Chapter 21
Population Principles, Climate Change, and the "Collapse" of the Rapa Nui Society

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1 Introduction

The agrarian society's dynamic from Easter Island (Rapa Nui) and its apparent collapses has fascinated scholars for several decades, although societal demises have been described in other places and times. The phenomena of societal collapses have been highlighted as recurrent events in Humankind history triggering a growing concern for identifying convergences/divergences among different cases to explain tipping elements and points between breakdown or resilience. Still, collapse is a general term with different meanings leading to a heated debate in the scientific community. In general, the concept has been applied to different entities such

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as states, nations, or complex societies, and how they can arise and decline. However, in most of these studies, the variables involved are diverse, such as sociopolitical organization, economy, environment, and population size (Butzer 2012). For instance, Tainter (1988) defines collapse as a political process related to a rapid sociopolitical complexity loss. Conversely, collapse can be viewed as a population process characterized by negative population growth rates that impact several generations. In this sense, such process should be referred as demographic collapses (Meadows 2004). Both definitions, however, are not necessarily exclusive. Sociopolitical collapses could arise without major demographic consequences. Indeed, both processes usually interact, generating a concurrent loss of sociopolitical complexity and population declines (e.g., Lee and Zhang 2010; Turchin 2009).

Past agrarian societies can provide unique natural, socio-ecological laboratories for testing different hypotheses explaining how the interaction between ecological factors, climate, and human population can lead to societal collapse. The relationship between human population dynamics, food production, and climate change is an ancient problem in human societies, especially in agrarian societies, with profound implications for current societal problems (Butzer 2012). For instance, Bevan et al. (2017) as well as Warden et al. (2017) showed how climatic conditions mediate changes in human population growth rates.

Assessing the role of ecological and climatic factors through the Population Dynamic Theory (PDT, Box 21.1) can often shed light on why demographic collapses happen by testing different hypotheses. The application of the PDT framework (Box 21.1) and all its methods borrowed from ecological theory is a powerful perspective to detangle links between climate variability and population dynamics of past societies. This is because formal modeling methods provide the means to test hypotheses rigorously and quantify the evidence supporting each of these (Berryman 1999; Royama 1992; Turchin 2003).In a simple first scenario, the relationship between population size and climatic variables could be represented as an additive effect in statistical models (Stenseth et al. 2004), a vertical perturbation where both equilibrium density and maximum reproductive rate change (Royama 1992). Nevertheless, climate effects have often been proved to be non-additive (Royama 1992) (Box 21.1). The first example of this non-additive effect is the so-called lateral perturbation (see Fig. 4c in Lima et al. 2020; Box 21.1). Here, exogenous forces modify only the equilibrium density, but the maximum reproductive rate remains unchanged.

Since in agrarian human populations equilibrium levels are usually set by crop productivity, we should anticipate lateral perturbation effects whenever climate or other exogenous factor is suspected of influencing food production/crop yields (Box 21.1). Hence, explanations of climatic effects on past agrarian societies need to consider the possible effects of climate on food production. Another related problem is that when the exogenous factor, such as climatic variability, influences a limiting resource, such as crop production, it is very likely that, in those cases, climate represents a lateral perturbation on the crop productivity itself. The problem with this kind of exogenous effect is that it affects the availability of some limiting factor or resource (e.g., food); hence, the per capita resource availability shared for the individuals is also influenced (Royama 1992). These non-additive effects are normally expected when the ratio (i.e., population/crop production) characterizes the per capita share of the resources and the competition strength, changing the limiting factor’s availability. Under this scenario, small changes in a climate variable could have large changes in population growth rates because there is an interaction between climate, crop production, and population size resulting in potentially nonlinear responses of populations to changes in climate (Berryman and Lima 2006; Lima and Berryman 2006; Lima et al. 2006; Royama 1992). Therefore, the primary objective of this chapter is to analyze the Rapa Nui archeological data employing a simple approach to understand how climate affects human population dynamics. In this way, we propose an alternative view of the population changes of the Rapa Nui people.

Population changes of the Rapa Nui society have several causal explanations, receiving the most attention those invoking an anthropogenic-driven ecological catastrophe. This “ecocide hypothesis” assumes a punctuated demographic crash caused by the abrupt reduction and replacement of native palm forest by grasslands, ultimately driven by unchecked population growth coupled with social fractions and friction as crop productivity decreased (Diamond 2005; Flenley and Bahn 2002; Rolett and Diamond 2004). In contrast, the “genocide hypothesis” emphasizes violence, slaver raids, and epidemics introduced shortly after European contact in the early eighteenth century (Hunt and Lipo 2006; Hunt and Lipo 2009). Proponents of this genocide hypothesis suggest that Rapa Nui populations did not decline until the European colonization (1722 CE). Alternatively, Rull et al. (2013) emphasize the socio-ecological resilience and identify a first societal crisis (1450–1550 CE) linked to hydroclimate–cultural synergies. Meanwhile, the occurrence of two population downfalls is recognized after 1722 CE (Rull et al. 2013).

Although these explanations constitute major advances in understanding Rapa Nui’s history, none of these scenarios have been evaluated using models that integrate hydroclimate and demographic data as independent sources of information to portray the local socio-ecological systems. This chapter is dedicated to exemplifying the power and feasibility of the PDT perspective for analyzing and interpreting past human population dynamics, specifically in Rapa Nui. We review the framework adopted in Lima et al. (2020) to test and integrate explicitly coupled agencies and cascading feedback between climatic, demographic, and ecological factors that affected the Rapa Nui people’s trajectory. In particular, in this chapter we develop in detailed way how climatic perturbations acting on the agricultural land carrying capacity can be included in population dynamic models for proposing a formal hypothesis of socio-demographic changes in Rapa Nui people.

Box 21.1 The PDT Framework

The classical PDT proposes that climatic variability will affect the long-term food production or crop yields, affecting the equilibrium density (also called carrying capacity) of a given agrarian society. Thus, let k will be set by the amount of land available for agriculture and the current agrarian technology (yields per unit of area), which represents the limiting resource base for an agrarian society. A simple population dynamic model for this system is:

$$P_{t+1} = \frac{R_{t+1}}{R_{max}} = 1 - \left(\frac{N_t}{a \cdot k}\right), \tag{21.1}$$

Here R_{t+1}, is the realized per capita population growth rate over a given interval of time with $R_{\max}$ being the maximum possible rate. Hence, P_{t+1} measures the relative growth rate over a particular period of time. Note that the maximum per capita rate of increase $R_{\max}$ defines the maximum per capita birth rates (B) and minimum per capita mortality rates (D) (Berryman 1999). The expression on the right of Eq. 21.1 defines how the average individual fitness changes in relation to the size of the population N and the rate of renewal of an essential limiting resource k, with a being the unit value of that resource (arable land/crop yield). This can also be thought of as the relative "biological fitness" or "standard-of-living" or "well-being" of an average individual in the population. This equation predicts that individual performance will decline in proportion to the size of the population (or social structure), all else being equal. The term on the right of Eq. (21.1) defines the relative degree of competition for a limiting resource, expressed as a function of the density (or concentration) of humans per unit value of land productivity. It is not too difficult to see an economic analogy in the demand of a population N for a supply of resources k.

As the population increase in size, all available resources will be used (k), for example, cultivable land. Further increase of population numbers immediately (without time lags) results in lower average consumption rates. Since there is no time lag, there should be no over-shoot of the carrying capacity. However, these societies may face long-term climate changes that may shrink the land available for agriculture or the yield per unit of area (k) or the unit value of the crops (a). The explanation relies on the combination of Malthusian theory (Malthus 1798) with climatic variability as an exogenous forcing factor. Climatic variability determines agricultural land carrying capacity, which affects the population growth of agrarian societies (Lima 2014; Zhang et al. 2007; Zhang et al. 2011). Lateral perturbations result from exogenous factors, like climate, acting on the limiting resource availability or renewal rates (Berryman 2004; Royama 1992) and causing non-additive effects. These non-additive effects on net fertility, mortality, or both are a

(continued)

Box 21.1 (continued)
function of climate through resource limitation. For example, an unfavorable climate could reduce fecundity due to energetic limitations, or mortality in infants or elders increases due to food acquisition constraints. As equilibrium population sizes are usually set by a resource in short supply (food production or crop yield), it is possible to anticipate lateral perturbation effects whenever climatic variability is suspected of influencing food supply. These non-additive effects are normally expected when the ratio (i.e., population/crop production) characterizes the per capita share of the resources and the competition strength, changing the limiting factor’s availability. Under this scenario, small changes in a climate variable could have large population growth rates because there is an interaction between climate and population size (Berryman and Lima 2006; Lima et al. 2006; Royama 1992). Consequently, the climatic variable’s effect cannot be evaluated independently of the population size because the exogenous effect (climate) acts in conjunction with population size (Berryman and Lima 2006; Lima 2014; Lima et al. 2006; Royama 1992). The dynamics of this system can be easily defined as a logistic equation with lateral perturbation effects (Royama 1992):

$$P_{t+1} = \frac{R_{t+1}}{R_{max}} = 1 - \left(\frac{N_t}{a \cdot C_t}\right), \tag{21.2}$$

Let P_{t+1}, R_{t+1}, R_{max}, N_t, and a being the same dynamic variables and parameters from eq. 21.1, but the limiting resource k is replaced by a dynamic variable represented by C_t, the climatic changes influencing the food production. In fact, previous studies have hypothesized that “food supply per capita” is the key variable driving population collapses in pre-industrial societies (Zhang et al. 2011). Under this model, the mechanism for explaining the population collapses is the direct link between long-term climate and land productivity (Lima 2014; Nefedov 2013; Zhang et al. 2007). Although social scientists have been discussing the role of Malthusian factors in shaping human population dynamics (Lee 1987; Lee and Anderson 2002), few studies have attempted to model environmental fluctuations (climate) as a lateral effect that directly affects the limiting factors in the long term (food production) (but see Royama 1992).

2 Putting Rapa Nui Population Changes into the Test through the PDT Framework

We propose a population dynamic model to evaluate expected predictions from a climate-ecology-demography dynamic. We used the summed probability density

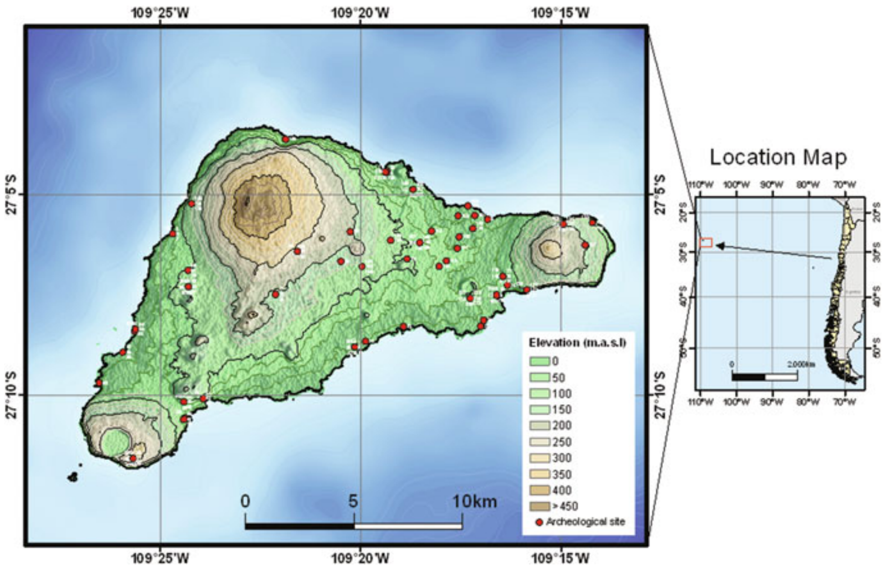

Fig. 21.1 Location for 91 archeological sites and 244 radiocarbon dates considered in this study for inferring paleodemographic trends in Easter Island. White numbers indicate the exact location for each ^{14}C-date. Note that considerable overlap exists between these data

(SPD) as paleodemographic proxy-data (Freeman et al. 2018) obtained for 244 radiocarbon dates from 95 archeological sites (Lima et al. 2020) (Fig. 21.1). Albeit the chronology for initial Polynesian colonization of the island is still a matter of debate, the oldest and youngest cultural radiocarbon dates considered here are 1180 ± 230 ^{14}C yr. BP (890 CE) 125 ± 30 ^{14}C yr. BP (1850 CE), respectively. Hence, we generated a 960-year time-series by summing the normalized posterior densities of these ^{14}C-dates in the R's carbon package (Crema and Bevan 2020). Further details on statistical procedures for controlling biases inherent to SPD reconstructions are presented in Lima et al. (2020). Before fitting models, the resulting SPD time-series were sectioned into time-step intervals of 30 years since 890 CE. With this procedure, we aimed to capture large population patterns and reduce high-frequency noise sources of variability.

Since the positive cold phase of El Niño Southern Oscillation (ENSO) is capable of reducing annual rainfall in Rapa Nui (Gallardo et al. 2016; Lima et al. 2020), a 2000-year reconstruction for the SOI index (Yan et al. 2011) serves as a proxy for ENSO-driven local hydroclimate anomalies.

In practice, the genocide scenario predicts that after the initial colonization, the population grew exponentially until an equilibrium population size determined by land area and crop/food productivity (Mann et al. 2008; Mieth and Bork 2010; Polet and Bocherens 2016; Rull et al. 2015). This scenario is described by eq. 21.1 with a constant or fixed renewal rates of the limiting resource k. On the other hand, the interplay between climate and demography (eq. 21.2) leads to a dynamic in that the island's human population's growth rate depends on the combined effect of recurrent droughts and ecosystem losses brought by large demographic levels. In turn, as negative rainfall anomalies progressed, human population sizes decreased gradually. Such synergic scenario for the human (N) population was described with a negative relationship of limiting resources (crop productivity) and the Southern Oscillation index values, high SOI values represent less annual rainfall (Lima et al. 2020). Therefore eq. 21.2 can be expressed as:

$$P_{t+1} = \frac{R_{t+1}}{R_{max}} = 1 - \left(\frac{N_t}{a \cdot \frac{1}{SOI_t}} \right), \tag{21.3}$$

Therefore, eqs. 21.3 and 21.1 can be used by fitting simple linear regression models to compare both hypotheses. Our starting point is to use the *R*-function (Berryman 1999) as a central element for connecting the model and quantitative paleodemographic, vegetational, and paleoclimate data. The realized logarithmic per capita population rate of change for a given interval of time can be estimated from a time-series data as the difference between the natural logarithms of population sizes *N*, $R_{t+1} = log\ N_{t+1}$ - $log\ N_t$, where N_t is the human population size (SPD data) at time t (Turchin 2009), and the realized relative per capita growth rates P_{t+1} are estimated as the ratio R_{t+1}/R_{max}, where R_{max} is the maximum observed growth rates.

Plotting P against the initial SPD values gives us the simple relationship predicted by eq. 21.1 for a constant limiting resource *k*, although the linear negative slope indicates the necessary and sufficient conditions for population regulation (Berryman et al. 2002), it is suggestive from Fig. 21.2c, that the limiting resource supply (crop productivity) could be fluctuating in time, causing changes in the equilibrium population sizes (blue arrows, Fig. 21.2c). However, when the data are expressed as eq. 21.2 the ratio of population size/limiting resources, we find that the relationship can be expressed by a simple negative linear regression model with a very good fit (Fig. 21.2d). As described in Lima et al. (2020), the role of hydroclimate changes and its impact on Rapa Nui people's population size gets its better representation through models including lateral effects. These results give support to the hypothesis that relates population dynamics, including population collapses, to a complex interaction of climate, farming, and human population. Also, these results emphasize the strong non-additivity of this interaction (Fig. 21.2d).

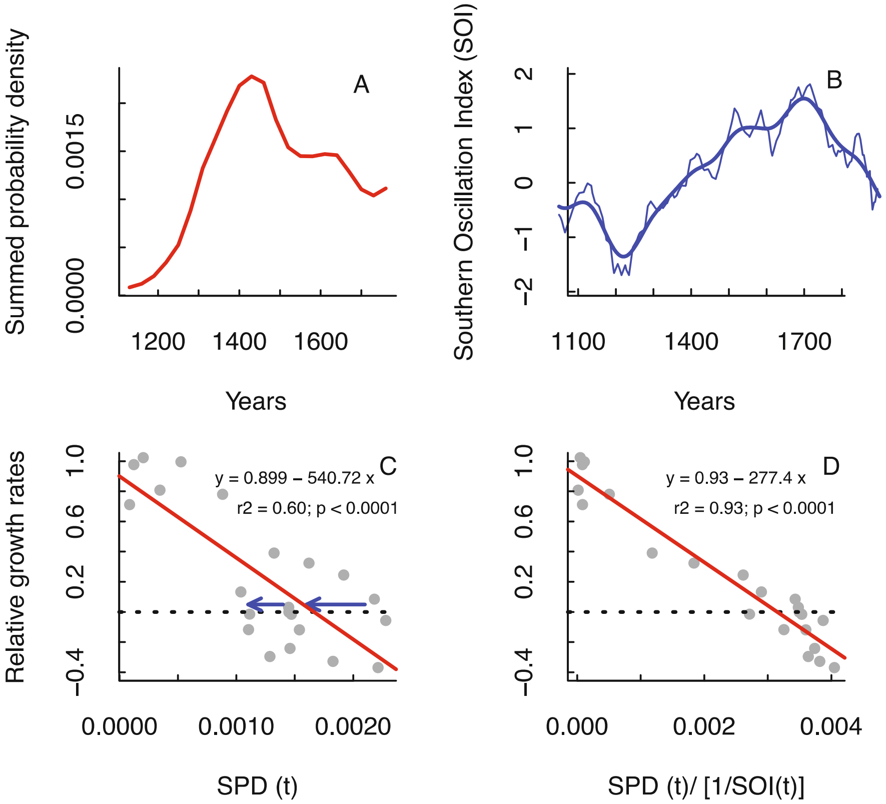

Fig. 21.2 (**a**) Reconstructed Summed Probability Density (SPD) for Rapa Nui (red line). (**b**) Southern Oscillation Index reconstruction (SOIpr) annually resolved (blue thin line) and smoothed time-series. (**c**) Relative per capita growth rates ($P_{t+1} = R_{t+1}/R_{max}$) plotted against the reconstructed SPD (one generation before = 30 years). Blue arrows indicate equilibrium population sizes during two declines. (**d**) Relationship between per capita relative growth rates (P_{t+1}) and the SPD by the unit of the Southern Index Oscillation for the same period. Text in the plots are the fitted linear regression model statistics

3 The Dynamics of Rapa Nui People

The application of the PDT framework for studying the Rapa Nui demographic trajectory suggests that long-term variations in ENSO activity can modulate the island's carrying capacity. Rapa Nui society's observed population dynamics is consistent with the hypothesis of non-additive long-term effects of ENSO variability on crop productivity (Stevenson et al. 2015). Evidence presented here and in Lima et al. (2020) suggests that population crashes in Rapa Nui arise from the long-term impact of hydroclimate change on the local carrying capacity, but more specifically on the "per-capita food supply" (Royama 1992). In fact, it is possible to link the role of hydroclimate change to the extensive deforestation that underwent in the island through the demand for farming lands, also linked to soil erosion and exhaustion. In the same sense, these intensified agricultural activities could have accelerated palm forest loss after 1200 CE [21]. This interplay between population size, long-term climate variability, and carrying capacity explains other populations collapses (Lima 2014)**.** By this means, the long-term direction trend between 1250 and 1700 CE (represented by the positive trend of the SOI index; Fig. 21.2b) might have led to a slow but persistent and cumulative reduction in the island’s crop productivity. Nevertheless, it is important to state that we are dealing with indirect proxies of human population size, crop production, and social complexity and our results are far from a definitive explanation.

The role of hydroclimate fluctuations on the island ecosystem services and demography has been debated (Diamond 2007; Junk and Claussen 2011). Nevertheless, severe negative hydroclimate anomalies during the Little Ice Age (LIA) have been associated to cultural and demographic changes in Rapa Nui (McCall 1993). We add up that the island’s demographic changes were indeed related to decadal fluctuations in ENSO activity that also affected other Eastern Pacific regions (Conroy et al. 2008; Morales et al. 2020). Furthermore, we evince that the impact of hydroclimate conditions on limiting factors was adjusted by population size (non-additive effects) via the effect on the per capita resource share (Royama 1992). This dynamic, however, operated independently on the magnitude or intensity of droughts. This implies that even small changes in a relevant climate factor—in this case, water supply—might generate disproportional demographic crashes if the population approximates its equilibrium size. Conversely, less pronounced demographic changes are expected when such populations experience the environmental change during the phase of exponential growth (Fig. 21.2c). A logical corollary for this is that the potential role of climate in driving demographic changes cannot be explained without including the role of population sizes.

Understanding feedback relationships between human population dynamics and climate change emerges as an urgent need for envisioning a sustainable future for human societies under the ongoing environmental crisis (Costanza et al. 2007; Cumming and Peterson 2017). In this vein, we demonstrate that the PDT offers a simple tool to test formal predictions and explanations for past demographic changes in Easter Island. Our results suggest that Rapa Nui society’s demography seems to be coupled to a gradual reduction in the water supply (rainfall) and productivity loss which seem to be consistent with archeological, ecological, and paleoclimatic data (Cañellas-Boltà et al. 2013; Mann et al. 2008; Mieth and Bork 2010; Rull et al. 2013). Well beyond previous controversies (Lima et al. 2020)—Rapa Nui people appear as an agrarian society that inhabited a small and isolated island and faced resource scarcity, overpopulation, and climate change as many others (Tainter 1988).

We believe that more productive than asking whether the Rapa Nui society collapsed or not, it is to formulate a classical population dynamic question, what causes the population and societal changes in the long term (Royama 1992; Taylor and Tainter 2016). Our results suggest that the long-term changes in the population size are a response to gradual increases in La Niña conditions (less rainfall) that could be closely linked with the observed ecological (deforestation) and socio-cultural (transition from moai cult to the birdman cult) transformations of the Rapa Nui society (Nunn 2007; Rull 2016). Increases and declines in population size and/or social complexity are changes commonly observed in human societies, and they are closely linked with processes of cooperation, competition, limiting resources, and problem solving (Taylor and Tainter 2016). Considering that overpopulation and global changes in temperature and precipitation regimens represent latent threats for modern and future human societies, we feel that the historical trajectory described here for Rapa Nui provides important insights on food security and ecological resilience.

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