Chapter 20
Ecology Limits Population, But Interaction with Culture Defines It: Carrying Capacity on Rapa Nui

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> *Quantifying the unquantifiable is sometimes a necessary academic practice, but it is justifiable only if the essentially artificial nature of the exercise is never forgotten.*
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> *–Tim Bayliss-Smith (1980: 62)*

1 Introduction

The study of island populations allows us unique insight into the relationships between human behavior and the environment. As Kirch (2007a) and others have pointed out, the Pacific represents a marvelous natural experiment because large parts of it were rapidly settled by descendants of a common founding population, bringing with them similar beliefs, agricultural practices, and technology. But despite the common origin of Polynesia settlement, by the time of European contact there was (and still is) tremendous diversity in population density, socio-political organization, the extent of inequalities and social stratification, diet, and the nature of daily life. This variation in response to variable environmental conditions holds the promise of deep insight into the study of human history, evolution, and ecology.

Importantly, one of the key elements in this natural experiment, the quantification of population, remains elusive. There are no detailed written census records from before European contact. In their absence, we can break the study of traditional Polynesian populations into three distinct phases: first-hand European observa-

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tions, second-hand knowledge, and the modern effort. First-hand observations of European visitors varied widely in their quality. Some simply recorded general impressions, while others attempted a more systematic estimate of the population numbers at the time of their arrival. Many of the most careful observations were made by members of the expeditions led by Capt. James Cook as they met with people from numerous islands across the Pacific in two voyages. In general, European observers were surprised by the size, and in some cases, wealth, of the populations they encountered. Johann Reinhold Forster, a naturalist on Cook's second Pacific voyage, was much impressed by the crowd that greeted the expedition's ships off Tahiti, and he used his counts of participants, along with estimates of the length of the coast and the productivity of sample breadfruit trees, to conclude that 121,500 people might live there (Forster 1996 [1778]). Cook's Lt. James King estimated 500,000 people lived on the Hawaiian Islands based on extrapolation of the population along the coastline (Beaglehole 2017), a number he later reduced to 400,000. Lt. William Bligh estimated 242,200 people without explanation of his reasoning (ibid.). This first informational phase is characterized by the observations of alien visitors, who often reported being surprised at the large population densities they encountered, but with limited opportunity to observe the interior and having no opportunity for a systematic survey of population.

The second informational phase centers around the early censuses of Christian missionaries who followed the whalers and traders, arriving decades after first contact to spread their religion and quantify the number of souls that might be saved. These earliest systematic accounts paint a dramatically different picture. Across the Pacific population densities are quite low, with evidence of abandoned homes, villages, and agricultural land. There are some accounts of the way life had been around the time of European contact (e.g., Malo 1951 and Iʻi 1959), but by the time these accounts were recorded all aspects of Polynesian society had undergone tremendous change. Population was much reduced by deadly diseases brought by the Europeans, and sexually transmitted diseases further reduced the fertility rates of the survivors for generations. By some estimates, populations were reduced by as much as 95% within decades of contact (see Stannard (1989) and Rallu (2007)). In the 1830s, one observer lamented that "the Sandwich [Hawaiian] Island race is fast diminishing, in but a few years it is to be feared that they will be spoken of as a people that were, but are not" (Rooke 1838).[1]

Modern scholars find themselves in the third informational stage, with direct observation no longer possible and those who witnessed the immediate aftermath of contact long gone. Beyond the records of the earlier two phases, we are left with two main resources to understand what life in Polynesia might have been like at the cusp of European contact. These sources are (1) the discovery and interpretation of information about that era, including evidence of residential occupation, economic activity, and land use, as well as information gathered from human remains, and

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[1] Quoted in Dye (1997).

(2) the characterization of agricultural and economic potential, given its cultural and ecological context, with the goal of estimating some measure of the number of people who might have been able to live in a place under a particular set of assumptions.

This third phase has been defined by a debate that has endured for multiple generations of researchers. It has its beginnings in the work of Norma McArthur, a demographer, who argued that the first careful records available to us, via the early missionary reports, suggest that the precontact populations were relatively small, even accounting for some effect of introduced disease, and that the observations of the first European visitors were likely gross overestimates of the actual populations (McArthur 1967). McArthur's view became the dominant one, and it took a new generation of scholars to begin the process of overturning it. Jean-Louis Rallu (2007) recounts how in 1989 his Ph.D. defense jury insisted he include only the lower bounds of his estimates of Tahiti's population if he wanted to pass. Similar battles were fought over population estimates in the Americas.[2] Rallu regards the reluctance of Western scholarship to recognize and accept the possibility of dense settlement in the Pacific and the Americas as a vestige of colonialism. Kirch (2007b) describes the difficult unraveling of McArthur's position in the Pacific, led by David Stannard's (1989) examination of the Hawaiian Archipelago and the population it might have supported when Cook first arrived. Stannard argued that Lt. King's estimate of the population was probably too conservative and based on evidence of land use and mariners' accounts that there may well have been 800,000 or more people living on the islands in 1778. In the decades since there has been some effort to confront McArthur's legacy, led in no small part by the growing number of indigenous Polynesian scholars. It has become more generally accepted that McArthur underestimated the true numbers, but there is no consensus as to the magnitude of the error. Our aim here is to address a number of these shortcomings and consider a framework by which we might incorporate ecological data into our estimates of ancient populations. In this chapter we describe how environmental and social factors influence human population and then move to an examination of two modeling approaches that incorporate these elements into estimates of maximum population size. We adopt Rapa Nui (Easter Island, Chile) as a case study, parameterizing the two models for the island and comparing the results to previous estimates of its population.

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[2] The father of one of this chapter's authors, archaeologist Dennis Puleston, was presented with an almost identical demand by his Ph.D. committee to reduce his estimates of the population of the Maya city of Tikal some 20 years earlier. A draft of the dissertation with the handwritten comments from his committee is available in his papers at Princeton's Firestone Library (http://arks.princeton.edu/ark:/88435/br86b3627).

2 What Limits Polynesian Populations?

One aspect immediately apparent to anyone interested in studying the past or present of Polynesia is that there was and is tremendous variation in population size and density from island to island. Land area is not a particularly good predictor of population, suggesting that there are multiple drivers at work. If one wanted to make a prediction about population on one of these islands at the point of European contact, what information would be most useful? Despite our uncertainty about exact population sizes, a few discriminating questions emerge. Is the island an atoll, a high volcanic island, or continental in nature? The first is made up of a coral cap atop what was once a volcanic island that has since submerged. Its soils are calcareous and generally poor. Crops are either rain fed or rely on access to the freshwater lens that usually lies below the ground of atolls, creating productive swampy areas in some. High islands are characterized by volcanic soils which, depending on their age, may be a good source of essential rock-derived nutrients. They are also likely to experience greater rainfall and more likely to feature seasonal or year-round waterways appropriate for irrigation. Islands of the continental type are characterized by more complex geology and may host a wider variety of endemic species than the previous two types. It might also be useful to know something about the climate where the island is located. Is it more temperate, like Aotearoa New Zealand, where some Polynesian staple crops can only grow in parts of the archipelago in parts of the year, and many staples do not grow at all? Or is it tropical, like Tahiti in French Polynesia? How much rainfall does the island receive?

All of these questions get at the *resource potential* of an island: the availability of land suitable for the important cultigens of taro, sweet potato, breadfruit, bananas, and coconut. They also tell us something about the availability of animal protein, including the fish and shellfish found in greater abundance around atolls, and terrestrial domesticates, which may be more likely to thrive on the bigger high islands.

It seems reasonable that access to food resources might limit populations on islands and elsewhere, but how do we generate a model, or equivalently, a set of general principles by which we might estimate the greatest number of people who might have lived in a particular place? One approach, and perhaps the most deeply entrenched, is to focus on the availability of carbohydrates, which are fundamentally important to the Polynesian diet. Tim Bayliss-Smith (1974) did a careful study of several Polynesian Outliers near the Solomon Islands in the early 1970s. He was interested in the question of population limitation and chose the location because the islands were relatively isolated (“closed”), the inhabitants still ate essentially a subsistence diet, and the imported foods that they consumed were arguably simple replacements for traditional diet items. He suggests that although population on these atolls was self-regulated by “cultural controls” (including abortion and infanticide) as opposed to starvation, the desirable population levels were informed by food availability. In other words, resource limitation created an upper bound that the islanders were aware of and worked to avoid.

But food is more than just calories. What is acceptable as a diet varies across time and space and people may suffer hunger in the presence of plenty if the resources do not meet their definition of edible, or if the food cannot be balanced with other resources considered essential. Echoing observations made elsewhere in Polynesia, Bayliss-Smith (1974) writes that going very long without taro (a starchy root crop of particular importance across the Pacific) "is considered a great hardship," and that of all the foods available, the starchy tuber is "the main determinant of the maximum carrying capacity" for cultural reasons as well as for its caloric density and return to labor inputs. He defines "carrying capacity" as "the ceiling to population growth that the ecological constraints in a given system of resource management determine," by which he means a maximum population in a specific agricultural and technological context. Unlike taro, coconut appeared to be available in surplus on these islands, despite its favorable caloric density and return to labor inputs. In three surveys of diet and food resources on the atolls, he found that although diet composition changed across time and space, taro and its substitutes made up a minimum of 30% and maximum of 70% of the caloric input, and averaged close to 50%. Coconut was 15–20%, and fish 10–30%. As plastic as the diet was, there were bounds of acceptability that appeared to be defined as much by culture as nutrition. These populations desired some 50% of their calories to come from taro and other starches, but 25% represents the "extreme limit of acceptability." Bayliss-Smith acknowledged that dietary preferences might have changed since precontact times, but felt justified in using these findings as the basis for his analysis.

To estimate carrying capacity, Bayliss-Smith calculated the area available for the two dominant taro varieties grown on the atolls. Some of these areas were not in use for taro or even at all at the time of his study, but he believed they likely were used in the precontact era. Using local yield estimates he calculated the maximum sustainable population based on the total productivity and the minimum consumption level of each of the two staples. This food output was divided by the mean energy requirement per individual, which was estimated at 1800 kcal/day after considering the population structure and several studies of energy consumption.

On two of the atolls "overcrowding became a perceived reality when numbers were only 70–80% of the maximum carrying capacity" (Bayliss-Smith 1974). Bayliss-Smith found that expressing population density as a function of agricultural area (taro-suitable area in this case) made more sense than using total land area (see Kirch (2010) and others for later applications of this approach). He also found that population density (in the 1970s) was negatively correlated with atoll size across a larger sample, but that may well have been because a number of the larger atolls in the comparison were drier and were less agriculturally productive as a result. In any case, Bayliss-Smith cautions against using his data and findings to make more general statements about Polynesian populations on atolls. His results hinge on the agricultural area and productivity of the staple foods, and Bayliss-Smith warns that the analysis should not be ventured upon without reliable local data. And although he finds a relationship between the carrying capacity calculation and modern and past population estimates, he emphasizes that in some places periodic natural disasters may keep populations below this threshold, or induce the population to manage its own numbers to mitigate the risk of famine.

The three food categories Bayliss-Smith (1974) examines, taro, coconut, and fish (and their substitutes), map well onto the three major macronutrients in the human diet: carbohydrates, fats, and proteins, respectively. These are important sources of energy, and are often important sources of other essential micronutrients. Modern health experts suggest that the acceptable macronutrient distribution range (AMDR) is 45–65% of total calories from carbohydrates, 20–35% from fat (for ages 4+), and 10–35% from protein (for ages 18+) (Institute of Medicine 2005). However, there are examples of populations that have existed for long periods on diets that do not meet these requirements, including the Inuit of extreme North America and the Moriori on Rēkohu (Chatham Islands, Aotearoa New Zealand), both of whom consumed considerably less carbohydrate than the AMDR, replacing much of it with the blubber (fat) of marine mammals (Leach et al. 2003).

That fat and carbohydrate might be exchanged for one another raises the question of protein. Protein is made up of amino acid building blocks, which our bodies may break down and use in our own metabolic machinery to make new proteins for our own use. However, there are a number of amino acids deemed “essential” in that our bodies are unable to manufacture them and so we must acquire them from proteins in our diet. Even in the presence of an abundance of fat and carbohydrate, a shortage of these essential amino acids will lead to hunger, wasting as the body breaks down muscle tissue to free up amino acids, and finally death.

In response to Bayliss-Smith (1974), anthropologist Stephen Beckerman was interested in whether access to protein might limit population sizes on the high islands of the Pacific, because in comparison to the atolls Bayliss-Smith studied, these islands supported a greater variety of food sources, and because there seemed to be arable land that lay uncultivated, as if available in excess (Beckerman 1977). The idea of protein limitation on population growth had been proposed for the Amazon, and although Beckerman was skeptical of its applicability there, he thought it might make more sense in the Pacific. He proposed that if coconuts and reef fish were the main sources of scarce protein, and these were concentrated along the shore of most Polynesian islands, then maximum subsistence population should correspond to island circumference. He gathered shoreline length estimates for 10 Polynesian high (volcanic) islands representing a range of sizes and used estimates of population size at the time of European contact, all generated in the previous 10 years to reflect the post-McArthur revisions then underway. He plotted the population estimates against the shoreline length and performed a linear regression. He reported a correlation coefficient of 0.967, and the resulting equation predicted that once a minimum threshold was met (approximately 50 km), each kilometer of shoreline supported 222 people. A plot of population vs. area did not show a strong linear relationship, encouraging Beckerman to conclude that shoreline-associated protein sources were indeed limiting.

Citing their observations from Micronesia, Rosalind Hunter-Anderson and Yigal Zan responded that the protein limitation hypothesis did not explain what archaeologists and anthropologists were finding on Yap and its surrounding island complex

(Hunter-Anderson and Zan 1985). They argued that Beckerman's analysis did not stand up to closer scrutiny. First, they pointed out that the Yap Island Complex probably supported two or more times as many people as Beckerman's equation predicts, based on house counts. And Yap is a perfect candidate for a fish-dependent population, being surrounded by a rich lagoon, unlike the islands in Beckerman's analysis. They argue that despite the presence of a correlation in Beckerman's data, shoreline extent is not necessarily an indicator of protein availability in the diet. In the Hawaiian Archipelago, the seven islands showed only a weak relationship between reef length and shoreline length ($r = 0.101$), and the islands with the largest populations in the study (the geologically younger Hawai'i and Maui) had less reef. In addition, areas of known population concentration in the precontact era did not correspond well with reef zones for five out of the seven islands in the chain. The authors also cite evidence that coconut was not an especially important part of the diet among the Hawaiians. The correlation Beckerman observed could be explained just as easily by factors related more closely to agricultural potential, including the presence of soils suitable for rain-fed and/or irrigated agriculture, or the presence of brackish swampy areas suitable for the production of starchy staples often found at the edges of volcanic islands.

Hunter-Anderson and Zan proposed the more general "intensification hypothesis": "the upper limit of population size appears to be conditioned by the presence of intensifiable resources. Under certain geographical conditions, these resources might involve protein, and under others, starch. In small tropical high islands, the intensifiable resources tend to be starchy" (Hunter-Anderson and Zan 1985:63). Accepting Beckerman's proposed relationship between island perimeter and population, they found that perimeter was in fact a better predictor of terrestrial resources (land area) than marine resources (reef length) among islands in the Hawaiian Archipelago. They found strong relationships between perimeter length and the (1) extent of replaced-vegetation cover, (2) area of swampy brackish water, and (3) area of all intensifiable soils. Further, they point out that Beckerman's model is inapplicable to islands smaller than 50 km circumference runs counter to the protein hypothesis as well. These small islands are mostly coral atolls, and it would be reasonable to expect these populations would be most closely tied to resources from the sea. The intensification hypothesis is a better explanation of population limits on these coral and limestone atolls: "In these settings intensive taro cultivation is possible due to the subterranean fresh water lens which is thickest towards the centre of the island. Accordingly, taro gardens tend to be located in the centre of coral islands rather than on their peripheries, which are either rugged reef rock or excessively drained beach sands" (Hunter-Anderson and Zan 1985:64).

3 Carrying Capacity

Each of the studies we have examined so far is an attempt to describe "carrying capacity," whether numerically, as in the case of Bayliss-Smith (1974) and Beckerman (1977), or in more general terms (Hunter-Anderson and Zan 1985). A key moment on the path to the modern concept of carrying capacity occurred when mathematician Pierre-Francois Verhulst (1977 [1838]) derived an equation that seemed to capture important aspects of how populations grow to their maximum density. All one needed to know was the maximum growth rate, r (assumed to exist when the population was infinitesimally small), and the maximum population size, K. The growth rate at any point is determined by the equation:

$$\frac{dN}{dt} = rN\left(\frac{K - N}{K}\right),$$

where N is the population size and t is a measure of time. Verhulst's equation imagines a population whose per capita growth rate is unfettered when the population is small and resources are abundant, but each new individual draws down those resources and thus reduces the growth rate going forward. There are only enough resources to maintain K individuals, so as a population approaches K, which later came to be termed the carrying capacity, the balance of its birth and death rates get closer and closer to zero. Although the equation does capture the dynamics of some populations, it has a checkered history in the study of humans. Despite both its potential utility and the inherent reasonableness of the idea that resources are finite and populations that subsist on them should be, too, "pragmatic and conceptual problems bedevil attempts to calculate human carrying capacity, and this simple cybernetic model has been left without effective application. This has led to redefinition, to circumlocution, and, finally, to denials that such a thing exists" (Dewar 1984:601).[3]

Dewar (1984) argued that we have often confused two related concepts in our thinking on carrying capacity. The K described by Verhulst is a demographic construct, based on how the growth rate responds dynamically to population density. This should be separated from what some have called the ecological, or environmental, carrying capacity, which can be defined as "the maximum ability of an environment to continuously provide subsistence at the level of culture provided by the inhabitants" (Hayden 1975:11). Others have identified an additional host of uniquely human variables that would further reduce maximum, or equilibrium, populations from the environmental carrying capacity. This has been called the social or cultural carrying capacity, defined as "the maxima that could be sustained under various social systems" (Daily and Ehrlich 1992:762). Or, as Seidl and Tisdell (1999:403) put it:

> The application of carrying capacity to the human species requires the recognition that the carrying capacity is foremost socially determined, rather than biologically fixed due to the important influence of human consumption patterns, technologies, infrastructure, and impacts on the environment or food availability.

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[3] Similarly, Tuljapurkar et al. (2007:37) called carrying capacity an "intuitively appealing if slippery concept."

Human populations affect their food resources through exploitation (and overexploitation) of wild foods. We also have the ability to develop new food production practices and technologies, which in Polynesia included the development of more efficient fish hooks, selecting for better cultivars, constructing fish weirs and ponds, investing in agricultural infrastructure (e.g., irrigation systems, stone mulching, or linear alignments or walls for windbreaks), or environmental engineering to modify geomorphological settings, and other forms of niche construction. To make generalizations even more difficult, human culture may lead to choices about food and other resources that vary across time and space, requiring the consideration of cultural attributes. Examples of these choices, or behaviors, include the degree of social stratification and expected amounts given in tribute, the degree to which individuals and neighboring communities cooperate or engage in hostilities with one another, the sexual division of labor, the presence of formal or informal methods of fertility or mortality control, the degree of agricultural intensification, and diet composition. There is also the issue of the time period that individuals are considering in their decisions about subsistence production and the likelihood of "good" or "bad" years within that time period. The sad truth is that any estimate of human carrying capacity must make assumptions about all of these things, and more. These difficulties do not invalidate the practice, but we would be wise to expend the effort to understand the ones that are most likely to affect our results. In the next sections, we will consider the role a number of these factors play in two models of population size parameterized for the island of Rapa Nui (Easter Island, Chile).

4 Considering Human Welfare, a Rapa Nui Case Study

When the Dutch explorer Jacob Roggeveen's ships became the first European vessels to arrive at Rapa Nui in 1722, he made two relevant observations in the ship's log. The first was that the population had every appearance of health: "These people have well proportioned limbs and large and strong muscles; they are big in stature .... These people also have snow-white teeth with which they are exceptionally well provided, even the old and hoary, as was evidenced by the cracking of a large and hard nut, whose shell was thicker and more resistant than our peach stones" (González 1903:15).[4] This appraisal of the health and robustness of the islanders was echoed in the notes of other members of Roggeveen's party and is supported by modern research.[5] The second observation was that the island appeared to be well suited for agriculture, even if it was not being used at its full capacity:

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[4] An excerpt of Roggeveen's lost and rediscovered ship's log was translated into English and published in the Hakluyt Society's series on great explorers in a volume, along with the account of the second known visit to Rapa Nui by a European, Don Felipe González's 1770 landing.

[5] A study of the remains of 125 Rapanui who died in the contact era lends credence to Roggeveen's observations. Biological anthropologist Caroline Polet (2006:269) concluded that analyses of the bones and teeth "indicate a relatively good state of health among the Rapanui during

> [W]e found it ... exceedingly fruitful, producing bananas, potatoes, sugar-cane of remarkable thickness, and many other kinds of fruits of the earth; although destitute of large trees and domesticated animals, except poultry. This place, as far as its rich soil and good climate are concerned, is such that it might be made into an earthly Paradise, if it were properly worked and cultivated; which is now only done in so far as the Inhabitants are obliged to for the maintenance of life (ibid., p. 21).

This description of hearty Rapanui with pearly white teeth stands in stark contrast to the sad, rotten-mouth natives described in Jared Diamond's best-selling book *Collapse* (2005). He points to their leaky boats, the treeless, wind-swept landscape, rock-mulched gardens, and modern signs of erosion in one portion of the island as evidence of their misery. Based on this sorry scene, he concludes that Rapanui society ultimately failed to navigate the essential challenges of their environment, echoing the thesis of his book. Diamond has come in for much criticism for his characterizations of the Rapanui and Maya, in particular, in his effort to make the worthy point that humans would be wise to heed the fragility of our environment. But the more relevant story of the Rapanui may be one of adaptation and resilience in the face of a difficult environment in one of the most isolated places on the planet, a case made by biologist Jan Boersema (2015). By the time Roggeveen set foot on the island, the Rapanui had survived and changed their culture in several important ways over the more than 500 years since their arrival. In those years they adapted to the deforestation of their island and managed the transition from an expanding population to one confronting the limits of its environment, while at the same time managing to create the nearly 1000 stone moai statues that captivated visitors from Roggeveen to this day. Evidence of land use suggests that despite claims of a population crash or collapse, while some areas of the island were becoming less heavily used and occupied, other more favorable areas were still growing at the point of Roggeveen's visit (Stevenson et al. 2015).

The tremendous interest in the history of Rapa Nui and the effort devoted to understanding it has led to some remarkable discoveries. However, the size and nature of the population that lived there in the time before European contact remains a heated topic. In the following we will consider two models of population size parameterized for Rapa Nui, each proposed as an improvement on the carrying capacity approach.

The first was developed by Bayliss-Smith (1980) to incorporate the idea of human welfare into the carrying capacity debate. Why would islands in Fiji in the 1970s be observing depopulation if by any measure they were below their carrying capacity? He thought the answer lay at least in part in human agency, or people acting on their desires and expectations about what life should be like. In practical terms, what happens if we assume people are only willing to work at some fraction of the theoretical maximum? As Ester Boserup (1965) described in her groundbreaking work on population pressure, it is often possible to get more

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their childhood, compared to other ancient samples from the Pacific and to Medieval European samples."

food energy per unit of land, but in preindustrial societies without pack animals, the price of this intensification is paid in human energy. Which brings us to a key question: Why would anyone choose to work harder than they already do? There are, of course, reasonable answers, including that you foresee or feel the consequences of population growth and want more food, or perhaps you are compelled to in order to satisfy the need for tribute, taxation, or exchange for other things you require or desire. But several years after his efforts to model atoll populations (Bayliss-Smith 1974), Bayliss-Smith became interested in what happens if people limit their work effort. How do variable levels of labor input affect population? And how do we account for surplus production? Certainly, an agrarian population that is required to feed a large non-producing class has to work harder to maintain the same standard of living as one that does not.

Bayliss-Smith (1980) developed a 10-step process to incorporate work effort and level of surplus production into the study of population (Box 20.1). The first five steps are required to calculate the carrying capacity, by which he means the population that can be supported at the "ultimate level of intensity that is acceptable" (Bayliss-Smith 1980) from a staple production system contributing some known fraction of the total diet. The two models we discuss in this chapter conform to the Hunter-Anderson and Zan (1985) "intensification hypothesis," in which we are mostly concerned with the production of starchy staples as the most important and limiting elements of the islanders' diet. The assumption that protein was not limiting is supported by DiNapoli et al. (2019), who surveyed the literature for information on the island's resources and described a significant input of marine foods.

The final output contains what Bayliss-Smith called "standard populations," which are population sizes that correspond to a certain expectation of labor and a certain fraction of surplus production in a given place using specified crops with a specified technology. That is extremely powerful. And if we know something about the surplus requirements and/or the expectation of labor, it allows us to narrow the likely population size estimates. Bayliss-Smith (1978) found that on many small islands of the Pacific the effort by the productive population was typically in the range of 10–20 person-hours per week.

Box 20.1 Calculating Bayliss-Smith's Standard Populations

Bayliss-Smith (1980) describes a 10-step process for calculating "standard populations," which are the population sizes that account for the effects on carrying capacity of differing levels of work intensity and also for various levels of surplus production. The original work includes description and several worked examples. The first five steps calculate the carrying capacity, which assumes maximum intensification of agriculture and that all food goes to support an egalitarian population. The next five steps account for how total yields respond to diminished intensification (labor inputs) and how

(continued)

Box 20.1 (continued)

the diversion of increasing fractions of production into "surplus" affects population size. The final step assembles the data into a table of population sizes under combinations of labor intensification (hours) and surplus.

Step 1 specifies the quality and extent of land available to the population. **Step 2** describes the economy, specifically the fraction of total calories derived from the staple production and the fraction of the population that is actively involved in production. **Step 3** describes the "maximum acceptable intensity level," which refers to the minimum return to labor. Specifically, if a person-hour of labor provides less than 1750 kcal, then it is unlikely to be deemed worth planting. **Step 4** requires the calculation of productivity of land and labor. These vary according to the crop and context. Bayliss-Smith (1980) assumes in his worked examples that a person-hour of work expends 175 kcal. This figure is used to turn the agricultural labor requirement (the observed or estimated person-hours required to produce a hectare of a particular crop) into human energy input requirements. We must also estimate the food energy output per hectare in the particular context. **Step 5** calculates the carrying capacity from these figures:

$$K = \frac{YA\left({}^{1}\!/_{F}\right)}{R},$$

where Y is the crop yield in kcal/ha/year, A is the area in ha that meets the minimum return to labor threshold, F is the fraction of the energy in the diet that comes from the modeled staples, and R is annual energy requirement on a per-person basis, in kcal/year. The first two factors in the numerator determine the total staple output, staple fraction is the fraction of the diet that comes from these agricultural staples, and R is the energy requirement per individual per year, which Bayliss-Smith estimates at 800,000 kcal/year, or 2192 kcal/day.

The remaining steps address the questions of welfare. **Step 6** calculates the person-hours each worker is required to labor to produce the maximum food output. For this, we need to know something about population structure and the division of labor. If only men work in the fields and men make up half the population and only half of these are working age, then the "productive population" is 25% of the total. These workers are responsible for all the person-hours required to produce the staple, so we calculate person-hours per week required of the typical worker. In **Step 7,** you begin to assemble a table, starting with the population size at various fractions of K (i.e., 90% K, 80% K, etc.), and determine the size of the productive population for each. Then you calculate the food energy required to feed each population and the number of person-hours per week required of the productive population in each case. In

(continued)

Box 20.1 (continued)

his worked example, a reduction in population size from K to 90% of K meant that the productive population's effort fell from 28.1 to 17 hours per week.

Step 8 is the creation of a graph of output per person-hour vs. output per hectare of all land in the agricultural system, including fallowed land. **Step 9** involves the calculation of person-hours per worker when the population is required to produce a surplus, expressed as a fraction of the subsistence requirement (S). That is, if the population produces $S + 50\%$, each worker now has to work some additional amount to provide the extra. Some combinations of population size and surplus may not be feasible, as the food energy required exceeds the potential output of the available land, or the effort required to maintain a population exceeds what most subsistence populations regard as acceptable. **Step 10** assembles a table of results with producer population person-hours on the rows and total production (subsistence plus surplus) across the columns. The entries are population sizes. This step requires interpolation from the data in the table created in Step 7.

The parameterization of Bayliss-Smith's model for Rapa Nui involves making assumptions, some of them "heroic," to borrow a phrase from population biologist Shripad Tuljapurkar (Pers. Comm.). Some of these unknowns have already been estimated by Bayliss-Smith and we use these values where better, more local, options are unavailable.

For Step 1, the island of Rapa Nui is approximately 164 km^2 in area, and 3134 ha, or 19%, was deemed suitable for agriculture using shifting cultivation (Puleston et al. 2017). However, in low-yield scenarios some or all of this land may be considered too poor to farm, which is discussed below. Step 2: Following Bayliss-Smith (1980), we assume that sweet potato was the dominant starchy staple in the diet and that it provided 80% of the energy in the diet, the remainder coming from all other sources, including domesticated animals, fishing, and garden foods. The model only tracks labor dedicated to farming the main staple(s), and the acquisition of all other foods and the completion of all other tasks are assumed to be done in the remainder. This parameterization is not tied to any particular era in Rapa Nui history, although we assume that all the agricultural land was in regular rotation (i.e., had been cleared of primary forest) and that the island had completed the early phase of human habitation when some native resources (e.g., wild birds) were more plentiful. For Step 3 we accept Bayliss-Smith's minimum threshold for return on labor in subsistence economies as 1750 kcal/person-hour. Step 4 requires the description of the relationship between human energy input and energy output (crop yield). Bayliss-Smith (1980) includes an estimate for sweet potato in the New Guinea Highlands in his Figure 5, but laments the paucity of data. Puleston et al. (2017) used a nutrient cycling model of sweet potato growth parameterized with climate data gathered on Rapa Nui. That model bracketed likely nitrogen availability, which is unknown, including a low-N and high-N scenario. It is unsurprising that yields per hectare would be lower than observed in more tropical parts of the Pacific and those with more plant-available nitrogen. Much of the data on sweet potato cultivation comes from Papua New Guinea, but as the yields reported there are so much higher, and the labor estimates are so much lower there than elsewhere in Polynesia, it suggests that they are not representative of conditions in Remote Oceania. Unfortunately, there are only a handful of estimates of labor inputs for traditional sweet potato farming from outside New Guinea. We averaged the four estimates known to us, two from Burtenshaw and Harris (2007) and one each from Christiansen (1975) and Jones (1989) to get 2810 person-hours/ha (CV $= 0.71$, where CV is the coefficient of variation, or standard deviation divided by mean).

For Step 5 for our two nitrogen scenarios we calculate K, the carrying capacity for Rapa Nui, following Bayliss-Smith's (1980) assumption that each person requires at most 800,000 kcal per year, and at the yields representing maximum labor intensity, or continuous cultivation. Replacing Y in the carrying capacity equation above with the low-N continuous cultivation value of $1.59\text{x}10^6$ kcal/ha/year and the high-N equivalent of $5.56\ \text{x}10^6$ kcal/ha/year gives $K_{lo} = 7786$ and $K_{hi} = 27{,}227$ individuals, respectively.

For Step 6 we follow Bayliss-Smith's assumption that only men work in the fields and men represent half the population. Further, only half of the men are of working age, meaning that all field labor is the responsibility of 25% of the whole population. The "productive population" (worker pool) at K_{lo} and K_{hi} is thus 1947 and 6807, respectively. The 8,806,540 person-hours per year required to tend the entire island's crops results in a work week of 87.0 and 24.9 hours per week in the low-N and high-N scenarios, respectively, for the productive population. Already we can see a problem. It is not impossible for preindustrial workers to put in the hours of a junior partner at a white-shoe law firm, but recall that based on Bayliss-Smith (1978) 10–20 hours per week is more to be expected. But these are the hours required to maintain K, the theoretical maximum population size, and there are tradeoffs to consider. Bayliss-Smith (1980) examines the dependence of population size on the expectation of labor (hours worked per week) and the size of the burden of surplus, meaning any food that exceeds what is required for the population's upkeep at the level specified.

Following Bayliss-Smith (1980) we calculated the work hours required from the productive population at 10 population sizes from 25% K to K, and under seven surplus regimes from no surplus to the subsistence requirement (S) plus 150%. For each nitrogen scenario in Puleston et al. (2017) we had three yield values, each associated with a level of intensification (fallow regime). Following Bayliss-Smith (1980), we fit piecewise linear functions to the returns to labor vs. returns to land for each nitrogen scenario to find yields for the levels of labor inputs required to fill out our tables. Finally, we used a spline interpolant in MATLAB to determine intermediate values and present the results in a form where population size is the dependent variable, varying with weekly labor expectation and surplus requirement. The resulting "standard populations" are found in Tables 20.1 and 20.2. Figures 20.1 and 20.2 illustrate the dependence of maximum population size

Table 20.1 Standard populations for the low-N scenario on Rapa Nui, following Bayliss-Smith (1980). The values in the table are the population sizes predicted under the combination of expectation of labor and surplus production. *S* represents subsistence production, and the level of surplus required of the population is proportional to this value. Missing values in the upper left represent combinations falling below the minimum return to labor. Missing values in the lower right represent places where the population size fell below 25% *K*

Low-N regime							
Weekly Hrs	Standard populations at stated productive levels						
Per worker	S	S + 10%	S + 20%	S + 30%	S + 50%	S + 100%	S + 150%
50							
40						2344	
30			4375	3880	3120		
25	5228	4553	3997	3506	2759		
20	4686	4022	3444	2981	2221		
15	3782	3114	2564	2078			
12.5	3079	2406					
10	1997						
7.5							

Table 20.2 Standard populations for the high-N scenario on Rapa Nui, following Bayliss-Smith (1980). The values in the table are the population sizes predicted under the combination of expectation of labor and surplus production. *S* represents subsistence production, and the level of surplus required of the population is proportional to this value. Missing values in the upper left represent unviable combinations, either exceeding *K* or falling below the minimum return to labor. In the lower right, they represent combinations where the population size fell below 25% *K*

High-N regime							
Weekly Hrs	Standard populations at stated productive levels						
Per worker	S	S + 10%	S + 20%	S + 30%	S + 50%	S + 100%	S + 150%
50						13,653	9833
40					18,573	11,873	8875
30		25,566	22,826	20,457	16,467	10,638	7839
25		23,842	20,909	18,479	15,060	10,146	7292
20	24,716	21,312	18,641	16,162	13,640	9382	
15	21,026	18,556	16,762	14,934	12,274	8031	
12.5	19,951	17,522	15,743	14,069	11,321	7036	
10	18,599	16,208	14,271	12,547	9937		
7.5	16,070	13,761	11,755	10,083	7394		

on the expectation of labor and the burden of surplus production under low and high nitrogen availability, respectively. The three-dimensional surface is similar in both cases, although the scale differs. Unsurprisingly, population is maximized when labor is plentiful and the surplus requirement is small. However, increasing labor inputs eventually results in nonviable populations because the investment in additional labor is not rewarded with enough additional production to justify the expense. The return to labor falls below the subsistence threshold of 1750 kcal per

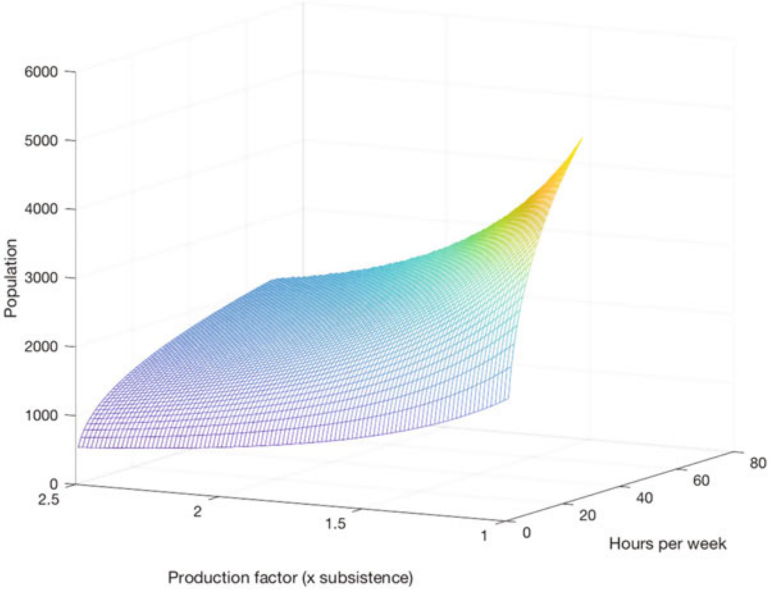

Fig. 20.1 The surface of Rapa Nui standard populations as production requirements and hours worked per week vary in the low-N environment under the Bayliss-Smith (1980) model, parameterized as discussed in the text. The maximum population of 5291 occurs when there are no requirements to produce a surplus and when the productive population works 28.0 hours per week. Increasing intensification beyond this point results in a return to labor below the subsistence threshold. The axes are oriented to give a sense of the shape of the surface, which might make it difficult to accurately identify population levels

hour of work, making the combination untenable. Also, the surfaces show that as hours per week increase, the response flattens out, meaning a diminishing return for each unit of extra labor. Population size is most responsive to the burden of surplus when the demands are small. At higher levels of surplus, the response is quite linear.

Unfortunately, the uncertainty surrounding nitrogen availability leaves us with the conclusion that the maximum precontact population on Rapa Nui was probably somewhere between the low estimates and the high ones. However, this approach does narrow the range of solutions, namely by allowing us to exclude some combinations of parameters because they rely on yields that would likely never be realized as the return to labor is too low. Imagine a poor hectare that could grow a meager pile of sweet potato, but it required all the same labor to prepare, plant, and tend as a better patch. At some point, even if you were starving, it might not be worth it to grow there because the food it produced would not compensate you for the energy you put in, or that other activities might give you a better return on your efforts.

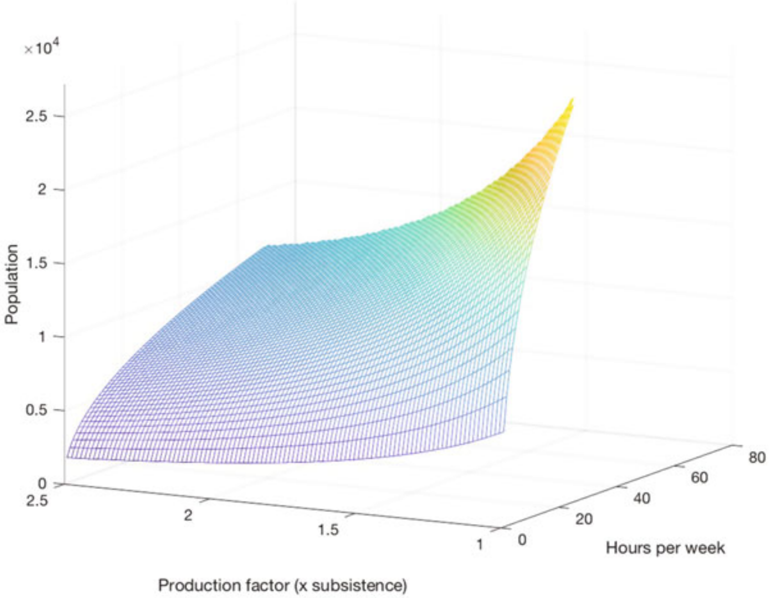

Fig. 20.2 The surface of Rapa Nui standard populations as production requirements and hours worked per week vary in the high-N environment under the Bayliss-Smith (1980) model, parameterized as discussed in the text. The maximum population of 27,227 occurs when there are no requirements to produce a surplus and when the productive population works 24.9 hours per week. The surface is quite similar to the low-N equivalent, although the scale of population is greater

5 Modeling the Effects of Hunger on Rapa Nui Population

After estimating sweet potato yield in the two Rapa Nui nitrogen scenarios, Puleston et al. (2017) used those values to consider population size in the space-limited model described by Puleston and Tuljapurkar (2008) to capture the dynamics of a subsistence agrarian population that grows in size until it eventually finds it is running out of land to farm. In contrast to the approach of Bayliss-Smith, this model (illustrated in Fig. 20.3) is built around the concept of the food ratio, which is the ratio of food availability to the amount required to maximize survival and fertility (Lee and Tuljapurkar 2008). If the food ratio is 1 or greater, then the population is capable of producing as much food as it needs to avoid hunger, and vital demographic rates are assumed to be maximized. If the food ratio falls below 1, then survival and fertility rates begin to decline. If a small population arrives in a suitable location for agriculture and the initial food ratio exceeds 1, the population will grow at its maximum (baseline) rate. This small population might only have enough labor available to farm a small part of the land available. It continues to grow at its baseline rate while expanding the area of cultivation and perhaps

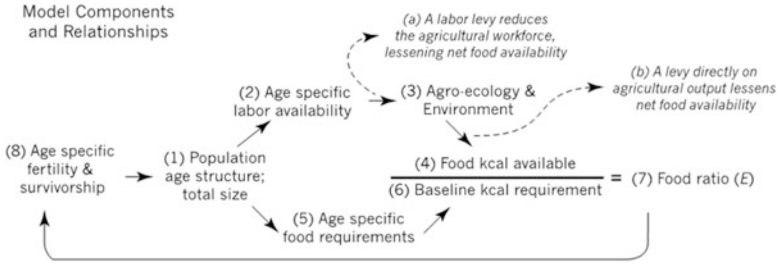

Fig. 20.3 A schematic of the space-limited model. Given some population of a given size and age structure we can calculate food availability based on its labor potential and the characteristics of the food production system. The minimum number of calories required to avoid any negative effects of hunger can also be calculated. The ratio of availability to need (the "food ratio") is used to determine the age-specific fertility and mortality rates that generate the population at the start of the next cycle. A small colonizing population on suitable land in a constant environment will grow at its maximum rate until the food ratio falls below 1. At this point hunger begins to reduce fertility and survival rates and growth slows at it approaches an equilibrium. The dotted lines indicate where tribute and taxation influence the system, whether taken as a work levy (a) or as a food levy (b). Figure adapted from Winterhalder and Puleston (2018)

intensifying production, with diminishing returns as it approaches the maximum of total production, which occurs when all land is in use. Along this trajectory eventually the food ratio falls below 1 (the number of mouths grows, but land is limited) and the effects of hunger begin to rein in growth. The population approaches an equilibrium where the increasing death rate and decreasing birth rate balance and growth slows to zero.

Puleston et al. (2017) determined the equilibrium population size for Rapa Nui for a variety of scenarios, chosen to represent likely combinations of environmental and cultural parameters that remained unknown (also see Lipo et al. 2018 and Puleston et al. 2018) (Table 20.3). Expected sweet potato yield was modeled across three intensification levels (continuous cultivation, 5 years of cultivation followed by 5 years of fallow, and 3 years of cultivation followed by 15 years of fallow) and across the two nitrogen availability regimes. The authors also considered three cultural features: the requirement to pay tribute to maintain a non-producing elite, the fraction of the working-age population working in agriculture, and the presence of rapid and strong fertility control measures in response to increasing hunger. The tribute in the hierarchical scenario was assumed to be fixed at 10% of total food production. The worker fraction was set at 50%, 75%, or 100% of the working-age population. The authors assumed each full-time equivalent worker (working-age population times worker fraction) could farm just under a single hectare as an ongoing responsibility, representing a conversion of the expectation of labor into units of land. However, as more and more of the total agricultural area was put into use, the return to labor decreases, leading to an asymptotic (ever-slowing) approach to full utilization of land. This feature of the space-limited approach captures the expected decreases in quality of remaining land as better areas are allocated first,

Table 20.3 Equilibrium population sizes on Rapa Nui (commoners and elites) under the space-limited model under multiple scenarios. Empty cells represent nonviable combinations under the assumptions of the model. After Puleston et al. (2017) Table 2

Organization	Egalitarian						Hierarchical					
Pop Control	No Fertility Control			Fertility Control			No Fertility Control			Fertility Control		
Work frac	0.5	0.75	1	0.5	0.75	1	0.5	0.75	1	0.5	0.75	1
Low-N fixation regime												
Continuous		4023	6176			1952			2633			
Shift 5/5	3889	5775	6385	42	2655	3613	11	3612	4933		138	1951
Shift 15/3	5165	5319	5343	3103	3437	3519	4241	4703	4816	2070	2835	3075
High-N fixation regime												
Continuous	27,752	28,912	29,120	16,155	18,482	19,094	22,069	25,285	26,132	9703	14,786	16,443
Shift 5/5	22,717	22,866	22,878	14,601	15,094	15,175	19,977	20,661	20,774	11,862	13,298	13,660
Shift 15/3	16,778	16,778	16,778	11,135	11,141	11,142	15,243	15,252	15,253	10,059	10,123	10,128

and the decreasing efficiency of infill plots and plots at greater distances from home. Adding another worker to a crowded field system does less to improve the total yield than it might have when there was much unused land left.

In the absence of fertility control, Puleston et al. (2017) used the response of fertility and survival rates observed in famines (described in Lee and Tuljapurkar 2008), and in the fertility control scenario the authors dramatically increased the responsiveness of fertility to hunger to examine the consequences of strong attempts to limit population size when it was detrimental to welfare. In this scenario, when the food ratio drops below 1 fertility quickly declines and the population approaches equilibrium at a smaller size but with greater food availability per capita (Puleston et al. 2014). In practice fertility control could take multiple forms, including infanticide, delayed onset of marriage, or coitus interruptus, all of which have been described in traditional Polynesian societies. It is also probable that at times survival rates were diminished either intentionally or not (high-risk voyages of exploration, armed conflict, human sacrifice) to similar effect on the equilibrium population size. If the increases in mortality decrease the most reproductively successful age classes, fertility will also decline.

Other key assumptions in the application of the space-limited model to Rapa Nui were that 25% of the labor pool of the population was diverted from agriculture in the form of tribute, equivalent to a tax paid in the form of labor in addition to the tribute paid in the form of food. Also, the elite (and non-agricultural) population was modeled as a simple 1% of the size of the commoner population.

The study confirmed that soil nitrogen availability has a powerful effect on yields, which has a subsequent effect on population size. Of the social factors, fertility control generally had the largest effect on population size while at the same time keeping the equilibrium quality of life high. Under strong fertility control the population was well fed, and life spans of those surviving infancy were near their maximum. The effect of social stratification was not great, but the model was set to exact relatively modest tribute in food and labor. Generally, population sizes decrease as fallow requirements increase, but there are exceptions where labor is in short supply. This occurs most often under combinations of continuous cultivation (maximum area) at lower worker fractions (fewer workers) in the low-N scenario (low returns to labor).

6 Comparing the Two Models

The space-limited model shares some features with Bayliss-Smith's (1980) model in that population size is conditional on measures of welfare or well-being. Where Bayliss-Smith (1980) highlights the effect of the expectation of labor inputs (hours worked per week), the space-limited model is centered on hunger and its effects on the growth rate. Bayliss-Smith includes the expectation of food availability as a parameter to calculate population size, and the space-limited model parameterizes an expectation of labor in terms of how much land a typical worker can farm. Both models also include an estimate of the fraction of the population directly involved in agriculture.

Bayliss-Smith's calculation of *K*, or the maximum number of people who might be fed under the most efficient use of resources available, is comparable to the space-limited model's equilibrium population under the default assumptions: egalitarian organization, no fertility control, and continuous cultivation. The worker fraction has typically been assumed to be 50% of the working-age population in previous applications of the space-limited model, and this matches Bayliss-Smith's (1980) parameterization. That the Bayliss-Smith model's maximum of 27,227 people (at 24.9 hours per worker per week) in the high-N scenario is comparable to the 27,752 people in the space-limited model should not be particularly surprising given that they both rely on the same estimates of total food production. But there are differences. Note that the space-limited model is responsive to additional inputs of labor, resulting in a maximum population of 29,120 when the entire commoner working-age population participates in agriculture. Also, under the Bayliss-Smith assumptions, the entire population receives the equivalent of 2192 kcal/day, while in the dynamic space-limited model the population initially is able to receive the desired 2785 kcal/day, but at equilibrium the allotment has fallen to 1917 kcal/day.

In the low-N scenario Bayliss-Smith's model predicts a maximum population of 5291 (at 28.1 weekly hours per worker), which is less than *K* because it assumes workers will reject any situation that returns less than 1750 kcal/ha. In the space-limited model, the low-N scenario is an extremely difficult balancing act. The losses of N from the system under continuous cultivation make it inefficient, and populations are small or nonviable. We expect a population under those limitations to employ some degree of fallow to increase total productivity. The alternating 5-year fallow regime yields an equilibrium population of 3889, and the 15-year fallow with 3 years of cultivation regime supports 5165 people in the egalitarian, no fertility control scenario with 50% of the working-age population employed in agriculture. These maximum populations would be reduced as demands for surplus or tribute increased, or if the population refused to work the hours the calculations require, or if there were any degree of fertility control.

While the degree of nitrogen availability remains a vexing unknown, we can narrow the range of several other parameters to eliminate less likely population numbers. One such change is to assume that most subsistence economies rely on 10–20 hours of agricultural labor per week (Bayliss-Smith 1978) and expand that to 30 hours per week to include some outliers, simplifying the picture. We can also treat the demand for surplus in the context of what is known about Polynesian social stratification specifically. The vast majority of Polynesian populations had some degree of social inequalities, although the extent was varied. On larger and more productive islands of the Pacific (e.g., the Hawaiian Archipelago, per Hommon (2009)), there was a larger proportion of non-agricultural elites and a more complex bureaucracy than on smaller volcanic islands and atolls, where the difference in the lifestyles of elites and commoners could be minor. Hommon (2014) estimates a chiefly class that was 2.3% the size of the commoner population in the leeward Kohala field system of Hawai‘i, and that approximately 3% of the commoner population would have been required as full-time herders of the pigs required for their needs. Elsewhere Hommon estimates the chiefly class on Hawai‘i Island was 1–2% of the population (Hommon 2020), but it required 3–6% of the total agricultural land to feed the pigs they required in tribute (Hommon 2008). He calculates the cost of feeding a male member of the chiefly class was 9 to 17 times greater than that of a commoner.

If we use Hommon’s sketches of the Hawaiian elite as a basis, while acknowledging that Hawai‘i probably had greater social inequalities than Rapa Nui, Puleston et al.’s (2017) estimate of elites as 1% of the commoner population size seems a conservative but reasonable assumption. The distinction between the commoner and elite subpopulations lies in agricultural labor contributions and the differences in diet. The cost of maintaining the elite class might be in the neighborhood of 10 times (in terms of calories) the cost of maintaining an equivalent number of commoners, after we account for the fact that the elites included women and children and Hommon’s estimates focus on male consumption of pig meat. Consider also that feed conversion efficiency for chickens (the only domesticated meat source for the Rapanui) is about twice that for pigs, meaning that pigs take much more food energy inputs than poultry for the same caloric output in meat. In terms of surplus to subsistence production as Bayliss-Smith (1980) defines it, this is equivalent to N_C times (elite fraction) times (per capita kcal) times (elite need multiplier), where N_C is the commoner population size, elite fraction is the elite population as a fraction of commoner population (0.01), per capita kcal is commoner food need (2192 kcal/person/day), and elite need multiplier is the multiplier to convert commoner food need to elite food need (10), yielding a result expressed in kcal per unit time. To express surplus production as a percentage of subsistence production we divide this by subsistence production (N_C x per capita kcal) and multiply by 100. The resulting surplus is 10%. If these parameters are accurate, then we can narrow the standard populations from Tables 20.1 and 20.2 to the column “S + 10%” and the rows in the vicinity of 20 hours per week or less. Let us assume that 30 hours per week dedicated to sweet potato production is a reasonable maximum. That corresponds to a maximum commoner population of 4913 and 25,566 in the low-N and high-N regime, respectively. Including elite populations would add 1% to these totals, yielding 4962 and 25,822, respectively.

For comparison, we can update the population projections in the Puleston et al. (2017) parameterization of the space-limited model to incorporate a number of Bayliss-Smith’s assumptions. Specifically, we will for this parameterization assume that sweet potato production represents 80% of all calories, rather than 100%. The 10% tribute in food and the elite population modeled as 1% of the commoner population remain unchanged. We impose fertility control, tuned to achieve an equilibrium food availability of 2192 kcal/person/day to match Bayliss-Smith’s (1980) parameter. The expectation of labor remains unchanged. We eliminate the requirement that 25% of labor be provided in tribute. We also incorporate Bayliss-Smith’s lower limit on returns to labor (1750 kcal/ha), which eliminates any agricultural zone that yields less than 4.51 mt/ha/year of sweet potato. This minimum productivity threshold eliminates all agricultural area in the two more intensive cultivation regimes in the low-N scenario, but does not affect the low-N long-fallow regime, or any of the three high-N cultivation regimes.

The results of the space-limited model after reparameterizing to incorporate Bayliss-Smith's (1980) parameter values do not change the range of the low-N scenario very much from the results of Puleston et al. (2017). The more intensive usage (no-fallow and short-fallow) scenarios are nonviable, and only a 15-year fallow, followed by 3 years of cropping, allows for a sustainable population. However, the high-N scenario generates generally larger populations than the previous parameterization. The greatest contributors to the increases are the assumption that only 80% of the population's food comes from sweet potato, and that under fertility control the population equilibrates to Bayliss-Smith's (1980) caloric intake of 2192 kcal/worker/day, as opposed to the 2785 kcal/worker/day under the more extreme fertility response in Puleston et al. (2017). In addition, we have eliminated a requirement in this iteration that 25% of available labor be diverted from agriculture to meet other societal obligations. The most appropriate comparison to Bayliss-Smith's standard populations is the continuous cultivation scenario, as the standard population approach assumes the most intensive land use available to calculate maximum population size. The high-N continuous cultivation space-limited population estimate of 26,393 compares well with the 25,566 Bayliss-Smith standard population in the high-N scenario at S + 10% and 30 hours of work per week. Note also that the standard population calculations do not include the elite population, which could add another 256 individuals.

As closely as these models agree, it remains impossible with the information we have to distinguish between two quite different pictures of life on Rapa Nui at its peak of population. In the absence of the use of nitrogen-boosting sugar cane that was used elsewhere in Polynesia to border dryland plots (Kamakau 1976, Lincoln and Vitousek 2016, Marshall et al. 2017) and is believed to have predated European contact on Rapa Nui, the island was probably quite sparsely inhabited. The population would have been small and worked relatively long hours tending plots that could only be used maybe one year in six to allow the buildup of nutrients required to make it worth the effort. However, if a windbreak of sugar cane is allowed to decompose as mulch the expected yields increase from an untenable average of 1.46 mt/ha/year of sweet potato to as much as 5.09 mt/ha/year under continuous cultivation. Such a difference is remarkable with regard to the prospects for the size and welfare of the human population and reinforces the high dependence of Rapanui society on soil resources and agricultural innovation.

7 Living in a Variable World

Environmental variability and its effect on population size and well-being can be key in various island settings. Even in well-controlled experiments of traditional agriculture, yields can vary wildly from year to year. Burtenshaw and Harris (2007) planted two experimental gardens with kumara sweet potato in Aotearoa New

Zealand using traditional techniques and observed a coefficient of variation in yield of 0.43 over seven years at one location and 0.47 over six years at another. These would be considered highly variable yields in any agricultural system (where CVs of 0.2 or 0.3 are more commonly assumed), but in a place like Rapa Nui, with limited ability to store food from one year to the next, the population-level consequences would likely be much more extreme. Winterhalder et al. (2015) found that "variance compensation" in a preindustrial subsistence agrarian context required farmers to over-plant in an average year to avoid the harsh consequences of coming up short. In other words, to prepare only for the average shortfall is bad policy given the consequences of rare but really poor yields. In the Rapa Nui context, we do not have the same system of individual farmers making decisions about seed and effort allocations, but the underlying problem is the same. If your food comes from a crop with a high degree of variability you can either ride the wave in which some years see high survival and fertility rates and every once in a while suffer calamitous famines, or you can limit your population to a size that can still find enough food even in bad years.

The dynamics of taxed natural fertility populations in a variable environment were discussed in Winterhalder and Puleston (2018). Analyzing a version of the space-limited model, they found that, first, if two natural fertility agrarian populations achieve identical average yields, but one is variable and the other constant, the population with the variable food supply will on average be expected to be significantly smaller. Figure 20.4 shows the commoner population on our simulated Rapa Nui landscape under the space-limited model parameterized for comparison to Bayliss-Smith (1980). This represents the low-N scenario under the shifting 15/3 cultivation regime from Table 20.4. Instead of the constant yield we have considered to this point, each year we draw a yield value from a normal distribution with the identical mean in all simulations. Each draw is independent of previous draws. How much the yield varies from year to year is determined by the coefficient of variation. The constant-yield scenario stabilizes after about 450 years at 4883 people (ignoring the 1% elite population here, whose inclusion totals the 4932 found in Table 20.4). As variation in yield increases, the population size also becomes more variable and, importantly, smaller. At yield CV = 0.2, the long-run population is 8.2% smaller than the default, constant-yield case. At yield CV = 0.3 it is 17.5% smaller, and at yield CV = 0.4 it is 31.2% smaller than the constant-yield population.

A second implication from Winterhalder and Puleston (2018), of particular importance to small, isolated populations, is that the form of taxation and its magnitude contribute to the risk of local extinction. The risk becomes particularly acute when the elite insist on a fixed level of total tax revenue (in the form of food) in a variable environment. See their Figure 8 for an illustration of the half-lives of various populations under combinations of a fixed tax and yield variability. Their Figure 6 describes the state space of a population under a per capita tax in food. There exists a trade-off between commoner population size and the size of the per capita food levy. The elite class may attempt to maximize total taxes by incrementally increasing the per capita rate, but with each step they come closer and

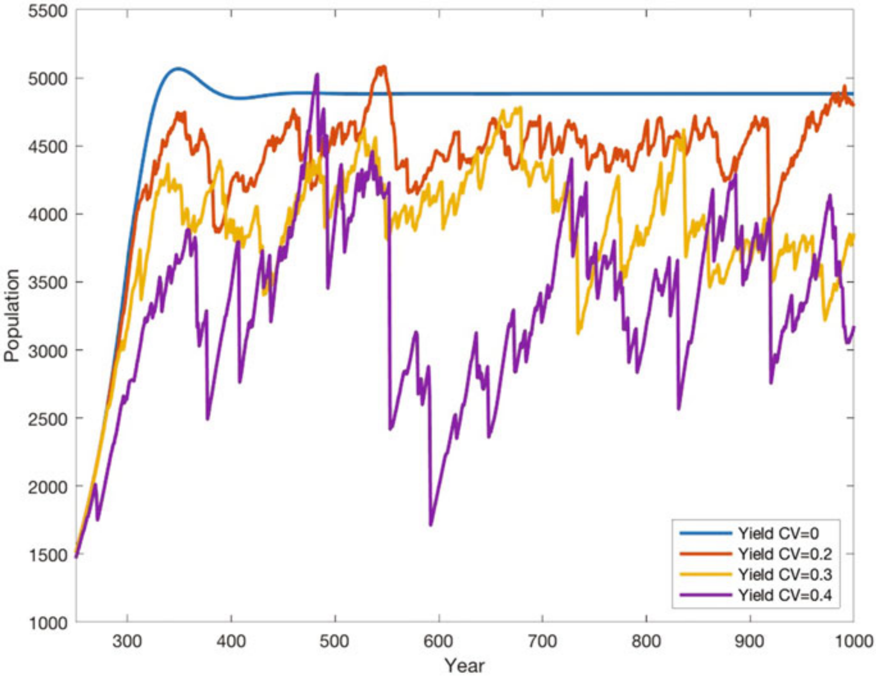

Fig. 20.4 Simulated Rapa Nui commoner population trajectories under variable yields, starting at year 0 with 20 individuals (detail). The average yield should be identical in all scenarios. The blue line represents the constant-yield scenario in low-N long-fallow conditions under the space-limited model parameterized for the Bayliss-Smith (1980) comparison (see Table 20.4 low-N, shifting 15/3 scenario). The mean between year 450 and 1600 (after the populations have settled into their long-run dynamics) is 4883 commoners (in the case where CV = 0). The reddish line is a CV = 0.2 scenario with the same mean yield and other parameters. Its long-run average is 4840 (CV = 0.04). The yellow line is yield CV = 0.3 and the population averages 4030 (CV = 0.08), and the purple line is yield CV = 0.4, where the average population becomes 3358 (CV = 0.18)

closer to the point of unsustainability in which the burden is too great to bear without inducing starvation and negative population growth. We can imagine this balancing act being attempted and even accomplished in a constant-yield environment, but in the case of variable yields it becomes an extremely dangerous endeavor. A year of bad yields with a high tax burden might trigger a mass mortality event that would require nimble management to recover from. There are, of course, checks that might bolster the stability of the system. Hommon (2020) discusses the process of tax collection on Hawai‘i, in which communities that were seen as falling short of their obligations were punished and plundered. At the same time, chiefs who were seen as extortionate could be murdered as a response. But usually taxes were based on a subjective assessment of the wealth of the community: its size, the size of its working population, and history of tax payments. “To reduce the risk of repression from above or rebellion from below, various participants including

Table 20.4 Sustainable Rapa Nui population sizes under the space-limited model using Bayliss-Smith's (1980) assumptions, where applicable, and Puleston et al.'s (2017) assumptions elsewhere. In the low-N regime only the lowest-intensity land use meets the minimum return to labor of 1750 kcal/ha. We assume that 50% of the working-age population is engaged in agriculture and a moderate degree of fertility control is practiced. The elite population demands an additional 10% of subsistence production and is 1% the size of the commoner population

Low-N fixation regime	
Continuous	–
Shift 5/5	–
Shift 15/3	4932
High-N fixation regime	
Continuous	26,393
Shift 5/5	21,764
Shift 15/3	16,095

ahupuaʻa [the basic unit of Hawaiian political division] residents, *ahupuaʻa* chiefs, tax collectors, and the king, may have applied such information to arrive at estimates of an *ahupuaʻa*'s tax liability that could be negotiated with the other parties" (Hommon 2020). The incentive for chiefs to be flexible in their demands (within limits) was strong, as this would help populations to ride out "bad" years while still maintaining social inequalities. Other forms of buffering the effects of lean years would include the suppression of population numbers via the diversion of labor away from subsistence activities into costly public projects. Graves et al. (1995) and Hunt and Lipo (2011) proposed the diversion of labor required to build and move Rapa Nui's many moai statues, as well as other costly investments of resources into efforts that provided no immediate benefit to survival or fertility was an adaptive trait that limited population size with the benefit of minimizing the risk of famine.

Manifestations of social inequalities and the accompanying demands for tribute may have complex consequences for the dynamics of an agricultural population in the face of variable yields. It is likely that these consequences increase the burdens on the commoner population in ways that reduce its average size compared to static calculations based on estimates of carrying capacity, perhaps as much as 30% or more (Fig. 20.4, yield CV $= 0.4$) even after accounting for numerous other likely factors.

8 Independent Estimates of Rapa Nui Population

The Bayliss-Smith quote that opens this chapter reminds us of the limitations of models. Models can be useful, but are limited by the questions they are crafted to address. The two models we have considered are concerned with a theoretical question: How many people *could* have lived on Rapa Nui? This is a separate but related question from: How many people *did* live on Rapa Nui? In this section, we consider the best estimates of Rapa Nui's population near the time of contact, along with more general estimates of Polynesian population density, and briefly compare them to the model estimates of maximum population under our assumptions.

In his careful survey of the records of early European visitors, Boersema (2015: Table 6.1) summarizes the observations on population size and ventures a guess that in the eighteenth century the island's population stood between 1500 and 3000 individuals. While Roggeveen and his shipmates made no estimate of population (other than to remark on "thousands" of swimmers), we know that life on Rapa Nui was changing dramatically in between 1722 and the multiple contacts between 1770 and 1804. It may be impossible to rule out a decline in population immediately after Roggeveen's visit similar to the declines that occurred elsewhere in Polynesia after European contact. Hunt and Lipo (2011) consider this possibility. Estimates and best guesses at to the island's maximum precontact population among the modern experts vary. At the low end are Hunt and Lipo (2011:32), who suggest a maximum population of about 3000, probably achieved within 200 years of arrival, around 1350 AD. Jo Anne Van Tilburg (1994) considered the estimates of several previous researchers based on archaeological features and concluded that 7000–9000 seemed a reasonable number. At the high end, Jared Diamond (2005) settled on 15,000 after some calculations and consultation with other researchers.

The population densities of comparable populations elsewhere in Polynesia may be useful here. Kirch (2007c) estimated from archaeological data the densities in the more productive zones of Kahikinui, Maui at between 43 and 57 persons/km^2, and 19–25 persons/km^2 over an entire territory (*ahupua'a*): "These values are on the low end of ethnographically documented population densities in Polynesia and are probably realistic in view of the environmental marginality of Kahikinui" (ibid.:101). He assumed 4.9 mt/ha/year sweet potato yields at Kahikinui to separately estimate the carrying capacity for a population requiring 2000 kcal/person/day. He used a definition of carrying capacity that relates to the maximum conversion of expected food supply into people, without discounting for wastage, exchange, animal feed, tribute, or the significant effect of variability in food supply. He found the density at carrying capacity would have been 174 persons/km^2 in the occupied (agricultural) zone, concluding that although it probably significantly overestimated population, the exercise was useful in confirming that the numbers of the archaeological estimate could have been supported on the resources that were available to them. Ladefoged and Graves (2007) estimated 139.4 persons/km^2 from archaeological features in a 112 ha detailed study area in the midst of the expansive dryland agricultural system of the Kohala Peninsula (Hawai'i Island). Kirch (2010) estimated roughly 262 person/km^2 for prime agricultural land across the whole island of Hawai'i, arguing that the value was a reasonable one for intensified dryland areas on the archipelago. Hamilton and Kahn (2007) estimated a minimum density in the 'Opunohu Valley of Mo'orea, French Polynesia, of 52 persons/km^2 based on archaeological features, and 87 persons/km^2 in the area of greatest occupation and use, although the population may still have been growing at the time of contact. Taken together these studies suggest that a density of about 50 persons/km^2 of agricultural land should be a reasonable minimum and 250 persons/km^2 a reasonable maximum. If we apply these densities to the estimate of 3134 ha of agricultural space on Rapa Nui, we get a low of 1567 people and a high of 7835 people for Rapa Nui.

Can these estimates be reconciled with the results of the Bayliss-Smith and space-limited approaches for Rapa Nui? Well, easily, if we assume the low-nitrogen scenario. But we already suspect it may be too conservative with regard to sweet potato yields, as we know the Rapanui grew sugar cane of the variety that boosts plant-available nitrogen as it decomposes. Both modeling approaches work from a form of ecological carrying capacity estimate, in which the maximum yield is assumed to be available. And much can happen along the way as we work from hypothetical yields to the human populations that need actual yields to live. Bayliss-Smith (1974) found that the actual population was some 70–80% of the estimated carrying capacity. Bellwood (1971, 1972) concluded that only 50% of the estimated maximum yield in valleys in the Cook Islands and Marquesas was actually produced. Hamilton and Kahn (2007) estimated that the archaeological estimates of the population of Moʻorea were only 11% of the carrying capacity. Explanations for the discrepancies between carrying capacities may lie in overestimates of realized production, either due to an overestimate of the quantity or quality of agricultural land. As described in the previous section, the effect of expected variation in the food supply is known to be powerful, but is generally unaccounted for. Then there are the behavioral factors to consider. Bayliss-Smith allows us to examine the consequences of different expectation of labor inputs, and it is possible in places like Rapa Nui that the working population either chose not to work very many hours or competing obligations reduced the hours they had available. This possibility is supported by Roggeveen's observation that good land appeared to be unused, as if left fallow in a less-intensive agricultural regime. Fertility control (including infanticide) could similarly reduce the equilibrium population, as a matter of individual choice or societal pressure.

9 Conclusions

Our goal has been to examine the meaning and role of carrying capacity as it applies to subsistence agrarian populations of the Pacific. The first, and perhaps most important, conclusion is that the term "carrying capacity" itself has no single meaning and comes burdened with its own baggage. We find the concept of a carrying capacity to be a useful one, but that utility is easily eroded by imprecise language. We favor the manner in which Bayliss-Smith (1980) uses it, representing an estimate of the maximum number of people who could be fed in a particular place given the location's ecological characteristics and the population's technology. This estimate is an intermediate stopping point on the way to a more nuanced consideration of reasonable population sizes. The second point is that attempts to estimate carrying capacity, without good ecological and cultural information, might be an empty endeavor. In the case of Rapa Nui, we can consider several scenarios. The range of estimates of sweet potato yields in Oceania before European contact encompasses the yields we use here: approximately 1.5 to 5.1 metric tons per hectare per year under continuous cultivation. But the populations that might have lived on those yields on Rapa Nui, after considering several important qualifiers, range from approximately 5000 to 25,000. We do not argue that either population number is supported by this exercise. We do argue that the result depends largely on whatever yield the Rapanui were actually able to achieve and, additionally, how variable that yield was. The impact of sugar cane mulching in elevating N levels and productivity is key, and unfortunately, we do not know the extent to which this was practiced. It is highly encouraging, however, that two different models of maximum population size agree so closely in their predictions, despite quite different conceptions of human welfare and its role in population regulation. Ultimately, we find that although ecological characteristics can constrain a population's size in important ways, cultural and behavioral attributes can reduce its expected size well below the theoretical maximum.

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