DEMOGRAPHY AND FOOD IN EARLY POLYNESIA

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Abstract

The analysis of prehistoric demography requires a robust understanding of demographic rates and their changes, of food production in relation to agriculture, technology and soils, and of their interactions. Many key concepts and models used in analyzing prehistoric populations are complex and difficult to define or operationalize. We discuss the limitations of some key ideas, including Malthusian limits, carrying capacity, marginal areas, and sustainability. To address the limitations of demographic models, we suggest a data-driven approach that extracts the most from data on early humans – we illustrate this by developing a new model mortality schedule for prehistoric populations. To address the dynamics of food and soils, we describe a model of nutrient-cycling dynamics and explore the effects of different levels of harvesting intensity under water and nitrogen limitation. We interpret these results in terms of their likely effects on food availability. Such a modeling approach can provide a solid basis for analyzing productivity, resilience and sustainability over long time scales in prehistory.

Introduction

The study of prehistoric populations relies on heterogeneous and incomplete data – archeological, ethnographic, ecological, historical – which need to be interpreted and integrated using conceptual and analytical models. For the island populations of Polynesia, Kirch (1984, 1994) provides a synthetic summary and model of demographic and cultural evolution over a millennium. This synthesis frames history in a temporal demographic sequence: founding immigrants begin a period of exponential numerical increase in time and of spatial spread; then follows a confrontation with Malthusian limits which is manifest in expansion into marginal areas and in the slowing or cessation of population increase; the latter period is marked by the evolution of sociocultural hierarchies in the form of chiefdoms. This temporal story rests on assumptions concerning the relationship between agriculture and long run population dynamics, including the productivity of agriculture in prehistory, the nature of marginal areas, Malthusian limits and carrying capacity. This paper examines these and related concepts from demographic, ecological and comparative perspectives. First, we examine briefly and critically Malthusian limits and carrying capacity, and then the concepts of marginal areas and sustainability. Second, we consider the problem of demographic reconstruction based on the limited data available for prehistoric populations. We present a new data-driven method that uses data tabulated by Weiss (1973) on various prehistoric populations to generate a new family of model life tables. The success of this approach suggests that we may be able to reduce reliance on mortality models for contemporary

populations. Finally, we discuss an ecologically based approach to the interaction between agricultural practices and soil dynamics. Sowing, fertilizing, and cropping alter the cycle of nutrient flow from the atmosphere and the soil into plants and back again. We propose a quantitative model of this cycle and its dynamics, and discuss its use in studying the relationship between agriculture and demography in prehistory. We argue that such an approach can provide robust insights into the dynamic processes that underlie population change and population-environment relationships in prehistory.

Malthusian Limits and Carrying Capacity

Population change results from an arithmetic difference between birth rates, death rates, and immigration. Assuming no net long run immigration (probably appropriate for early Hawaii but not necessarily for other islands) and initially exponential growth, a transition to population limitation requires either a decrease in birth rates or an increase in death rates. Malthus (see e.g., Lee 1987, Cohen 1995) argued for increased mortality as a result of declining per capita resources; a less likely alternative was a decrease in birth rates. The Malthusian view has been grafted onto the ecological model of logistic population growth, in which the rate of population change (i.e., of the difference between birth and death rates) is assumed to decrease when a population increases towards a number called the "carrying capacity." The time trajectory of a population that follows an upward logistic is a saturating S-shaped curve that flattens at the carrying capacity.

We say a real population's dynamics are "Malthusian" if we can demonstrate that birth or death rates are negatively affected by the population number (Lee 1987) – a more measured view than one which equates Malthusian dynamics with catastrophic checks. Lee (1987) reviews evidence of Malthusian feedback in human and animal populations. Direct density feedback is hard to demonstrate in human populations, so analyses usually focus on intermediate variables, such as fluctuations at annual and longer time scales in harvests or wages, likely driven by variation in weather. Long time series of English population data, ca. 1400 to 1700, provide some of the best evidence, and there is weaker evidence from other studies of early humans. Fertility appears to respond negatively to density; there is weaker evidence for a response in mortality. While these effects serve to reduce long run population growth rates towards zero, historical population often show both short term and long term cycles. Other studies of European demographic history (Bengtsson and Saito 2000) show that demographic responses to changes in food supply and weather are complex and vary with local factors (geography, topography, connectedness between populations, and so on). Negative feedbacks of the Malthusian sort may also be countered by positive feedbacks (e.g., the general ideas in Boserup 1981, or the complex adaptations discussed in Kirch 1994), which may complicate efforts to estimate population feedback effects. The estimates in Lee (1987) provide a basis for considering population dynamics over time in early Polynesia, using density-dependent stochastic models, but such an analysis has not been done as far as we know.

A different approach to density limitation is in terms of the intuitively appealing if slippery concept of "carrying capacity", which is thought of as estimating either the limits

of population or the "logistic" carrying capacity (an equilibrium level sustainable indefinitely). An operational assessment of carrying capacity is more problematic than an effort to establish Malthusian feedbacks. As discussed by Cohen (1995), any estimate of carrying capacity depends on contextual factors (technology, individual and social tastes and preferences) and the temporal and spatial scale at which one seeks to specify sustainability. It is difficult to go from general principles to an estimate of carrying capacity for a prehistoric population, given the limited data available; efforts to make such estimates even in data-rich situations have often been useless.

But two other approaches to carrying capacity have been used for early Polynesian populations. The first is illustrated by Kirch (1984) and estimates the largest sustained population numbers observed in a given area over a given time period based on archeological data. Ideally, this method requires population sizes to be estimated over at least a few generations (say 75 to 100 years), and that the estimates be stable over that time (e.g., the variation in numbers between years is small in some specified sense). Direct estimates are difficult (perhaps impossible) from archeological data alone, but indirect estimates based on habitation density can be made. Results from this method are clearly valuable in estimating a "carrying capacity" as a population level that was sustained for some time, but do not explain why that particular level was an equilibrium. The second approach, illustrated by Hamilton and Kahn (this volume) takes a different view of carrying capacity as the largest potential population size that could be supported in a specified area in a specified time period. Here the area and period of study define the technology – choice of crops, farming methods, use of animals, output per area per time

of various types of soil – and geographical data are used to assess the maximum productivity of soil and the area of soil that is worked. This approach is valuable in providing a geographical inventory but appears to lead to quite large estimates of potential food production. These approaches are probably limited in their ability to evaluate long run changes in food supply or soil condition. A dynamic approach (below) may help in this regard.

Marginal Areas and Sustainability in Agricultural History

The concept of the margin has played an important role in historical discussions of population change. For Polynesia, Kirch (1994) discusses the establishment and expansion of settlements in island areas that appear to be poor in rainfall or water storage, soil quality, and access to marine resources. For medieval England in the early part of the last millennium, Postan (1966) argued a similar interpretation of the expansion of population into the boundaries of established arable land in England during the period 1100 to 1200 AD, followed by a retreat from the margins when population collapsed during the 1300s. In both cases, the movement into marginal areas is thought to be a reflection of population increase and Malthusian limits in more fertile areas, and marginal areas are thought to be of poor agricultural potential and susceptible to degradation of soil and natural resources. Over the years, there has been a reevaluation of the concept of a "margin" in the literature on medieval England that ties in to our earlier discussion of Malthusian limits and carrying capacity.

Bailey (1989) and Hatcher and Bailey (2001) show that the notion of a marginal area in the English setting was tied (at least implicitly) to the concept of economic rent, which Ricardo defined as "a return due to the land alone as a factor of production." Thus a marginal area was one where this rent was low for one or more of a variety of factors: poor soil quality, the need for high labor inputs to create or maintain production, or the distance from markets or other places of exchange. These authors point out that an area may seem marginal if viewed purely in terms of the potential productivity of soil per unit of labor, but that the economic rent depends on other factors. These include: institutional factors (e.g., a marginal area may provide freedom from communal or institutional restrictions on individual behavior, crop selection, or farming practice; or, a marginal area may remove or reduce burdens of taxation) and specialization (e.g., marginal areas may benefit from specialization in cloth making, collection of shells, quarrying or other activity.) Such factors would seem relevant in Polynesian societies, especially as they underwent a transition to complex societies with hierarchical controls (Kirch 1994). Our point here is that the role of "marginal" areas needs to be evaluated in a broader context of the relationships between people and institutions.

Sustainability of agriculture is another concept that plays a role in the discussion of Malthusian limits and of marginal areas. The notion that soil fertility is an exhaustible stored component of soil is often used in discussions but needs critical examination. Indirect evidence for soil degradation can be found in historical reports (e.g., of declining tree cover, and production and imports of food – Angel 1972 reviews such evidence for the Eastern Mediterranean over a long span of prehistory). But in other cases, as with

medieval England (e.g., Postan 1966), records of agricultural output can be misleading. Whitney (1923) provides an early re-assessment of a suggested decline in English wheat harvests over the period 1200 to 1600 AD, showing that statistical evidence for a decline is weak. Long (1979) returns to this question, arguing that technology (implements and methods used to work the soil) rather than soil quality was probably the limiting factor on production over this period. Long notes the famous Rothamstead experiment on long term (over a century) wheat cultivation on a plot with no manuring where annual yields were maintained at a constant level with no sign of exhaustion. We believe that the exhaustion or degradation of soils and environment are not inevitable consequences of long-term habitation and population growth, but need to be demonstrated. We return to this question following our discussion of soil nutrient dynamics.

Demographic Reconstruction in Prehistory

The reconstruction of Polynesian demographic history faces the problem of estimating or assuming appropriate vital rates for mortality, fertility, and migration (e.g., Rallu 1990, Pool 1991). The crux of the problem is that we know much about modern human demography but relatively little about prehistory, so there is a tension between borrowing methods based on modern data and a reliance on the sparse and potentially inaccurate data on early populations such as come from skeletal series. Wood et al. (1992) and Meindl and Russell (1998) provide good reviews of the difficulties involved, and both discuss in detail models of the age-pattern of mortality. Although these authors advocate some newer methods, many scholars still go back to the seminal work by Weiss (1973)

who developed the first systematic model life tables based on prehistoric data. Weiss relied on the Gompertz model of mortality which works well for modern human adults, and to that extent his models are perhaps biased. We show that it is possible to rely entirely on data from prehistoric populations to generate a family of model schedules of mortality. Our approach avoids some (but certainly not all) of the criticisms that have been made of mortality models in paleodemography.

We selected from the life tables collected in Weiss (1973) a subset of 36 tables that included data on ages under 10 years. We focused on this subset because infant and child mortality is a key element of the overall life table; a separate analysis, not reported here, was conducted using the other tables and leads to similar results for adult ages. We used a simple smoothing procedure to generate life tables for age groups in 5-year wide intervals for ages 0 to 70, giving us a set of life tables $l(a,s)$ for ages a and samples s. The first step is to transform the data to a logit scale, i.e., we compute logits $n(a,s)$ such that

$$l(a,s) = exp[n(a,s)] \mathbin{/} [1 + exp[n(a,s)]].$$

This is a standard transformation in mortality analysis that essentially puts the life table values on a more useful logarithmic scale. Defining the average logit over all samples to be $k(a)$ we then performed a singular value decomposition (SVD) of the deviations from this average. An SVD will yield a set of age "patterns" that are an orthogonal decomposition of the data, and each pattern has an associated positive weight called a singular value. These weights tell us what fraction of the variation in the set is described

by the corresponding patterns: in our case we find that the first pattern explains 79% and the second pattern another 15% of the variation, for a total of 94%. Thus we conclude that the pattern in any sample is effectively described by a model of the form

$n(a, sample) = k(a) + A h(a) + B g(a),$

where *k(a)* is the observed mean, *h(a)* and *g(a)* are the first and second SVD patterns, and A, B are constants. Figure 1 displays the values of the logits for these three schedules – observe that *h(a)* shifts the entire schedule downwards (if A is positive), whereas *g(a)* shifts young ages down and old ages up (if B is positive). To find a model life table for any particular sample we must choose A and B to fit some overall parameters of the data, such as the expectation of life at different ages. To illustrate the procedure, Figure 2 shows contours of the expectation of life at birth *e0* for a range of values of A and B, and Figure 3 shows the expected life *e10* at age 10 for the same parameter ranges. To fix A and B one must specify the values of both *e0* and *e10*. Alternatively, one could use different computations to specify how A and B can be fixed in terms of other measures of mortality (e.g., survival to age 10, and e10).

We find it striking that a 2-parameter relational model describes so much of the variation in the data we used. Our finding surely reflect strong underlying regularities in early mortality patterns, even if they are not the same as in modern human data. These results suggest that further analysis along these lines should be fruitful.

Agriculture and Soil Nutrient Dynamics

Models describing the interaction between plants and soils are a subject of active interest in ecosystem ecology because of their utility for addressing questions about how natural systems may respond to global climate change. These models, including CENTURY, RothC, G'DAY, and many others, generally take the form of parameter-rich computer simulations which vary in some details, and in their ability to accurately describe different natural communities (Smith et al. 1997). Mathematical formulations of such models attempt to capture the broad similarities between the different simulations and to reveal essential characteristics that hold across ecosystems (Jenkinson 1990, Agren and Bosatta 1996, Comins and McMurtrie 1996, Bolker et al. 1998, Baisden and Amundson 2003). The insights gained from analytical descriptions of ecosystem dynamics provide a framework in which to approach ideas and questions important to agroecosystems, such as the notion of sustainability and the importance of observed spatial or temporal environmental variability in terms of yields of food crops.

We know of at least one study that pairs a simulation model with its analytical counterpart to explore questions about agricultural systems (Baisden and Amundson 2003), but we are not aware of any work that is appropriate to subsistence agriculture. Here we describe the essential features of nutrient cycling and present an analytic model derived from the well-validated CENTURY simulation model. We use the models to explore the effects of harvesting on sustainable plant production under water and nitrogen limitation. We vary the effective amounts of the limiting factor to determine what strategies might increase production. We also investigate the dynamics of cropping, and interpret our findings in terms of subsistence agriculture.

Our goal is to show how this mechanistic approach can play an important role in models of population and agriculture and to illuminate our understanding of early agricultural populations.

A Model of Plant-soil dynamics

Nutrients in all ecosystems cycle between the soil and the atmosphere. Plants take up water and inorganic nutrients such as nitrogen from the soil, and obtain inorganic carbon from the air. When plants die, they return carbon and nitrogen to the soil in organic forms. Soil microbes digest organic matter, releasing carbon dioxide back into the air as a byproduct of respiration and leaving behind more recalcitrant organic material. They may incorporate nitrogen into their own tissues, or release nitrogen in inorganic forms that are again available for plant uptake or escape in gaseous form to the atmosphere. Nitrogen from the atmosphere returns to the soil via biological fixation of nitrogen gas or by atmospheric deposition of mineral nitrogen (Brady and Weil 2002).

Soil organic matter (SOM), like radioactive material, decays linearly (Jenkinson 1990, Townsend et al. 1995), but not all organic material decays at the same rate. Compartment models treat SOM as made up of discrete fractions, each of which has a unique exponential decay rate. Perhaps the most successful compartment model is CENTURY (Parton et al. 1987, 1988) which has been successfully applied to a wide variety of natural systems (see, e.g., Schimel et al. 1997, Raich et al. 2000). An outline of

CENTURY's compartments is shown schematically in Figure 4. From that figure it will come as no surprise that CENTURY is a parameter-rich simulation model which makes it difficult to set up and run, especially in situations with limited data; simulation results from the full model can also be hard to interpret. What we seek are robust insights into the relationships between agricultural practice, soils, and climate. To obtain these, we follow Parton et al. (1987) and Bolker et al. (1998) and develop a compact system of equations that represent the model's core of exponential organic matter decays and coupled nitrogen flows. Below, we present a description of the model's general behavior (the equations, code, and other technical material are avaiable from the authors on request).

Plant growth (or 'productivity'), which provides the inputs of organic material to the soil, is a function of light, water, carbon dioxide, and nutrient availability. The component that is in shortest supply relative to plant needs limits plant growth (Sterner and Elser 2002). In this chapter, we assume for simplicity that the only factors that can be limiting are the water and nitrogen in the soil that are available for plant uptake. Monthly rainfall, temperature, and soil texture, all model parameters, combine to determine soil moisture. Plant-available mineral nitrogen is a model variable, and its abundance therefore depends on external inputs and removals as well as on its cycling through the system. What determines how much water and nitrogen plants need? In CENTURY, a fixed parameter specifying the maximum carbon-to-nitrogen ratio of new plant tissue and fixed functions for the maximum production per unit of water define these needs. For a given set of parameter values, we can compare available water and nitrogen to the amount needed by

plants to find out which factor limits the system. The identity of the limiting factor has

important consequences for nutrient cycling in the model ecosystem, as we discuss in

more detail below.

Once we understand the general behavior of the model we can ask and answer questions

about the effects of human participation in the nutrient cycle. For instance, we can

discuss sustainable ecosystem states in terms of model equilibria, since we know that the

latter are indefinitely sustainable system configurations. Below, we explore the effects of

adding harvesting to the model, which we represent by removing a fraction of new plant

growth from the system rather than returning it to the soil. We determine how increasing

harvest intensity affects model equilibria and dynamics under varying levels of nutrient

and water availability, and interpret our results in terms of food supply to subsistence

agriculturalists.

Impact of human harvesting activity

The effect of harvesting on plant production and harvest size depends on what factor

limits production at equilibrium. Increasing harvest intensity where water is limiting

does not affect equilibrium plant production, and therefore harvesting larger fractions of

production yields larger harvests (Figure 5). Even though only water is limiting here, the

equilibrium amount of mineral nitrogen and of organic nitrogen decrease linearly with

increasing harvest fraction (Figure 6).

Under conditions where nitrogen is limiting at equilibrium, increasing harvest intensity lowers initially low levels of equilibrium mineral nitrogen dramatically (Figure 7). Organic soil nitrogen decreases similarly, and is zero at 100% harvest. These decreases in availability of the limiting nutrient drive proportional decreases in equilibrium production with increasing harvest intensity. The result is a very slow increase in equilibrium harvest size with increasing harvest fraction over about 30% (Figure 8). The maximum sustainable harvest fraction, about 4% of the production in the uncropped system, occurs at 100% harvest. Increasing N inputs while remaining in the nitrogen-limited regime results in proportional increases in production and harvest levels, but increasing N inputs enough can switch the system to water limitation.

Even without changes in inputs of water or nitrogen, changing harvest intensity can itself change the factor that limits production at equilibrium. Figure 9 shows such a situation, where water is limiting for harvest fraction less than 0.5, and nitrogen is limiting for harvest fraction 0.5 and above. Each half of the figure shows the behavior expected from limitation by the corresponding factor at all harvest intensities.

We examine the impact of harvesting on system dynamics by simulating the system without harvest until it reaches equilibrium. We then impose 30% harvest, allow the system to equilibrate again, and return to 0% harvest to examine recovery. When water is the limiting factor, harvesting does not affect plant production, so this procedure does not actually result in any dynamics in production or harvest. Figure 10 shows how production responds to this treatment in a nitrogen-limited system at two levels of

rainfall.   Both runs show the same qualitative behavior: production plummets under harvest and then returns after cropping stops. The equilibrium levels of production and the temporal scale of system responses depend on soil moisture.   20 cm of monthly rainfall leads to higher production equilibria than 100 cm with cropping as well as without. All system responses are faster in the high-rainfall case. The dramatic drop in productivity occurs over roughly 80 years with low rainfall and about 50 years in the high-rainfall case. Recovery to pre-cropping equilibrium levels takes about 2000 years and 800 years, respectively.

Implications for food supply

Harvesting does not affect equilibrium plant production when water is the limiting factor because plant growth in that case depends on rainfall levels, and not on any factor that cycles through the plants. Only at the point where losses of organic matter change soil water-holding properties could harvesting change water availability. In contrast, harvest lowers steady-state production under nitrogen limitation because removing plant material imposes an additional loss of the limiting factor on the system. One implication of this difference is that, under water limitation, cropping a larger fraction of plant production increases the size of the sustainable harvest; whereas if nitrogen is limiting, harvest sizes are small compared to productivity in an equivalent uncropped system no matter what level of harvest effort is applied. In both situations, however, harvest constitutes a loss of nitrogen from the soil. Therefore, the possibility exists for intense enough cropping in a water-limited system to drive nitrogen levels low enough to become limiting (Figure 9).

Aside from its impact on plant production, reducing system nitrogen below the point where it becomes limiting would lower the nutrient quality of the harvested material. Whether or not a switch in limitation is possible and the precise level of harvest intensity where it would occur is a function of plant needs and of inputs and losses of water and nitrogen.

How relevant are equilibrium results to subsistence agriculture? We examined the dynamics of applying harvest to an uncropped system with two very different moisture inputs, and found that harvest sizes decline to equilibrium levels over just a few decades in both cases. Larger harvests might be possible if expansion of agriculture to new areas is possible before old ones suffer declines in productivity. Alternatively, landscape-level strategies that set aside portions of land in fallow may provide a way to increase harvests. Given that the time needed to recover soil nutrient status after relaxing harvesting is so much longer than the time needed to draw nutrients down, however, equilibrium levels of harvest are likely to be the relevant standard for agricultural systems.

One way to increase equilibrium harvest size without collecting a larger fraction of plant production is to add nutrients or water. Model behavior demonstrates that increases in the limiting factor increase plant production (and therefore harvest size) proportionally. Modern industrialized agriculture takes advantage of this fact in the forms of extensive irrigation and intensive fertilization. The activities that subsistence populations may undertake to improve their agricultural fields deserve careful attention if we are to understand their potential food supply.

Soil moisture affects nutrient cycling dynamics via its effect on decay rates as well as via water limitation. The analysis shown in Figure 10 demonstrates that spatial heterogeneity in soil moisture may have important implications for subsistence agriculture. The most important question is what is limiting in each place. If low-moisture areas are limited by water and high-moisture areas are limited by nitrogen, harvesting will affect the two locales very differently. Even if the same factor is limiting in both places, different levels of moisture can result in different levels of equilibrium productivity and different rates of responses to change. Additionally, as it affects the balance between weathering and leaching, abundant rainfall can induce enrichment of or limitation by rock-derived nutrients such as phosphorus (Vitousek et al. 1997), which is a process we have not considered here. Phosphorus can be included in the model, however, and analysis of its effects using the approaches illustrated here is an important avenue for future research.

Applications and Implications for Understanding Prehistory

We have shown how an understanding of plant-soil nutrient cycling dynamics as a linear dynamical system can illuminate how agricultural practice and natural conditions influence food production. The approach described here allows for much future work. One direction would be to introduce seasonality to the model, in harvesting as well as in environmental conditions and plant growth, to allow representation of processes that occur over annual or multiyear time scales. Another major issue is the effect of temporal stochasticity, for example to study the effect on agriculturalists of droughts or climatic

regime shifts. Tillage effects are also potentially important, as mechanical disturbance of soil can result in the conversion of organic nitrogen to plant-available mineral forms (Baisden and Amundson 2003). An exploration of these factors using a combination of simulation and analytical modeling will contribute much to our understanding of how subsistence agriculturalists interacted with the natural world.

Discussion

We began this chapter by discussing the limitations of our understanding of the feedbacks between demographic change and subsequent population growth, and populations and their agricultural resources. We also pointed to the problems of using demographic methods based on modern data to model prehistoric populations. We suggest two strategies to advance our understanding. For demographic analysis, we believe that data on early humans do contain useful regularities that can be exposed by data-driven analyses: we illustrated this approach by developing a new model mortality schedule for early humans. For the study of resources, food and agriculture we suggest a systematic analysis of dynamic models that couple agriculture explicitly to the nutrient status and dynamics of soil. This approach marches well with modern approaches to defining and assessing the resilience, sustainability and degradation of soils (Lal 1997). These threads – demographic and agriculture – provide the elements that need to be combined into a coupled dynamical picture of human-environment dynamics in prehistory.

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