Chapter 16
Spatio-Temporal Patterns of Deforestation, Settlement, and Land Use on Easter Island Prior to European Arrivals

Peter Steiglechner and Agostino Merico

1 Introduction

The ecological and socio-economic history of Easter Island prior to European contact exerts a great fascination on both scholars and general public. The reconstruction of this history is primarily based on palaeoecological and archaeological data. Changes in forest patterns and land use, for example, are typically inferred from palynological indicators (Flenley and King 1984; Flenley et al. 1991; Mann et al. 2008), radiocarbon-based dates of charcoal remains (Mieth and Bork 2005; Hunt and Lipo 2006; Rolett and Diamond 2004; Mulrooney 2013), archaeological artefacts (Van Tilburg 1994; Martinsson-Wallin and Crockford 2001), and relicts of formerly cultivated gardens (Wozniak 1999; Stevenson et al. 2002; Bork et al. 2004; Ladefoged et al. 2013). Uncertainties affecting proxy data, however, can lead to difficult interpretations and conflicting views. While the existence of widespread deforestation is uncontested, there is less consensus in relation to

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P. Steiglechner (✉) · A. Merico
Department of Theoretical Ecology and Modelling, Leibniz Centre for Tropical Marine Research (ZMT), Bremen, Germany

P. Steiglechner · A. Merico
Faculty of Physics and Earth Science, Jacobs University, Bremen, Germany
e-mail: peter.steiglechner@leibniz-zmt.de; agostino.merico@leibniz-zmt.de

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timing (Hunt 2007), spatial extent (Rull 2020), and causes (Mieth and Bork 2010) of deforestation. Early results based on coarsely resolved pollen analysis (Flenley and King 1984; Flenley et al. 1991), for example, suggested a somewhat abrupt decline of the forest. A more comprehensive and recent dataset of pollen records suggested, instead, gradual and patchy patterns of deforestation (Rull 2020). Remains of tree stumps and charcoal led scholars (e.g. Mieth and Bork 2015; Bahn and Flenley 2017) to attribute the disappearance of the forest to anthropogenic activities such as the use of trees for tools and construction, for extracting sugary sap, or for clearing land for agriculture through slash-and-burn. The role played by rats in the deforestation—they were probably brought in intentionally as a food item by the first Polynesian settlers (Matisoo-Smith and Robins 2004)—is also subject to different interpretations (Hunt 2007; Mieth and Bork 2010). More recently, deforestation has been attributed to more complex climate–human–landscape feedbacks (Rull 2020, 2021). While the replacement of cleared land by agriculture (often in the form of lithic mulched gardens) appears well documented and undisputed (Bork et al. 2004; Ladefoged et al. 2013), soil characteristics such as fertility, important for determining the relevance of agricultural practices, are less understood, leading to large variations in the estimates related to the maximum number of individuals that could have been sustained by the environment (Puleston et al. 2017).

Although it seems clear that deforestation patterns varied among locations (Rull 2020), contrasting conclusions persist on whether land use and human population patterns were uniform throughout the island (Mulrooney 2013) or whether they varied between regions with some areas being fully abandoned prior to European contact (Stevenson et al. 2015). Motivated by these uncertainties and gaps, studies focused on regional spatial patterns are currently gaining momentum, especially thanks to the use of modern techniques and systematic data analysis. For example, Ladefoged et al. (2013) used satellite image analysis to identify garden structures, and DiNapoli et al. (2019) used point-pattern analysis to explain the distribution of *ahu*, raised platforms made of fitted stones and rubbles hosting the monumental statues called *moai*. Assuming that *ahu* platforms indicate control over limited resources, DiNapoli et al. (2019) found that their distribution is best explained by the proximity to tidal freshwater sources along the coast. The investigation of spatial heterogeneities in terms of environmental features and population dynamics is expected to become an exciting avenue of research in the near future (Merico 2017; Rull 2021).

By integrating different processes and scanty information, mathematical modelling played quite an important role in the reconstruction of Easter Island history. Modelling studies on Easter Island started more than two decades ago with the pioneering work of Brander and Taylor (1998). With an ordinary differential equation (ODE) model, designed as a Lotka–Volterra predator–prey system, in which the human population is the predator and the resource is the prey, Brander and Taylor (1998) showed that a population increase followed by a rapid decline was inevitable when the palm forest was assumed to have a regeneration rate slower than the harvest rate. Later modelling studies extended the work of Brander and Taylor

(1998) in several ways, for example, by considering complex economic processes (Anderies 2000), conflict about resources (Reuveny and Maxwell 2001), complex economic and social structures (Dalton et al. 2005; Good and Reuveny 2006), trade with another society (Roman et al. 2017), multiple resources (D'Alessandro 2007), and Polynesian rats (Basener et al. 2008). While these models undeniably contributed to the understanding and developing of Easter Island narratives, they exhibited certain gaps and shortcomings (Merico 2017) in at least three respects. First, despite introducing different details, they are all grounded on the same designing principle, a Lotka–Volterra type of system with a non- or slowly renewable resource, and are, thus, bound to produce an island-wide boom-and-bust dynamics for a broad area of the parameter space. This resource is often represented by palm trees (as in Brander and Taylor's original work), although there is, admittedly, scarce justification to model trees as preys in a way that the human population ultimately depends on them for their survival. Second, given the uncertainties associated with processes and parameters, such models may produce results that are compatible with multiple narratives (Brandt and Merico 2015). Third, they are all based on the same approach, whereby a set of ODEs reflects the dynamics of island-wide aggregate populations without concerns for environmental heterogeneities, differential impacts of such heterogeneities on local populations, or interactions among individuals.

With the ability to create diversified agents that interact on and with a heterogeneous environment, agent-based models (ABMs) represent an alternative approach to ODE models. ABMs are often used to describe how macroscopic system behaviours emerge from the interaction of microscopic agents with their local environment. For social systems, agents typically represent individual humans (or groups of humans) that interact with one another and with a local environment based on heuristic rules. These rules are typically heterogeneous, non-linear (e.g., discontinuous or discrete), stochastic, time-dependent, and adaptive and might also be memory- and path-dependent (Bonabeau 2002). Agent-based frameworks present, therefore, an interesting alternative with regard to system-wide, aggregate population models in that they can describe systems that, for example, exhibit emergent behaviour or are computationally irreducible (Bookstaber 2017). As such, ABMs offer a more realistic simulative framework to investigate how independent individuals can act in the face of resource constraints, uncertainties, stress, or crisis, to "generate" collective dynamics (Epstein 1999). ABMs should not be seen purely as tools for accurately reproducing the trajectories of observed data. By setting assumptions on the microscopic level of humans and by generating or inferring potential macroscopic phenomena from these assumptions, ABMs create their unique narratives, which can be scrutinised against our understanding of the system under study (Bookstaber 2017).

An example of such tools is the "Artificial Anasazi" model (Dean et al. 2000; Axtell et al. 2002). This model reproduced the population dynamics in the Long House Valley in the Black Mesa area of northeastern Arizona (U.S.), between 800 and 1350 A.D. The study not only showed that the agent-based simulation approach could replicate settlement patterns and rapid population decline, but also that the abandonment of the valley could not be explained solely by environmental constraints; agent heterogeneity in relation to institutional or cultural factors was a crucial modelling feature for matching the observations (Axtell et al. 2002). Other ancient societies studied with ABMs include the Maya (Heckbert 2013) and the Minoan civilisation in Crete, Greece, during the Bronze Age (Chliaoutakis and Chalkiadakis 2016, 2020). No ABMs have been developed so far to study Easter Island's history (Merico 2017). Given the possibilities for regionally different settlement patterns (Stevenson et al. 2015), environmental variations in terms of soil fertility (Puleston et al. 2017), and the existence of autonomous, independent groups, organised into different levels of social structures like clans, *mata* (Van Tilburg 1994), then agent-based models represent a fresh and appealing possibility for the study of Easter Island.

Here we present a new agent-based model of human–resource interactions based on an environment characterised by real geographic and orographic features of Easter Island. Agents represent households of a variable number of individuals located in the environment from which they harvest two resources: (1) trees, which we assume to be non-renewable, and (2) sweet potatoes, which are cultivated in gardens of specified areas. Over time, as agents use trees and cultivate more and more gardens, the population grows and heterogeneous patterns of deforestation and land use emerge. With the model, we investigate the effects of (1) spatial restrictions in relation to resource access and (2) agent's knowledge in relation to environmental features on the spatial and temporal patterns of deforestation, settlement, and land use. With the objective of fostering reproducibility, transparency, and flow of ideas, we make the model available as open-source software (https://github.com/systemsecologygroup/EasterIslandABM) so that it can be used, modified, and redistributed freely. The rest of the chapter is structured as follows. In Sect. 2, we describe the model in general terms, and full details can be found in the Electronic Supplementary Material, which includes an Overview, Design concepts, and Details (ODD) protocol (Grimm et al. 2006, 2020). The results of the study are presented in Sect. 3. In Sect. 4, we discuss the results and outline potential future avenues of model developments. We close the chapter with concluding remarks in Sect. 5.

2 The Model

2.1 Overview

We developed an agent-based model (ABM) that simulates the spatial and temporal dynamics of household agents and their interactions with the natural environment through resource consumption on Easter Island prior to European arrival. The environment is encoded on a 2D discretised map with real geographic and orographic features. Agents are represented by households, which comprise a variable number of individuals. Households rely on two resources: (1) palm trees, considered here a primary, non-renewable resource for essential tools, firewood, building material, sugary sap, etc. (e.g. Bahn and Flenley 2017) and (2) cultivated gardens of sweet potatoes, which constituted an important source of carbohydrates and water on the island (Tromp and Dudgeon 2015). Households use these resources by cutting trees and by creating gardens (i.e., by cultivating cleared, arable land available in their immediate surrounding). The growth or decline of households depends on the success with which they can obtain these resources. Households adapt to the changing environment and to the growing population in three ways. First, a household splits into two when it becomes too large and one of the two relocates in a different place. Second, households relocate when resources become scarce in their current location. Their moving behaviour is determined by resource availability and certain features of the environment, including elevation and distance from the three major lakes (Rano Kau, Rano Raraku, and Rano Aroi). Third, in response to the declining number of trees, households adapt their resource preference from a resource combination dominated by trees to a combination dominated by stable cultivation of sweet potatoes. In summary, the interaction between agents and the natural environment and the adaptive response of agents shape settlement patterns and population dynamics on the island.

In accordance with Vargas et al. (2006) and Bahn and Flenley (2017), the simulations start with two households (comprising a total population of 40 individuals) positioned in the proximity of Anakena Beach in the northern part of the island, in the year 800 A.D., thus mimicking the arrival of the first Polynesian settlers. Model updates occur asynchronously on time steps of one year until 1800 A.D. The model does not include processes such as spreading of diseases or slavery that were introduced after the discovery of the island by European voyagers in the eighteenth century. A schematic of the model is presented in Fig. 16.1. The model is coded in python, and the full code is freely accessible from GitHub https://github.com/systemsecologygroup/EasterIslandABM. A table including all parameters, their values, and sources can be found in Electronic Supplementary Material, Sect. 2. An Overview, Design concepts, and Details (ODD) protocol (Grimm et al. 2006, 2020) of the model, which contains all implementation details, is presented in Electronic Supplementary Material, Sect. 4.

2.2 Environment

The environment is encoded as a collection of Delaunay, triangular cells (with a constant area of $57.4 \cdot 10^3\ \mathrm{m}^2$) covering the island's total area of $167.4\ \mathrm{km}^2$. These cells provide a detailed, discretised representation of the island's actual orographic properties: elevation and slope. In addition, the environment includes the three crater lakes, Rano Kau, Rano Raraku, and Rano Aroi, which represented the only permanent source of freshwater on the island (Rull 2020). Following palynological evidence (Rull 2020), we externally force the aridification of Rano Raraku during two periods, from the arrival of the first settlers in 800 to 1200 A.D. and from

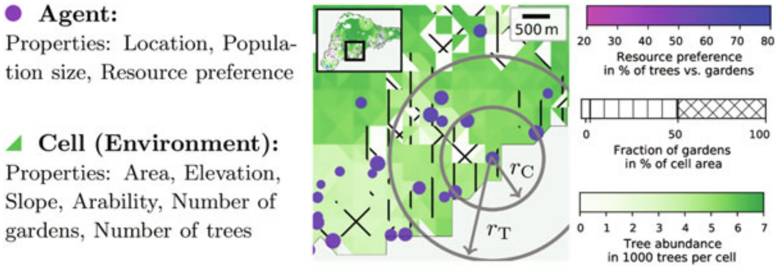

Fig. 16.1 Schematic of the model setup. Agents are characterised by their locations (dots), their population sizes (dot size), and their resource preferences (dot colour). The agents' surroundings (concentric circles) are defined by the tree harvest radius r_T and the cultivation radius r_C for cultivating gardens. Agents and their behaviour are described in detail in Sect. 2.3. The environment is subdivided into Delaunay triangular cells. Cells are characterised by fixed orographic and geographic features (area, elevation, slope, and arability index) and variable amounts of resources (the number of trees and number of cultivated gardens). The environment and its features are described in detail in Sect. 2.2

1570 to 1720 A.D. The discretisation method followed to create the environment is described in full detail in Electronic Supplementary Material, Sect. 4.3.1. A cell can provide two resources: (1) a variable number of trees and (2) a specific yield of sweet potatoes according to a cell's fixed arability index.

2.2.1 Palm Trees

A total of 16 million palm trees are uniformly distributed on the island at the start of a simulation, following Mieth and Bork (2015). Cells that are either too steep or too high in altitude are left empty (Fig. 16.2a). Thus, at the start of a simulation, 85% of the island is covered with trees. The number of trees in a cell can decrease over time as agents cut them down either for specific uses of the wood or simply to clear land for cultivation (see Sect. 2.3.1). To reflect the combined detrimental impact that human activities and Polynesian rats had on the regeneration of the forest (Hunt 2007; Bahn and Flenley 2017), palm trees are assumed to be a non-renewable resource.

2.2.2 Sweet Potatoes

As mentioned above, sweet potatoes constituted an important source of carbohydrates and water for the Rapa Nui, especially during the last centuries prior to European contact (Louwagie et al. 2006; Stevenson et al. 2015; Tromp and Dudgeon 2015). Archaeological evidence (e.g. Hunt and Lipo 2011; Ladefoged et al. 2013; Rull 2020) shows signs of agricultural activities organised on patchy, metre-scale areas called *manavai* (gardens). In our model, a garden is represented by a cleared,

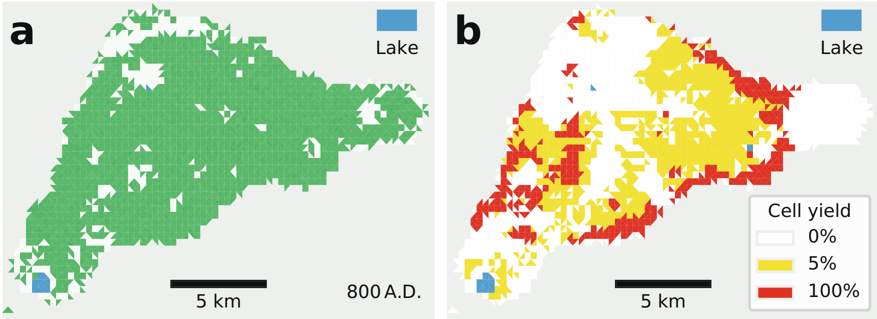

Fig. 16.2 Features of the environment related to the two resources: (**a**) initial distribution of trees and (**b**) cell arability in % yield of sweet potatoes. At the beginning of the simulation (800 A.D.), a total of 16 million trees are uniformly distributed on the map, covering 85% of the island. Each cell contains about 5500 trees. The classification of cells into "well-suited" (100%yield), "poorly suited" (5% yield), and "not suited" (0% yield) for cultivating sweet potatoes is based on the agriculturally viable zones identified by Puleston et al. (2017)

cultivated area of 1000 m^2 on an arable cell. At each time step, cultivation of such gardens provides agents with a constant yield of sweet potatoes. Given the cell's area of $57.4 \cdot 10^3$ m^2, one arable cell can host up to 57 gardens. Cells are characterised by a fixed arability index, which defines the suitability of a cell for cultivating sweet potatoes or, more specifically, the cell yield for sweet potatoes. We considered three categories: "well-suited" (100% yield), "poorly suited" (5% yield), and "not suited" (0% yield). To assign a specific arability index to a cell on the map, we considered the agriculturally viable zones identified by Puleston et al. (2017), based on the previous studies (Ladefoged et al. 2009, 2013; Louwagie et al. 2006). Following this approach, we obtain that "well-suited," "poorly suited," and "not suited" cells cover, respectively, 16%, 33%, and 51% of the island (Fig. 16.2b). In summary, through the opportunity to cultivate gardens in well-suited and in poorly suited cells, the environment provides agents with a stable, non-degrading second resource, sweet potatoes.

2.3 *Agent Characteristics and Behaviour*

A single agent in the model is represented by a household with a variable number of individuals, up to a maximum of 36 individuals, who live and harvest resources together as a single entity. An agent is characterised by three main properties: (1) the location on the island, (2) the number of individuals comprising the household, and (3) the resource preference (share of using palm trees over cultivated gardens). In each time step, which represents one year in the simulation, all agents are updated sequentially and in random order. During an update, the household interacts with its surrounding environment by cutting trees within a tree harvest radius r_T and by cultivating gardens within a cultivation radius r_C (Fig. 16.1 and Sect. 2.3.1). The number of individuals composing a household agent grows or declines according to a satisfaction index related to their resource harvest (Sect. 2.3.2). A household agent responds to changes in population size and local resource availability via three adaptation mechanisms: (1) splitting (and thereby creating a new agent), when the number of individuals reaches a maximum of 36, (2) moving to a new location, when a new agent is created or when the satisfaction index is too low due to insufficient resource harvests, and (3) updating the resource preference (i.e., the share of using palm trees over cultivated gardens) in response to local deforestation (Sect. 2.3.3).

2.3.1 Resource Requirement, Preference, and Harvest

For growing, a household is required to harvest a certain number of trees and a certain amount of sweet potatoes at every time step. Although humans did not consume trees directly, we posit that their primary use was destructive and essential for a household, e.g., to provide firewood and timber for building tools, and thus we assume that both resources play an equivalent role for the survival of agents and, over time, one resource can replace the other. This means that, in theory, an agent can harvest the required amount of resources either solely from trees (for a maximum of 10 trees per individual per year, Brandt and Merico 2015) or solely from continuously cultivated gardens (for a maximum of 6.79 gardens per individual, Puleston et al. 2017, weighted by the arability index, see derivation in Electronic Supplementary Material, Sect. 1). In practice, households always require a combination of both resources. The share of trees in this combination is determined by the resource preference of the household, which is bounded between 20% and 80%. The share of cultivated sweet potatoes follows accordingly. If, for example, the resource preference is 35%, then the requirements for using trees and cultivating gardens are 35% × 10 trees per individual per year and 65% × 6.79 gardens (weighted by their arability index) per individual, respectively. Thus, the population size and the current resource preference determine the combination of resources a household requires at every time step. In each update, an agent harvests resources sequentially, first from cultivated gardens and then from cutting trees.

Agents cultivate multiple gardens in arable cells and, at each time step, obtain an immediate, constant yield from them. If, at a time t, an agent requires more sweet potatoes than it required in the previous time step (for example, due to an increase in the number of individuals comprising the household or due to a decrease of its resource preference, following a decrease in the number of trees nearby), then the agent tries to increase the number of cultivated gardens. To cultivate new gardens, an agent needs to find a cell with the following characteristics: (1) it must be within the cultivation radius, (2) it must be well-suited for cultivating sweet potatoes, (3) it must contain an area of at least $1000\,\text{m}^2$ (the area of a garden) that is clear of trees and not yet cultivated. Since at the start of a simulation, trees are distributed uniformly within cells, the amount of cleared land in a cell corresponds to the fraction of removed trees at time t. Cleared land, however, may already include cultivated gardens. If no cell fulfils the three conditions, the agent clears land in one cell by slash-and-burn until the conditions are met. In this case, among all potential cells, the agent chooses the cell in which the least number of trees needs to be removed. If no cell fulfils all these conditions, the agent considers poorly suited cells (i.e., cells with a lower arability index and, thus, a smaller yield for sweet potatoes) as well. The cultivation of such low-yield areas is not limited by labour demand in this model. Gardens are cultivated continuously (i.e., fallowing is not considered). This sequential addition of gardens continues until the resource requirement of the household for sweet potatoes is met, or until no more suitable cells can be found.

After agents have tried to meet their resource requirement for cultivated gardens, they begin to satisfy their requirement for trees by cutting them down. To cut trees down, an agent needs to find a cell with the following, obvious characteristics: (1) it must be within the tree harvest radius and (2) it must contain trees. An agent cuts trees down until its resource requirement for trees is met or until the surrounding area is devoid of trees.

2.3.2 Population Dynamics

Over time, the population of a household increases or decreases depending on its success at harvesting the two resources. The success of an agent is limited by the smaller ratio between actual harvest and required harvest for both resources (trees and cultivated gardens), according to the Liebig's law of the minimum. Therefore, an agent is fully successful if both resource requirements are fulfilled and fully unsuccessful if one of the two resources could not be harvested at all. In particular, an agent is fully unsuccessful if it cannot find trees for building tools and other needs despite having been successful at harvesting the required amount of sweet potatoes, and vice versa.

Following previous modelling studies that assumed the rate of population growth to be maximal when resource consumption exceeds a certain threshold and to be reduced (or to be even negative) when resource consumption is insufficient (Lee and Tuljapurkar 2008; Puleston and Tuljapurkar 2008), we define an expected net population growth rate for a household as a function of a household satisfaction index, which measures the success of resource harvest over a scale ranging from 0 (fully unsatisfied) to 1 (fully satisfied). The household satisfaction index is calculated as the rolling mean between the success in the previous year and the success in the current year. The maximum expected net growth rate at full satisfaction is assumed to be 100.7% (i.e., 0.7% growth) per year, in line with previous suggestions (Vargas et al. 2006; Bahn and Flenley 2017). If the agent satisfaction declines, the expected net growth rate decreases and the household grows at reduced rate or even shrinks when satisfaction falls below a certain threshold. The satisfaction threshold is set at 0.69 (with a growth rate of 100% indicating replacement of the household), following the approach of Puleston et al. (2017) and by assuming that our satisfaction index reflects their "food ratio." For simplicity, we consider linear relationships between the net population growth rate

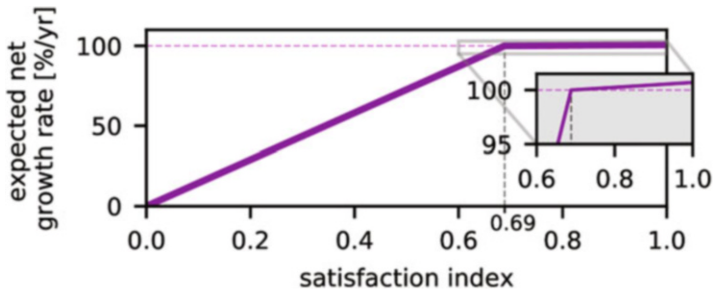

Fig. 16.3 Expected net growth rate of a household as a function of its satisfaction. While the actual population growth process is stochastic, on average a household grows or declines according to this expected net growth rate. The satisfaction threshold below which the population size decreases is 0.69 (marked by the vertical dashed line) and is adopted from a previous demographic modelling study (Puleston et al. 2017). The maximum expected growth rate is set to 100.7% per year (Vargas et al. 2006; Bahn and Flenley 2017)

and the household satisfaction index below and above the satisfaction threshold (Fig. 16.3).

Within a household agent, population growth is not a continuous process because birth and death of individuals are discrete and probabilistic events. These discrete processes are approximated by the household expected net growth rate, which determines, at each time step, the probability of an individual to survive (when the satisfaction index is below 0.69) or to reproduce (when the satisfaction index is above 0.69). For example, when a household has a continuous maximum expected net growth rate of 100.7% per year, its population size remains constant during most years and increases by 1, 2, or more individuals in some, rare time steps such that, on average, the household grows or declines according to the expected net growth rate. We finally note that if a household population decreases, that household may need fewer gardens to harvest a sufficient amount of sweet potatoes and can, thus, free the redundant gardens for other agents. A more detailed and technical description of these processes can be found in Electronic Supplementary Material, Sect. 4.3.3.4.

2.3.3 Adaptation Mechanisms

As agents harvest resources, they grow and the environment changes. Agents adapt to population growth and environmental change with three mechanisms: splitting, relocating, and updating the resource preference.

A household agent splits when its population size exceeds a maximum of 36 individuals. When this maximum is exceeded, a fixed number of 12 individuals split off from this household to form a new agent in a new location. If the population size of an agent falls below a minimum of 6 individuals, the household dies and is removed from the system.

Agents move to a new location if (1) they split off from an existing household or (2) the agent's satisfaction is below the threshold of 0.69 (Fig. 16.3) and its current success in resource harvest does not indicate rapid improvement for the next time step. To choose a new location, agents evaluate cells according to location preferences. We assume that agents prefer cells (1) with low elevation and low slope, (2) in the proximity of one of the three lakes, weighted by the area of the lake, (3) with low population density within the cultivation radius, (4) with high availability of trees within the tree harvest radius, and (5) with high availability of uncultivated and highly arable gardens within the cultivation radius. Note that only the last two preferences are directly related to the amount of resources an agent can access from the new location. The other preferences have only an indirect relevance for population growth or survival and may reflect decision-making based on heuristics or may account for factors that are not explicitly included in the model (such as easy access to fishing activities). Instead of finding an optimal location with respect to the location preferences, agents move according to a probabilistic decision-making approach, whereby cells with better characteristics in relation to the preferences are also those more likely to be chosen as new locations. This probabilistic approach reflects, for example, different views within the same household about the new location when an agent takes moving decisions. Note that after moving, conditions in the new location might change quickly as more agents may decide to move to the same area and, thus, impact the local environment. A more detailed description of the moving process can be found in Electronic Supplementary Material, Sects. 4.3.3.9 and 4.3.3.10.

The resource preference of an agent determines the share of using palm trees over cultivating gardens in the next time step. This property changes linearly as a function of local deforestation and is bounded between a minimum (20%) and a maximum (80%). This adaptation mechanism reflects the fact that the Rapa Nui initially relied on the destructive use of abundant palm trees and other natural resources and that agricultural activities increasingly replaced this dependency as deforestation progressed over time (e.g. Louwagie et al. 2006; Mulrooney 2013). The minimum resource preference of 20% is based on the assumption that people could not survive without trees even if agriculture would provide sufficient food resources.

2.4 Simulations and Sensitivity Analysis

To investigate the relative importance of different processes to the overall temporal and spatial dynamics of the agents on the island, we created three scenarios corresponding to three different model formulations. In the first scenario, named "unconstrained," households are neither limited by any spatial restrictions for harvesting trees and for cultivating gardens nor by any location preferences. Thus, agents consider all locations on the island equally suitable for settling. In the second scenario, named "partly constrained," access to resources is restricted within specified radii ($r_T = 2$ km and $r_C = 1$ km) and, as in the previous scenario, the moving of households is not influenced by location preferences. In the third and final scenario, named "fully constrained," access to resources is restricted within specified radii ($r_T = 2$ km and $r_C = 1$ km) and the moving of households is influenced by location preferences, which are based on environmental features. The three scenarios and their specific features are summarised in Table 16.1. To account for the stochastic nature of our model, we run 50 replicate simulations for each scenario.

Since our investigation is focused on the heterogeneity of population patterns on the island, we present the results as snapshots of the spatial distribution of trees, cultivated gardens, and agents for a single, representative simulation run at different times (or at all time steps in the video in Electronic Supplementary Material). In addition, we divide the island into a number of regions, as shown in Fig. 16.4, defined according to geographic characteristics, like elevation (e.g., the region *Uplands* comprises locations above the altitude of 100 m), distance from lakes (regions *Raraku* and *Kau*), or particular points of interest (e.g., *Anakena*). This

Table 16.1 Summary of the different scenarios considered in this modelling study

Scenario	Resource access	Location preferences
Unconstrained	Whole island	None
Partly constrained	Within radii r_T and r_C	None
Fully constrained	Within radii r_T and r_C	All

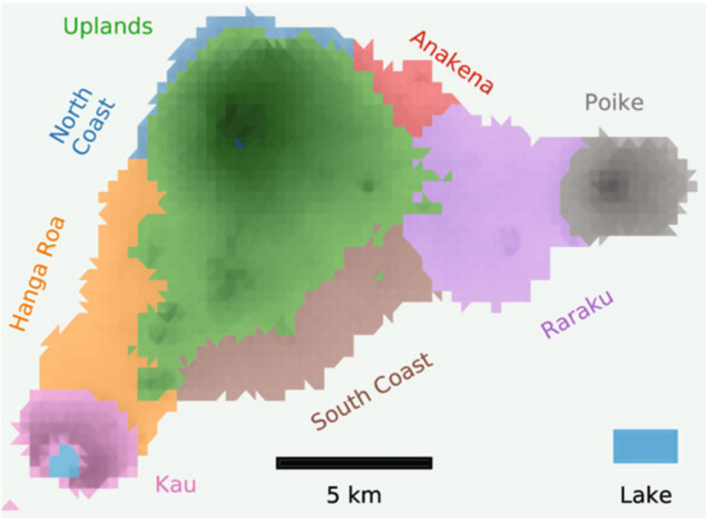

Fig. 16.4 To investigate the effects of environmental heterogeneity on population dynamics in our model, we divide the island into eight regions and present the results both as globally aggregated and regionally aggregated temporal patterns. The same colour-coding adopted here is used for showing the results in the corresponding regions (Fig. 16.5)

allows us to quantitatively compare the different population dynamics obtained in these different regions.

We complement our investigations with a sensitivity analysis of the model results in relation to specific model assumptions. There are many interesting insights one can infer from these analyses. Here, we focus our attention on the effects of parameters and processes to timing and size of a global population peak, obtained under the "fully constrained" scenario. We explore the effects of ±50% changes in the values of some crucial parameters: (1) maximum requirement for trees per individual per year, (2) maximum requirement for cultivated gardens per individual, and (3) resource access radii. In addition, we explore the effects of (1) different initial tree distributions, (2) droughts of Rano Raraku, and (3) minimum share of using trees over cultivating gardens.

3 Results

3.1 Scenarios

As explained in the previous section, to investigate the relative importance of different processes to the overall temporal and spatial dynamics of the agents in our model, we explored three scenarios, corresponding to three different model formulations (Table 16.1).

In the first scenario, "unconstrained," agents can access resources (use trees and cultivate sweet potatoes) anywhere on the island without any spatial restrictions or location preferences. Therefore, during the first centuries, households populate the island uniformly (Fig. 16.5a1). By the sixteenth century, on the global scale, the human population has reached its peak at around 8000 individuals, arable land has become scarce, as roughly half of the island gets occupied by a total of approximately 82,000 gardens (the maximum number of gardens that the island can sustain, which includes well-suited and poorly suited gardens, the latter with a very low yield of sweet potatoes), and almost 80% of the palm trees have disappeared (Fig. 16.5a2). The shift in resource preferences characterised by larger shares of garden cultivation over palm trees leads to an initial, small decline in population size, right after the population peak. From about 1600 to about 1700 A.D., the island is in a phase characterised by a relatively stable population size of about 7000 individuals relying for livelihood on the maximum possible number of cultivated gardens (Fig. 16.5a2). The minimum requirement for trees, however, causes a rapid collapse of the population once the island is deforested (shortly after 1700 A.D.) The population crash is immediately followed by a rapid decline in the number of cultivated gardens. The regional population patterns (Fig. 16.5a3) are very similar in shape to the global pattern.

In the second scenario, "partly constrained," agents can access resources only within specific spatial limits from their locations. During the first centuries, on

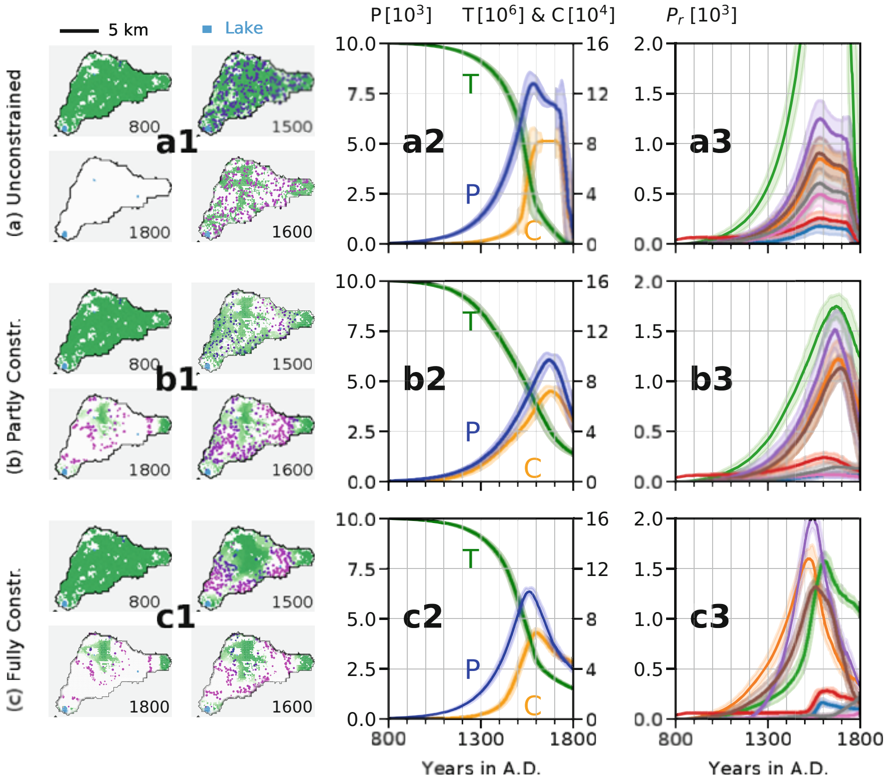

Fig. 16.5 Simulation results for the three scenarios: (**a**) unconstrained, (**b**) partly constrained, and (**c**) fully constrained. The left column (1) shows spatial snapshots of the results for corresponding scenarios at four different times, 800, 1500, 1600, 1800 A.D. These snapshots show: tree cover (green), density of occupied gardens (hatch lines), and agents (dots). The size of the dot reflects the number of individuals comprising the household. The colour of the dot reflects the resource preference of the household (decreasing resource preference for trees over cultivated gardens goes from blue to pink). The middle column (2) shows island-wide aggregates of the total population in thousand individuals, P (blue), the number of trees in millions, T (green), and cultivated gardens in ten thousand, C (orange). The thick lines represent averages of ensembles of 50 runs. The semi-transparent areas indicate the standard deviation of the ensemble runs. The right column (3) shows the dynamics of population sizes in thousands, P_r, aggregated in each region separately. The colours correspond to the specific regions defined in Fig. 16.4 (green: *Uplands*, violet: *Raraku*, orange: *Hanga Roa*, brown: *South Coast*, grey: *Poike*, red: *Anakena*, pink: *Kau*, and blue: *North Coast*)

the global scale, agents increase in numbers, occupy new locations randomly (Fig. 16.5b1), and settle in these locations for as long as their satisfaction index remains sufficiently high. In this phase, agents do not compete much with one another for resources that are abundant and distributed over the whole island. In contrast to the previous scenario, we observe now a less homogeneous distribution of agents (Fig. 16.5b1) because, as the number of agents increases, environmental differences in terms of resource availability become more pronounced. Under these conditions, the search for new locations slows down population growth, leading to a prolonged and slow period of growth that lasts until almost 1700 A.D. (Fig. 16.5b2). Regions with a higher number of cells well-suited for cultivation (Fig. 16.2b) sustain larger population densities (Fig. 16.5b1). However, regions that become highly populated are also those that experience a more severe environmental degradation in terms of tree reduction (Fig. 16.5b1), thus imposing a stronger pressure on agents to adapt. In contrast, regions with a small but still a sufficient number of arable cells (e.g., parts of the *Uplands* or *Kau*) host fewer agents per area throughout the whole simulation period (compare Figs. 16.5b3 and 16.5a3). The environment of these regions is degraded at a slow pace, and the local agent population tends to remain more stable than in other regions. However, as resources become scarce in large parts of the island, agents start to compete with one another more intensively. Newly created households or households dissatisfied with their resource harvest start to move to populated regions if such regions can still provide the necessary resources. Agents begin to cluster more strongly around 1600 A.D., so that pressure increases on resources in more and more regions (Fig. 16.5b1), initiating cascade-like population declines (Fig. 16.5b3). The island-wide population is halved within a century and is immediately followed by a similar decline in the number of cultivated gardens (Fig. 16.5b2).

Under the "fully constrained" scenario, agents can access resources only within specific spatial limits from their locations and, in addition, they have preferences for specific environmental features, thus qualitatively mimicking human decision-making when moving to new locations. Under these conditions, a quick clustering of agents is observed within more preferred regions like *Hanga Roa*, *South Coast*, and *Raraku* due to their overall high arability (Figs. 16.5c1 and 16.2b) or other attractive geographical features. These more densely populated regions are, thus, subject to increased deforestation in the early centuries. This increases the speed with which agents adapt to the disappearing forest via a transition to garden cultivation activities. The increasing number of cultivated gardens exacerbates forest clearance, thus establishing a positive feedback loop of deforestation in some locations (arability Fig. 16.5c1). In contrast to the two previous scenarios, clustered agents now compete over the common resources in local areas well before a large-scale (or island-wide) resource shortage develops. The global population peaks at 6000 individuals before 1600 A.D. (Fig. 16.5c2), roughly a century earlier than in the "partly constrained" scenario and at a slightly higher value. After this peak, the population decreases at a rate slower than in the previous scenario and is reduced by 50% within two centuries. During this period, the clusters of high population densities move from initially preferred but now depleted regions to less exploited regions (Fig. 16.5c1). Only in this scenario, we observe clear differences in the population dynamics of different regions (Fig. 16.5c3). For example, while the populations of the *Uplands*, *North Coast*, and *Anakena* enter a phase of slow demise around 1600 A.D., by this time the populations of *Raraku* and *Hanga Roa* had already entered a phase of abrupt decline, more in line with the previous scenario. In contrast, the relatively small populations of *Kau* and *Poike* increase continuously

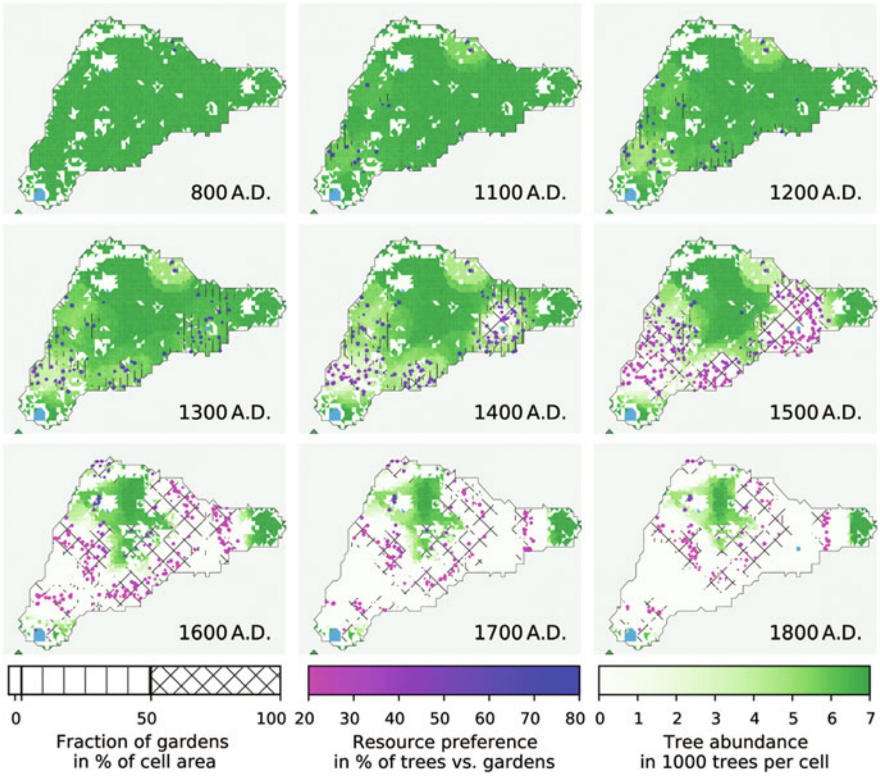

Fig. 16.6 Snapshots produced under the "fully constrained" scenario. Each panel shows the distribution of trees (with different green intensities) and the fraction of cultivated garden per cell area (shown as vertical or crisscrossed hatch lines for, respectively, sparse and dense cultivations). Agents are shown as dots, with the number of individuals reflected by the dot size and resource preference reflected by the dot colour. These snapshots can be compared to a collection of similar maps created by Rull (2020, Fig. 9) through the aggregation of spatio-temporal palynological and archaeological information around the three lakes. In the video in Electronic Supplementary Material we show the snapshots of this simulation run for all time steps from 800 to 1800 A.D.

until 1800 A.D. In summary, the different regions show quite different trajectories in terms of population dynamics and deforestation patterns.

Figure 16.6 shows the spatio-temporal patterns in relation to agent distribution, tree cover, and cultivation activities produced under the "fully constrained" scenario. These patterns are qualitatively consistent with a very recent collection of archaeological and palynological information presented by Rull (2020, Fig. 9). In line with these observations, our simulations show a relatively dense tree distribution in the regions around the three lakes. Deforestation around Rano Kau increases in the fourteenth century in both simulations and observations. In our model, some areas around Rano Raraku are already deforested before 1400 A.D., but, similarly to observational evidence, the clearance of trees strongly intensifies in the fifteenth century. The drying out of Rano Raraku (between 1570 and 1720 A.D.) suggested by Rull (2020) coincides in our model results with the disappearance of trees and population decline in this region, but also in the *South Coast* and in the region around *Hanga Roa*. Moreover, similarly to Rull (2020)'s data, the tree density around Rano Aroi remains unaltered in our simulation. Intensified deforestation in the *Uplands* is observed in both model and observations only from 1600 A.D. onwards.

3.2 Sensitivity Analysis

By determining the rate at which household agents need to extract resources, the constant maximum tree and cultivation requirements per individual have an obvious importance on limiting the global population size. A ±50% change in the maximum tree requirement per individual cause a ∓20% change in the peak population size (Fig. 1 in the Electronic Supplementary Material). A 50% increase in the maximum cultivation requirement per individual (corresponding to lower yields from a single garden) produces a decrease by 20% of the peak population size. More significantly, though, a 50% reduction in that parameter leads to a population peak that is delayed by 50 years and that is 50% higher than the peak produced with the standard parameter value (Fig. 2 in the Electronic Supplementary Material).

By restricting the number of potential locations from which an agent can obtain resources, the access radii for tree harvest and cultivation limit the amount of resources an agent can obtain. It is therefore not surprising that for smaller radii, this restriction tends to reduce the population size and vice versa. In fact, a ±50% change in resource search radii produces roughly a ±20% change in population peak values (Fig. 4 in the Electronic Supplementary Material).

The assumption of higher tree densities around the lakes, compared to the uniform distribution adopted in our standard simulations, does not impact island-wide population dynamics unless this clustering is very pronounced and, consequently, locations that provide access to trees are limited to only a few small areas around the lakes. In the case of pronounced clustering, the population peak is delayed by more than 50 years and the maximum value is reduced by 30% (Figs. 5 and 6 in the Electronic Supplementary Material).

In all model scenarios, droughts are simulated by drying out Rano Raraku during the two periods 800–1200 A.D. and 1570–1720 A.D. (Rull 2020). In Fig. 7 in Electronic Supplementary Material, we compare our standard runs, which include droughts, with runs that omit them. At a global scale, the influence of droughts is negligible. At a regional scale, however, the influence of droughts is more pronounced. In our standard runs, agents tend to avoid moving to *Raraku* during the first drought due to its distance from the available water sources (Fig. 8 in the Electronic Supplementary Material). However, after 1200 A.D., between the two droughts, *Raraku* becomes an attractive settlement location with its overall high arability and mostly uncultivated areas. This attractiveness causes a more rapid increase in the population size of the region compared to runs in which droughts are not included. It is important to note, however, that droughts in our model do not influence resources like soil fertility or tree availability but only the moving behaviour of the agents through the preference for lake proximity.

The minimum, non-zero level considered for the resource preference for using trees over cultivating gardens (equivalent to 20%) in our standard simulations is based on the assumption that people could not live without trees. This critical assumption produces the population declines observed in all scenarios and, ultimately, extinction once the island is completely deforested. If, instead, the minimum resource preference is set to 0%, reflecting the possibility that people could perfectly adapt to an environment without trees and sweet potatoes are the only determining factor of survival, then the population size remains constant after it reaches a peak at around 1580 A.D. (see Fig. 9 in the Electronic Supplementary Material) because it can rely 100% on cultivated gardens and soil fertility does not decline by model design.

4 Discussion

With respect to previous modelling works (for reviews, see Reuveny 2012; Merico 2017), the agent-based model presented here adds two elements of novelty: (1) a spatially explicit framework, which includes realistic geographic features and plausible soil characteristics, and (2) independent household agents that interact with their environment through tree harvest and sweet potato cultivation. As time progresses during a simulation, agents take decisions that shape the environment and the changing environment, in turn, affects agents' decisions.

To investigate the relevance of different processes in shaping the interactions between agents and environment, we created three model scenarios. All scenarios share the following conditions. Up to 85% of the island is initially covered with palm trees, in line with uncontested evidence supporting the existence of a dense palm forest prior to human arrival (e.g. Mieth and Bork 2015). Trees are assumed non-renewable to account for the detrimental impact of Polynesian rats (Hunt 2007; Bahn and Flenley 2017). The island is characterised by the overall low soil fertility, consistent with low nitrogen fixation rates suggested by a previous study (Puleston et al. 2017). Soil fertility remains constant throughout the simulations, thus providing stable yields of sweet potatoes. Yields, however, vary from location to location, according to a spatially heterogeneous arability index. Soil fertility is fixed because clear evidence in support of intensive lithic mulching practices on the island (Bork et al. 2004) suggests a continuous and strenuous effort to avoid erosion and maintain soil fertility. Agents are able to replace their initial, strong dependency on a declining forest (and the associated resources, not just essential timber but also fruit, sugary sap, and other forest-derived livelihoods) by the cultivation of new gardens. However, they can do so only up to a certain degree because we assume there is always a minimum, non-zero requirement for trees as a primary resource. Agents share the same objective in all scenarios: they harvest resources in order to maximise their instantaneous population growth.

In the first scenario, “unconstrained,” household agents can harvest trees and cultivate gardens anywhere on the island, regardless of the distances from their settlement locations, and can relocate on the island without constraints in terms of resource availability and other geographical preferences. Under such unrealistic conditions, this scenario produces a period of about one century of high (around 7000 individuals) and relatively stable, if not slightly declining, population size. This relative stability is primarily sustained by the continuous and steady supply of sweet potatoes from cultivated gardens. As the forest declines during the first centuries, the number of cultivated gardens increases until the whole arable area (comprising a maximum of about 82,000 gardens) on the island is cultivated. The number of cultivated gardens remains at this maximum level for more than a century because during this period there are enough trees to meet household requirements and soil fertility does not decline over time. Once deforestation is completed, the population collapses to zero and the number of cultivated gardens declines abruptly. This scenario mimics the typical conditions of differential equation-based models (pioneered by Brander and Taylor 1998) in which an assemblage of unspecified individuals, the population, cut trees and practice agriculture anywhere on the island without concerns for practical access to resources or environmental features.

In the second scenario, “partly constrained,” agents can harvest trees and cultivate gardens for sweet potatoes only within specified distances from their settlement locations (1 and 2 km for cultivation and trees, respectively), but they can still relocate on the island without constraints in terms of resource availability and other geographical preferences. In the early centuries, as the island is populated less uniformly than in the previous scenario, spatial heterogeneity in the environment leads also to different speeds with which agents can use and deplete resources. Regions with the overall high arability can sustain larger populations than those with the overall lower arability but are also depleted of resources at faster paces than others. Thus, agents in these regions have to adapt faster than in others and, eventually, they move to new locations, where an existing local population already uses the available resources. In other words, the agent objective to maximise instantaneous growth in combination with the constrained resource access of this scenario causes the emergence of intensified competition for new locations as resources become scarce. This leads to a region-by-region, cascade-like resource depletion and population declines. All regions exhibit almost synchronised boom-and-bust dynamics. This scenario produces results that correspond to the island-wide “ecocide” narrative (Flenley and Bahn 2003; Diamond 2005). The growth of a population that has, in the initial phase of the simulation, no concerns for resource availability falls, later, into a spiral of intensified competition for depleting resources and, eventually, into a collapse.

In the “fully constrained” scenario, agents have some form of environmental knowledge in terms of geographical features, which they use to move to locations that meet their geographic and resource-related preferences, thus constraining the random movement from the previous scenarios. This leads to a more effective exploitation of resources, to a consequent rapid population growth in the early centuries, and—in contrast to the previous scenarios—to a rapid and dense clustering of the agents in certain preferred regions. Patterns of resource depletion are quite different in the various regions. Clearly evident is, for example, the coexistence of areas with untouched forest and areas fully devoid of trees. When resources are depleted in one region, agents face relocation to areas that they might have rejected earlier in the simulation, because they could still find places with better characteristics (places with an overall higher arability or other favoured geographic features), but that are now acceptable because these areas provide a sufficient amount of resources. This is observed in particular in the *Uplands*, which cover the largest portion of central territories but remain mostly unpopulated in the early centuries. A relocation behaviour based on environmental knowledge represents, in principle, an effective adaptation strategy in the face of resource shortages. In our model, knowledge leads to an earlier peak and a slower decline of the island-wide population size than in the previous scenario. However, and quite importantly, knowledge of the environment does not avert the tendency of boom-and-bust dynamics on the global scale. This tendency is inevitable and depends on the designing principle of our model—and of any other previous model of Easter Island since the work of Brander and Taylor (1998), see the reviews of Reuveny (2012) and Merico (2017)—that is, agents always maximise growth on the base of a pool of finite and non- or slowly renewable resources. In fact, as in the previous scenarios, the global population dynamics follow the same general Malthusian patterns typical of pre-industrial societies (Clark 2007), an initial exponential growth turns into a decline when resources become scarce. However, in contrast to the other scenarios, the regional patterns of the "fully constrained" scenario vary strongly from one another. For example, some regions show population trajectories that are incongruous with the "ecocide" narrative and more in line with the "slow demise" hypothesis (Brandt and Merico 2015).

Among the three scenarios, we consider the "fully constrained" scenario the most realistic one because it produces spatio-temporal patterns of deforestation that are qualitatively very similar to the archaeological and palynological data summarised in Rull (2020, Fig. 9). Temporal changes in settlement patterns and in the distribution of cultivated areas on the island remain, however, matters of debate. Stevenson et al. (2015), for example, suggested region-specific declines of land use and, presumably, population densities in areas with low arability (corresponding to the *Uplands* region in our model) before European contact. Mulrooney (2013), in contrast, disputed the notion of a widespread shift of human settlements prior to European contact. Our results suggest that it is not only the heterogeneity of the environment to be relevant but also the way people responded to it. The condition of choosing locations based on environmental preferences, which we included in the "fully constrained" scenario, implies a profound knowledge of the environment—a plausible assumption given the small size of the island and given the form of governance that the monument construction and the rituals associated with it might have provided (Lipo et al. 2020)—and leads, therefore, to a more effective use of resources as compared to when this knowledge is not present, as in the "partly constrained" scenario. The combination of a diverse geography, a changing environment, and an awareness of such changes do create boom-and-bust like dynamics (albeit slightly less pronounced than in the other scenarios) on the global scale, but it shows much more complex and diverse population patterns on the local scale. These regional and rich differences indicate that single island-wide narratives of collapse are too simplistic and that observational inferences at the local scale cannot be reliably and directly extrapolated to the global scale.

The mathematical model presented here, and actually any other model of ancient human societies, however sophisticated, is a simplified representation of complex ecological and socio-economic issues. Our model constitutes an initial characterisation of the historical Rapa Nui society from environmentally realistic and agent explicit perspectives. This initial mathematical modelling treatment, although novel in relation to Easter Island (Merico 2017), has obvious limitations. However, the flexibility offered by this type of models allows for continuing developments and implementations (Bonabeau 2002). Avenues of future development may include a more elaborate social organisation of household agents. In our model, agents act independently from one another and are not governed by central organisations. Easter Island was divided into several clans run by chiefs that organised harvest activities, for example by limiting access to resources through taboos, *tapu* (Cauwe and Latsanopoulos 2011), and trading manufactured and harvested goods (e.g. Bahn and Flenley 2017). A clan with some political power would have access to resources in areas larger than the immediate surroundings considered in our model and in a coordinated manner. Exchange and distribution of resources across settlements could be a very interesting area of model development to understand, for example, the effects of different structures of trading networks to population size and the number and distribution of clans and communities, as recently demonstrated by the work of Chliaoutakis and Chalkiadakis (2020). The inclusion of additional resources like fishery, coastal freshwater seeps (DiNapoli et al. 2019), or diversified farming practices, including wetland agriculture (Rull 2020), also has the potential to produce valuable insights in relation to population dynamics. Complexity can also be added in relation to human behaviour, for example, by allowing continuing technological progress and capital accumulation typical of some pre-industrial societies (Tisdell and Svizzero 2015), despite the poverty and severe resource limitations imposed by the small size and isolation of Easter Island. A more advanced version of our model could allow agents to choose between cooperation and competition strategies, myopic and far-sighted behaviours, and to pass on the most successful strategy to following generations.

A growing body of research considers the effects of potential climatic perturbations on the Rapa Nui society (e.g. Rull 2020; Lima et al. 2020). The hypothesis that climatic variations may have affected population dynamics is based, for example, on the temporal correlation of drought periods and shifts of ceremonial centres (Cauwe and Latsanopoulos 2011), or on spatio-temporal patterns of forest density (Rull 2020). However, climate modelling (Junk and Claussen 2011) could not confirm the occurrence of climatic variations during Easter Island's late prehistory, and, more importantly, we have no clear information about how such climatic variations could have affected resources on the island. We include suggested periods of droughts of Rano Raraku (Rull 2020) in our model by making areas around this lake less attractive to agents during these periods but do not account for the consequences of such droughts on forest or soil fertility. In the sensitivity analysis, we show that while they influence regional population patterns, droughts have no noticeable effect on island-wide patterns. Future modelling studies may build up on our work to investigate how (heterogeneous) impacts of climatic perturbations affect resources and the population dynamics on regional and global levels.

Finally, while trees must have constituted a valued resource in particular for the firewood and the timber they provided (for building tools necessary for crucial activities such as agriculture, fishing, and statue carving), they were probably not essential for the survival of the society. The assumption that population growth depends on trees is not supported by clear and uncontroversial evidence. In particular, we know that the island was populated and, apparently, quite prosperously, according to some reports by the first European explorers (see, for example, Bahn and Flenley 2017) despite being entirely deforested. In this respect, a possible future improvement of our model could consider population growth independent from trees and rather treat this resource in the same way as we treated freshwater—easy access to trees in a location increases the attractiveness of that location.[1] Another uncertain assumption in our model involves the fact that even extremely low-yield cells are farmed despite some studies indicating that the amount of labour invested on agriculture by the productive population ranged between 10 and 20 person-hours per week on many small islands of the Pacific (Bayliss-Smith 1978). Our model assumptions lead to plausible spatio-temporal patterns, but this does not constitute a proof that such assumptions are correct. Different assumptions might lead to similar patterns or to results more consistent with a population that did not depend directly on the presence of a forest for survival. Given the uncertainties involved in the archaeological evidence, the aim of our study was not to pin down the exact patterns of deforestation and population growth, but rather to explore the impacts that people's knowledge and environmental heterogeneity might have exerted on such patterns.

5 Conclusions

The environment of Easter Island played an important role in limiting human growth. Despite its simplicity, our model provides valuable insights not only about this rather obvious relationship but also about how certain assumptions on human behaviour, specifically environmental knowledge in moving decisions, impact the dynamics of deforestation, population size, and land use at the local scale. A society, in which households are spatially restricted in their harvest, shows

[1] We thank the anonymous reviewer for this suggestion.

population dynamics more in line with a typical collapse narrative. A society, in which households use environmental knowledge to decide on settlement locations, follows a pattern that is similar to a collapse but less pronounced. Ultimately, the continuous dependency of the agents on a dwindling and non-renewable forest is the primary driver of population declines in our scenarios (the cultivation of sweet potatoes is not limited by soil degradation by model design). However, the model produces stable population sizes when cultivation can fully replace the dependency on trees in an entirely deforested island, provided that soil degradation is not an issue for agricultural activities. The model shows that environmental knowledge, a factor that we presume must have characterised the Rapa Nui society, leads, on a regional scale, to complex and diverse population dynamics ranging from collapse to slow demise and even to continuous growth. We note that the form of knowledge implied by our assumptions is still tied to an exploitative behaviour and not, for example, to a sustainable behaviour. The important implications of our study are that an island-wide narrative of collapse is too simplistic given the variety of population patterns we found at a regional scale. We conclude, therefore, that global-island narratives might not be representative for regional dynamics and, in turn, observational evidence on a regional scale cannot be reliably extrapolated to the global scale.

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