2008. Modeling life expectancy and surplus production of dynamic pre-contact territories in leeward Kohala, Hawai'i. J. Anthropol. Archaeol. 27, 93–110.
Ladefoged, T.N., Graves, M.W., Coil, J.H., 2005. The introduction of sweet potato in Polynesia: early remains in Hawai'i. J. Polynesian Soc. 114, 359–373.
Ladefoged, T.N., Graves, M.W., McCoy, M.D., 2003. Archaeological evidence for agricultural development in Kohala, Island of Hawai'i. J. Archaeol. Sci. 30, 923–940.
Ladefoged, T.N., Kirch, P.V., Gon, S.M., Chadwick, O.A., Hartshorn, A.S., Vitousek, P.M., 2009. Opportunities and constraints for intensive agriculture in the Hawaiian archipelago prior to European contact. J. Archaeol. Sci. 36, 2374–2383.
Ladefoged, T.N., Stevenson, C.M., Haoa, S., Mulrooney, M., Puleston, C., Vitousek, P.M., Chadwick, O.A., 2010. Soil nutrient analysis of Rapa Nui gardening. Archaeol. Oceania 45, 80–85.
Ladefoged, T.N., Flaws, A., Stevenson, C.M., 2013. The distribution of rock gardens on Rapa Nui (Easter Island) as determined from satellite imagery. J. Archaeol. Sci. 40, 1203–1212.
Laland, K.N., 2015. On evolutionary causes and evolutionary processes. Behav. Process. 117, 97–104.
Laland, K.N., O'Brien, M.J., 2010. Niche construction theory and archaeology. J. Archaeol. Method Theory 17, 303–322.
Laland, K.N., O'Brien, M.J., 2011. Cultural niche construction: an introduction. Biol. Theory 6, 191–202.
Laland, K.N., Odling-Smee, J., Feldman, M.W., 2000. Niche construction, biological evolution, and cultural evolution. Behav. Brain Sci. 23, 131–146.
Laland, K.N., Boogert, N., Evans, C., 2014. Niche construction, innovation and complexity. Environ. Innov. Soc. Trans. 11, 71–86.
Laland, K.N., Uller, T., Feldman, M.W., Sterelny, K., Müller, G.B., Moczek, A., Jablonka, E., Odling-Smee, J., 2015. The extended evolutionary synthesis: its structure, assumptions and predictions. Proc. Roy. Soc. B 282, 20151019.
Lansing, J.S., 2007. Priests and Programmers: Technologies of Power in the Engineered Landscapes of Bali, second ed. Princeton University Press, Princeton.
Lansing, J.S., Fox, K.M., 2011. Niche construction on Bali: the gods of the countryside. Philos. Trans. Roy. Soc. B 366, 927–934.
Latinis, D.K., 2000. The development of subsistence system models for Island Southeast Asia and Near Oceania: the nature and role of arboriculture and arboreal-based economics. World Archaeol. 32, 41–67.
Leach, H.M., 1976. Horticulture in Prehistoric New Zealand: An Investigation of the Function of the Stone Walls of Palliser Bay (Unpublished PhD Thesis). Department of Anthropology, University of Otago.
Leach, H.M., 1999. Intensification in the pacific: a critique of the archaeological criteria and their application. Curr. Anthropol. 40, 311–339.
Leach, H.M., 2005. Gardens without weeds? Pre-European Maori gardens and inadvertent introductions. N. Z. J. Botan. 43, 271–284.
Lepofsky, D.S., 1994. Prehistoric agricultural intensification in the Society Islands, French Polynesia (Unpublished PhD Dissertation). Department of Anthropology, University of California at Berkeley.
Lepofsky, D., Kirch, P.V., Lertzman, K.P., 1996. Stratigraphic and paleobotanical evidence for prehistoric human-induced environmental disturbance on Mo'orea, French Polynesia. Pac. Sci. 50, 253–273.
Lepofsky, D.S., Kahn, J., 2011. Cultivating an ecological and social balance: elite demands and commoner knowledge in ancient Ma'ohi agriculture, Society Islands. Am. Anthropol. 113, 319–335.
Leppard, T.P., 2018. Rehearsing the anthropocene in microcosm: the palaeoenvironmental impacts of the Pacific Rat (*Rattus exulans*) and other non-human species during island neolithization. In: Birch, S.E. (Ed.), PilaarMultispecies Archaeology. Routledge, London, pp. 47–64.
Lewontin, R.C., 1982. Organism and environment. In: Plotkin, H.C. (Ed.), Learning, Development, and Culture: Essays in Evolutionary Epistemology. Wiley, New York, pp. 151–170.
Lincon, N.K., Vitousek, P., 2016. Nitrogen fixation during decomposition of sugarcane (*Saccarum officinarum*) is an important contribution to nutrient supply in traditional dryland agricultural systems of Hawai'i. Int. J. Agric. Sustain. 14, 214–230.
Lincoln, N., Vitousek, P., 2017. Indigenous Polynesian agriculture in Hawai'i. Oxford Res. Encycl. Environ. Sci. https://doi.org/10.1093/acrefore/9780199389414.013.376.
Lincoln, N., Ladefoged, T., 2014. Agroecology of pre-contact dryland farming: the spatial extent, yield and social impact of Hawaiian breadfruit groves in Kona, Hawai'i. J. Archaeol. Sci. 49, 192–202.
Lincoln, N., Chadwick, O., Vitousek, P., 2014. Indicators of soil fertility and opportunities for precontact agriculture in Kona, Hawai'i. Ecosphere 5, 1–20.
MacArthur, R.H., Wilson, E.O., 1967. The Theory of Island Biogeography. University Press, Princeton.
Matthews, P.J., 2003. Taro planthoppers (*Tarophagus* spp.) in Australia and the origins of taro (*Colocasia esculenta*) in Oceania. Archaeol. Oceania 38, 192–202.
McCoy, M.D., 2006. Landscape, Social Memory, and Society: An Ethnohistoric-archaeological Study of three Hawaiian Communities (Unpublished PhD Dissertation). Department of Anthropology, University of California, Berkeley.
McCoy, M.D., Graves, M.W., 2010. The role of agricultural innovation on Pacific Islands: a case study from Hawai'i Island. World Archaeol. 42, 90–107.
McCoy, M.D., Mulrooney, M.A., Horrocks, M., Cheng, H., Ladefoged, T.N., 2017. Evaluating agricultural bet-hedging strategies in the Kona Field System: new high-precision ^{230Th}/U and ^{14}C dates and plant microfossil data from Kealakekua, Hawai'i Island. Archaeol. Oceania 52, 70–80.
McFadgen, B.G., 1980. Maori plaggen soils in New Zealand, their origin and properties. J. Roy. Soc. NZ 10, 3–18.
McIvor, I.H., Ladefoged, T.N., 2018. Intermittent irrigation in the Waimea Field System, Hawai'i Island: a computational fluid dynamics model. J. Archaeolog. Sci.: Rep. 17, 335–345.
McKey, D., Rostain, S., Iriarte, J., Glaser, B., Birk, J.J., Holst, I., Renard, D., 2010. Pre-Columbian agricultural landscapes, ecosystem engineers, and self-organized patchiness in Amazonia. PNAS 107, 7823–7828.
Mesoudi, A., O'Brien, M.J., 2008. The learning and transmission of hierarchical cultural recipes. Biol. Theory 3, 63–72.
Meyer, M., Ladefoged, T.N., Vitousek, P.M., 2007. Soil phosphorus and agricultural development in the Leeward Kohala Field System, Island of Hawai'i. Pac. Sci. 61, 347–353.
Morehart, C.T., 2010. The Archaeology of Farmscapes: Production, Power, and Place at Postclassic Xaltocan, Mexico (Unpublished PhD Dissertation). Department of Anthropology, Northwestern University.
Morrison, K.D., 1994. The intensification of production: archaeological approaches. J. Archaeol. Method Theory 1, 111–159.
Morrison, K.D., 1996. Typological schemes and agricultural change. Curr. Anthropol. 37, 583–608.
Morrison, K.D., 2006. Intensification as a situated process: landscape history and collapse. In: Marcus, J., Stanish, C. (Eds.), Agricultural Strategies. Costen Institute, Los Angeles, pp. 71–91.
Morrison, K.D., 2007. Rethinking intensification: power relations and scales of analysis in Precolonial South India. In: Thurston, T.L., Fisher, C.T. (Eds.), Seeking a Richer Harvest: The Archaeology of Subsistence Intensification, Innovation, and Change. Springer, New York, pp. 235–247.
Morrison, K.D., 2014. Captial-esque landscapes: long-term histories of enduring landscape modifications. In: Thomas-Hakansson, N., Widgren, M. (Eds.), Landesque Captial: The Historical Ecology of Enduring Landscape Modifications. Left Coast Press, Walnut Creek, pp. 49–74.
Morrison, A.E., 2012. An Archaeological Analysis of Rapa Nui Settlement Structure: A Multi-scalar Approach (Unpublished PhD Dissertation). Department of Anthropology, University of Hawai'i at Manoa.
O'Brien, M.J., Laland, K.N., 2012. Genes, culture, and agriculture: an example of human niche construction. Curr. Anthropol. 53, 434–470.

Odling-Smee, F.J., Laland, K.N., Feldman, M.W., 2003. Niche Construction: The Neglected Process in Evolution. Princeton University Press, Princeton.
Orzack, S.H., Sober, E., 1994. Optimality models and the test of adaptationism. Am. Nat. 143, 361–380.
Premo, L.S., Scholnick, J.B., 2011. The spatial scale of social learning affects cultural diversity. Am. Antiq. 76, 163–176.
Puleston, C.O., Tuljapurkar, S., 2008. Population and prehistory II: space-limited human populations in constant environments. Theor. Popul Biol. 74, 147–160.
Puleston, C.O., Ladefoged, T.N., Haoa, S., Chadwick, O.A., Vitousek, P.M., Stevenson, C.M., 2017. Rain, sun, soil, and sweat: a consideration of population limits on Rapa Nui (Easter Island) before European contact. Front. Ecol. Evol. 5, 69. https://doi.org/10.3389/fevo.2017.00069.
Quintus, S., 2015. Dynamics of Agricultural Development in Prehistoric Samoa: The Case of Ofu Island (Unpublished PhD Thesis). Department of Anthropology, The University of Auckland.
Quintus, S., 2018. Historicizing food production in Polynesia: a case study of 2,700 years of land use on Ofu Island, American Samoa. J. Field Archaeol. 43, 222–235.
Quintus, S., Allen, M.S., Ladefoged, T.N., 2016. In surplus and in scarcity: agricultural development, risk management, and political economy, Ofu Island, American Samoa. Am. Antiq. 81, 273–293.
Resner, K., Yoo, K., Sebestyen, S.D., Aufdenkampe, A., Hale, C., Lyttle, A., Blum, A., 2015. Invasive earthworms deplete key soil inorganic nutrients (Ca, Mg, K, and P) in a northern hardwood forest. Ecosystems 18, 89–102.
Rolett, B., Diamond, J., 2004. Environmental predictors of pre-European deforestation on Pacific Islands. Nature 43, 443–446.
Roullier, C., Benoit, L., McKey, Doyle, Lebot, V., 2013. Historical collections reveal patterns of diffusion of sweet potato in Oceania obscured by modern plant movements and recombination. PNAS 110, 2205–2210.
Rowley-Conwy, P., Layton, R., 2011. Foraging and farming as niche construction: stable and unstable adaptations. Philos. Trans. Roy. Soc. B 366, 849–862.
Scarborough, V.L., 2015. Human niches, abandonment cycling, and climate. Water History 7, 381–396.
Shennan, S., 2011. Property and wealth inequality as cultural niche construction. Philos. Trans. Roy. Soc. B 366, 918–926.
Smith, B.D., 2007. Niche construction and the behavioral context of plant and animal domestication. Evol. Anthropol. 16, 188–199.
Smith, B.D., 2009. Resource resilience, human niche construction, and the long-term sustainability of Pre-Columbian subsistence economies in the Mississippi River Valley Corridor. J. Ethnobiol. 29, 167–183.
Spriggs, M., 1981. Vegetable Kingdoms: Taro Irrigation and Pacific Prehistory (Unpublished PhD Thesis). Department of AnthropologyAustralia National University.
Spriggs, M., 1986. Landscape, land use and political transformation in southern Melanesia. In: Kirch, P.V. (Ed.), Island Societies Archaeological Approaches to Evolution and Transformation. Cambridge University Press, Cambridge, pp. 6–19.
Spriggs, M., 1997. Landscape catastrophe and landscape enhancement: are either or both true in the Pacific? In: Kirch, P.V., Hunt, T.L. (Eds.), Historical Ecology in the Pacific Islands. Yale University Press, New Haven, pp. 80–104.
Steadman, D.W., Pahlavan, D.S., Kirch, P.V., 1990. Extinction, biogeography, and human exploitation of birds on Tikopia and Anuta, Polynesian outliers in the Solomon Islands. Bishop Mus. Occas. Pap. 30, 118–153.
Sterelny, K., 2005. Made by each other: organisms and their environment. Biol. Philos. 20, 21–36.
Sterelny, K., Watkins, T., 2015. Neolithization in Southwest Asia in a context of niche construction theory. Cambridge Archaeol. J. 25, 673–691.
Stevenson, C.M., Ladefoged, T., Haoa, S., 2002. Productive strategies in an uncertain environment: prehistoric agriculture on Easter Island. Rapa Nui. J. 16, 17–22.
Sullivan, A., 1985. Intensification in volcanic zone gardening in northern New Zealand. In: Farrington, I.S. (Ed.), Prehistoric Intensive Agriculture in the Tropics. B.A.R. International Series 232, Oxford, pp. 475–489.
Swift, J.A., Miller, M.J., Kirch, P.V., 2017. Stable isotope analysis of Pacific rat (*Rattus exulans*) from archaeological sites in Mangareva (French Polynesia): the use of commensal species for understanding human activity and ecosystem change. Environ. Archaeol. 22, 283–297.
Tehrani, J.J., Riede, F., 2008. Towards an archaeology of pedagogy: learning, teaching and the generation of material culture traditions. World Archaeol. 40, 316–331.
Terrell, J.E., Hart, J.P., Barut, S., Cellinese, N., Curet, A., Denham, T., Kusimba, C.M., Latinis, K., Oka, R., Palka, J., Pohl, M.E.D., Pope, K.O., Williams, P.R., Haines, H., Staller, J.E., 2003. Domesticated landscapes: the subsistence ecology of plant and animal domestication. J. Archaeol. Method Theory 10, 323–368.
van der Leeuw, S.E., 2013. For every solution there are many problems: the role and study of technical systems in socio-environmental coevolution. Geografisk Tidsskrift – Danish J. Geogr. 112, 105–116.
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, 1665–1669.
Vitousek, P., Chadwick, O., Hilley, G., Kirch, P.V., Ladefoged, T., 2010. Erosion, geological history, and indigenous agriculture: a tale of two valleys. Ecosystems 13, 782–793.
Vitousek, P.M., Chadwick, O.A., Hotchkiss, S.C., Ladefoged, T.N., Stevenson, C.M., 2014. Farming the rock: a biogeochemical perspective on intensive agriculture in Polynesia. J. Pacific Archaeol. 5, 51–61.
Wallin, P., Stevenson, C., Ladefoged, T., 2005. Sweet potato production on Rapa Nui. In: Ballard, C., Brown, P., Bourke, R.M., Harwood, T. (Eds.), The Sweet Potato in Oceania: A Reappraisal. Oceania Monographs, Sydney, Sydney, pp. 85–88.
Whistler, W.A., 2009. Plants of the Canoe People: An Ethnobotanical Voyage through Polynesia. National Tropical Botanical Garden, Lawai.
Wilkinson, T.J., Boucharlat, R., Ertsen, M.W., Gillmore, G., Kennet, D., Magee, P., Rezakhani, K., De Schact, T., 2012. From human niche construction to imperial power: long-term trends in ancient Iranian water systems. Water History 4, 155–176.
Wilkinson, T.J., Rayne, L., Jotheri, J., 2015. Hydraulic landscapes in Mesopotamia: the role of human niche construction. Water History 7, 397–418.
Wozniak, J.A., 1999. Prehistoric horticultural practices on Easter Island: lithic mulched gardens and field systems. Rapa Nui J. 13, 95–99.
Yen, D.E., 1973. The origins of oceanic agriculture. Archaeol. Oceania 8, 68–85.
Zeder, M.A., 2012. The broad spectrum revolution at 40: resources diversity, intensification, and an alternative to optimal foraging explanations. J. Anthropol. Archaeol. 31, 241–264.