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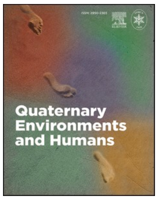

Modelling the impact of large-scale hydroclimate change on prehistoric Polynesian island life

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ABSTRACT

The South Pacific was one of the last regions on earth to be colonised by humans and offers a unique opportunity to study early climate-human interactions in environments previously untouched by people. Palaeoclimate evidence suggests the South Pacific has experienced shifts between dry and wet periods throughout the past three thousand years, the broad period of colonisation, with extremes in both modes being prevalent. Drought has significant repercussions for small Pacific islands, affecting water and food resources, with potential consequences on the viability of life on these islands leading to internal stress, conflict, collapse or migration. Previously, socio-ecological models have been developed to test mechanisms of change within prehistoric societies worldwide that can lead to migration or societal change, but thus far the connections between past climatic change and prehistoric island life within the tropical South Pacific have not been fully explored. This study utilises palaeoclimatic data alongside a new system dynamics socio-ecological model to explore the relationship between climate, agricultural carrying capacity and population dynamics on the Polynesian island of Mangaia (Cook Islands) in the tropical South Pacific. Model results suggest that as the population density of the island increases, the impact of drought events on population dynamics increases. We also show that the severity of the drought rather than the return frequency drove the largest changes in carrying capacity and population dynamics. Changes in long-term rainfall leading to persistent dry conditions impacted the timing and rate of population growth due to its role as a limiting factor for agricultural productivity. We compare our modelled results with the known history of population stress and societal change from Mangaia and found these corresponded with drought periods and low food availability. We demonstrate the potential for droughts to have impacted on the early colonisation and societal change on Eastern Polynesian islands.

1. Introduction

A growing body of literature on palaeoclimate indicates that there have been significant hydroclimate changes around key periods of human prehistory in the tropical South Pacific (Sear et al., 2020; Duprey et al., 2012; Toomey et al., 2016). The Pacific region is characterised by its highly variable rainfall and the reliance of water and food resources on available rainfall (Palanisamy et al., 2018). Despite high annual levels of rainfall, drought is a prominent feature in Pacific islands climate, particularly during El Niño Southern Oscillation (ENSO) events, which are strongly related to precipitation anomalies (McGree et al., 2016). Climate – specifically drought - has been cited as a potential driver of migration (Duprey et al., 2014; Cochrane, 2018; Sear et al., 2020) as well as other aspects of prehistoric Pacific island life including, voyaging (Anderson et al., 2006a; Goodwin et al., 2014), diet (Kirch, 1994; Allen and Wallace, 2007) and conflict (Kirch, 1984; Nunn, 2000; Field and Lape, 2010; Kirch, 2017).

Human migration across the Pacific occurred in two pulses, the first started approximately 1050 BCE and saw the colonisation of remote Oceania eastward to Samoa (Hunt and Lipo, 2017; Cochrane, 2018). After a 'long pause' of around 1700 years, the second pulse occurred between ca. 900–1250 CE and saw the colonisation of eastern Polynesia out to the three corners of the Polynesian Triangle – Hawai'i, New Zealand and Rapa Nui (Easter Island) (Wilmshurst et al., 2011; Ioannidis et al., 2021). The drivers of these migration pulses are contested, but climate is increasingly thought to have been a contributing factor (Sear et al., 2020). The reconstruction of ancient environments and the associated climates have provided insights into the changing

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environmental context that past societies have had to navigate (Kirch et al., 2012; Brandt and Merico, 2015; Kuil et al., 2016; Sear et al., 2020). However, whilst palaeoenvironmental and palaeoclimate studies discuss the potential impacts of environmental or climatic change on the systems and societies in their region of study (Kirch, 1984, 1994; Nunn, 2000; Cochrane, 2018), little has been done to explore these connections explicitly using modelling.

The impact of climate on ancient populations has been widely studied in other regions and examples extend across the globe. For example, it has been suggested that drought played a role in the fall of the classic Maya in Central America (Hodell et al., 2005; Evans et al., 2018), relative demise of Eastern Mediterranean societies in Egypt, Turkey, Cyprus and Syria during the Bronze Age (Kaniewski et al., 2015) and impacted Native American cultures between 11th and 13th centuries (Benson et al., 2007). Socio-ecological modelling can be a useful tool for reconstructing the dynamics of past societies and testing hypotheses around changes to these systems, including the relative influence of climate change (Barton et al., 2012). In the Pacific, archaeological studies have provided information about prehistoric island life and how it evolved through time (Burley, 1998; Anderson et al., 2006b; Bedford, Spriggs and Regenvanu, 2006; Bedford and Spriggs, 2008; Hunt, 2009; Allen, 2010, 2015; Field and Lape, 2010; Kinaston et al., 2014; Bedford and Spriggs, 2014; Hunt and Lipo, 2018). Used in conjunction with climatic or environmental palaeo-reconstructions, this information offers an opportunity to test these changes against possible drivers such as climate. This has been facilitated by the development of computational modelling to reconstruct the dynamics of prehistoric societies in a formal and systematic way (Barton et al., 2012; Elsawah et al., 2017). Simulation models can be particularly useful in archaeological interpretation where it is not possible to go into the field and make direct observations i.e. in the past. Narratives of social change can be tested and become the subject of experimentation to understand sensitivities and thresholds of change, and identify the main drivers and feedbacks. Archaeological data can be used to inform model parameter estimations and validate model outputs as well as testing working theories on the functioning of socio-ecological systems (Barton et al., 2012).

It is rare for socio-ecological studies to use modelling approaches to bring together palaeoclimate and archaeological data to identify the processes and impacts of climate on island life and specifically to use this to interpret the potential influence of climate on the timing of human migration in the tropical South Pacific. There are studies that have considered other drivers (e.g. conflict, societal change, ecological degradation), which do have relevance but do not explicitly consider climate variability or change (Brander and Taylor, 1998; Field, 2004; Brandt and Merico, 2015). There are several studies on the tropical Pacific that look at some aspects of the connections between climate, agriculture and population on islands (Hamilton and Kahn, 2007; Kirch et al., 2012; Lima et al., 2020). However, past model-based research in the tropical Pacific has been limited by either not including climate data at all or only using modern rainfall records that are not representative of past conditions (Freund et al., 2019); largely because high-resolution paleoclimate records have not been available for Pacific Islands. An example where socio-ecological models have been used elsewhere to examine the impact of climatic change on agriculturally dependent communities using palaeo data to reconstruct past rainfall for prehistoric societies was done by Kuil et al. (2016) on the classic Maya in central America. This study demonstrated how palaeo-climatic archives and modelling can come together to help answer archaeological questions, providing useful insights into the impact of climate change in the prehistoric era. However, to date no socio-ecological model for the tropical South Pacific explicitly examines the impact of drought on island life using palaeo rainfall data which reflects the climatic conditions during the prehistoric period. This limits our insights into how changing climate in the late Holocene impacted South Pacific island systems and the human populations during a period where we know there were significant changes in rainfall (Sear et al., 2020; Maloney et al., 2022).

The aim of this study is to understand how climate - specifically drought - impacted upon agricultural outputs, population dynamics and food availability in prehistoric Polynesia. To that end, the objectives of this study were to 1) develop a socio-ecological model representing past changes in rainfall based on palaeo records to assess the impact on food availability and population dynamics on a small island, and to 2) identify whether drought had a significant impact on island populations and was a potential driver of migration and societal change in the prehistoric Pacific.

2. The socio-ecological system of the prehistoric Polynesians

The islands of the Pacific vary from one another physically, ecologically and socially and so the socio-ecological system of each island is different. The model presented here was developed around the island of Mangaia (Cook Islands) for three reasons: 1) The archaeology of Mangaia is relatively well understood and provides good dating for human arrival and subsequent societal changes (Kirch, 2017), 2) Mangaia was one of the most densely populated islands in Polynesia (Kirch, 2017) – and therefore offers insight into an island system near its limit, and 3) the Southern Cook Islands, in which Mangaia is located, are considered the gateway islands from which the rest of Eastern Polynesia was colonised (Allen and Wallace, 2007) and therefore it offers insights into Pacific human migration and colonisation of Eastern Polynesia.

Key sources that document the island and offer insights on the socio-ecological system of prehistoric Mangaia come from the first Europeans to visit including Captain Cook in 1777, two English missionaries - John Williams (1837) who visited Mangaia between 1823 – 1831 and William Wyatt Gill, who lived on the island for twenty years from 1852 (Gill, 1894) and finally, Peter Buck (Te Rangi Hīroa), a doctor and anthropologist who resided on Mangaia between 1929 and 1930 (Hiroa, 1934). Gill (1894) produced the primary ethnohistoric text through collaboration with Mamae, a Mangaian pastor and member of the Ngati Vara clan. Other texts by Mamae have been transcribed and published more recently (Reilly, 2003, 2009). These reports and observations from the first missionaries and visitors offer the best representation of the prehistoric Pacific society available as no other written records exist. Ethnographic studies by early European visitors contain a level of bias and provide only a snapshot of their time on the island. These can be augmented by archaeological records that can provide further information into a period of prehistory where no written record is available (Bedford and Spriggs, 2008).

2.1. Geography

The Cook Islands are a South Pacific island nation made up of 15 islands that are geographically split into a northern and southern group (Fig. 1A-B). The islands are located more than 5000 km from Australia and stretch across two million square kilometres between American Samoa and French Polynesia. Mangaia (21°55'26.7"S, 157°55'19.4"W) is the southernmost island of the southern Cook Islands group and has an area of 59.8 km^2 (Nunn et al., 2016).

2.2. Climate and Hydrology

Mangaia receives 1900–2050 mm of rainfall annually on average (Thompson, 1986) and like most tropical South Pacific islands has two seasons; a dry season running from June through to November and a wet season that runs from December through to May, with most rainfall falling within the wet season. There are several short rain-fed streams on Mangaia that run from the higher inner volcanic cone out into the lowland swamp valleys (Fig. 1C). In the past, water gathered against the makatea escarpment – made up of raised ancient limestone reef - forming lakes from which the water then drains through tunnels dissolved through the makatea into the ocean (Ellison, 1994). Today, there is only one permanent freshwater lake on Mangaia, Lake Tiriara. During

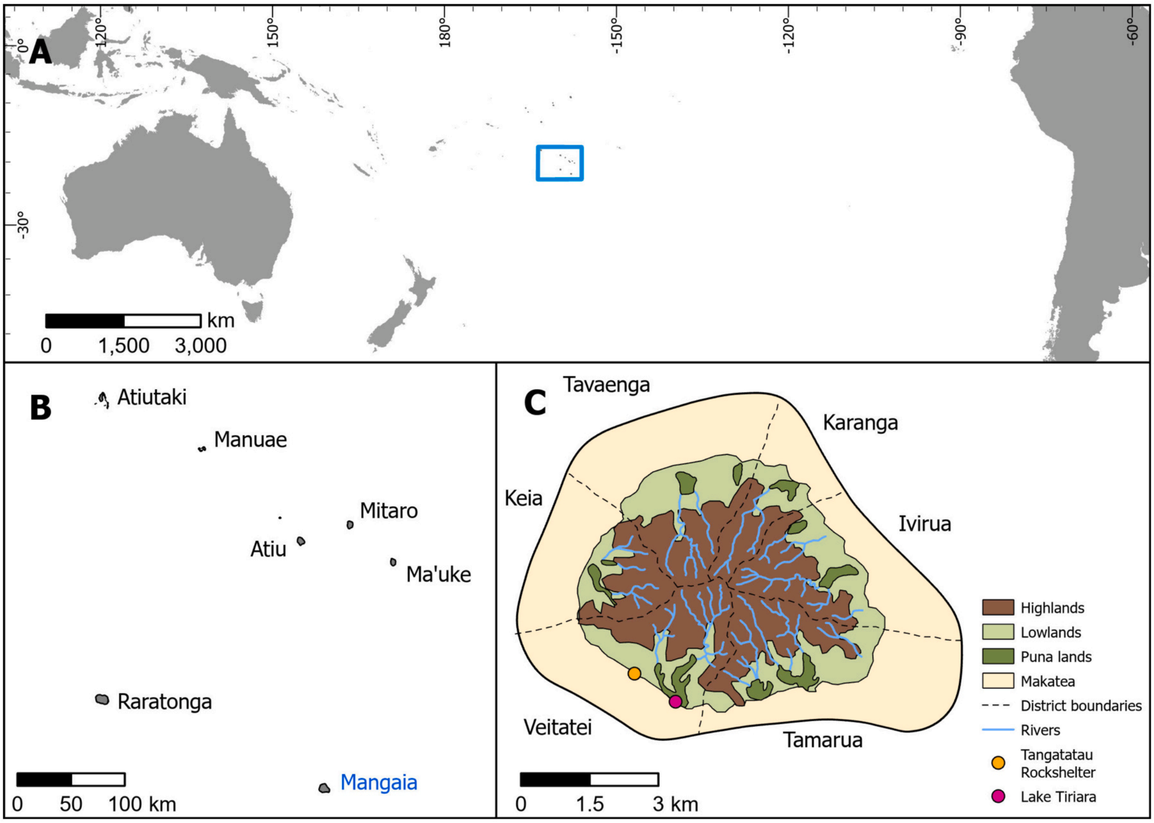

Fig. 1. A. Map of the location of the Southern Cook Islands (blue box) within the tropical South Pacific Ocean. Source: ESRI - ArcWorld Supplement. B. Location of Mangaia within the Southern Cook Island group (ESRI, 2025). Source: GADM. C. Map of Mangaia showing the major landscape types and district boundaries and names and the location of Lake Tiriara and the Tangatatau Rockshelter (GADM, 2022). Based on Kirch (2017).

the mid-Holocene there were at least five lakes although current data suggest the other four filled in prior to human arrival and were swamps throughout the subsequent human settlement (Ellison, 1994). Due to the volcanic geology of Mangaia's interior it is possible that there are perched pockets of water that permeate through the rock (United Nations, 1983) and in the present-day islanders utilise boreholes as a water supply (National Environment Service Government of Cook Islands, 2021), which indicates that groundwater is present on the island that would be dependent on rainfall for recharge. However, there is no evidence that suggests that groundwater was utilised as a major source of water during Mangaia's prehistory. Therefore, rainfall, surface water from streams, Lake Tiriara and swamps were likely the only sources of freshwater in prehistory.

2.3. *Demography*

Mangaia is split into six political districts that have persisted since the pre-European contact period – Kei'a, Tava'enga, Karanga, Ivirua, Tamarua and Veitatei – which also mirror geographic borders with the boundaries between each district reaching radially from the highlands to the ocean, and each district encompassing a section of highlands, lowland swamp and makatea (Hiroa, 1934; Allen, 1969; Kirch, 2017) – see Fig. 1. The prehistoric population primarily resided close to the streams and productive "puna" lands (swamps) in each of the districts during times of peace (Kirch, 2017). During periods of conflict people moved either toward highland hiding places or toward the makatea caves to avoid conflict (Hiroa, 1934). Following the arrival of Europeans in 1833, it was estimated that there were around 2000–3000 people living on the island, but since this was estimated sometime after European arrival, it is assumed that the population was previously larger and decreased due to introduced diseases (Williams, 1837). It has been suggested that Mangaia held the highest population density in Polynesia with up to 150 people per km^2 of agricultural land (Kirch, 2017). To date, there has been no estimation of the maximum population that existed on Mangaia during its prehistory.

2.4. *Land and water management*

Reilly (2009) provides a range of interpretations for the different land divisions of Mangaia from a mix of anthropological (Mark, 1976), geographical (Allen, 1969) and Hiroa's (1934) account and from an interview with a contemporary Mangaian. These interpretations break Mangaia up into five to six different ecological zones, starting from the coast and moving landward to the highlands. The zones are representative of all the six districts of Mangaia.

The primary zone of interest for this study is the fertile puna lands, which occupy the alluvial soils at the base of the small valleys where a majority of the taro cultivation on the island takes place. It is widely agreed that taro (also known locally on Mangaia as mamai) was an important staple food of Mangaia during its prehistory (Hiroa, 1934; Allen, 1969; Kirch, 1994, 2017). The importance of taro is illustrated in the mythology of Mangaia that intimately ties together plant and human growth within its stories (Hiroa, 1934). Furthermore, as Mangaian society developed, the status of the taro producing lands increased (Kirch, 1994). Taro was and is a vital crop for the Mangaians and played a role in the development of the complex society on the island (Hiroa, 1934; Kirch, 2017). Ethnohistoric accounts of conflict between groups on the island indicate they primarily occurred over the puna lands, with victors awarded these revered fertile areas and the vanquished assigned the agriculturally unproductive makatea land (Hiroa, 1934).

Taro requires humid conditions, and it is not drought resistant (Food and Agriculture Organization (FAO), 1999). The prehistoric Mangaians built terrace infrastructure for the taro pondfields creating an effective irrigation system that utilised wooden pipes made from hollow trees to transport water from the streams to the pondfield (Williams, 1837). However, whilst the development of irrigation systems may initially offer a buffer to dry conditions because of the water stored within them, the vital puna lands are still vulnerable to drought. In 1926, Hiroa observed that a drought event could impact on the puna lands causing the irrigation pondfields to dry up (Hiroa, 1934). This is confirmed by contemporary accounts from Mangaia that describe similar events leading to crop losses (Kirch, 2017) illustrating the impact of climate on key food and water resources.

Within Mangaian society there was a level of understanding of land management as evidenced from ethnographic studies (Hiroa, 1934). When certain resources - including agricultural and marine stocks - came under pressure or became depleted a meeting of the district and sub-district chiefs was called and a closed season or ra'ui was declared by the "Ruler of Food" that affected the whole island until the season was reopened once the relevant stocks were replenished (Hiroa, 1934). Despite this, there is evidence of environmental degradation on the island as the population grew and developed (Ellison, 1994; Kirch, 2017). This was primarily caused by the partial deforestation of the island's interior – typical of many South Pacific islands histories - but specifically the volcanic highlands and associated slopes, resulting in soil erosion that led to the deposition of clay from the volcanic core in the valley bottoms (Ellison, 1994; Kirch, 2017).

3. Methods

3.1. Model components

3.1.1. Conceptual Model

The socio-ecological conceptual model for prehistoric Pacific islands is illustrated in Fig. 2. This model represents one individual island and breaks down the island system into three main parts. On the left are the external environmental components, that are regional rather than a local control that can influence water and food resources on an island. Sea level change has been included within this part as it is an external environmental component that impacts water resources in Pacific islands through salinization of groundwater lenses (Dixon-Jain et al., 2014). Similarly, short-lived extreme events are included as the Pacific is a tectonically active region and experiences tsunamis as well as cyclones (Dawson, 2007; Goff, 2011; Goff et al., 2011; McNamara and Prasad, 2014; Chagué-Goff et al., 2016). Such extreme events can impact food and water resources on an island through pollution of freshwater sources with salt water or destruction of valuable crops. Finally, the last component is climate. Whilst this encompasses all aspects of climate, the key variable is rainfall and the changes that lead to drought conditions (Kuleshov et al., 2014; Sear et al., 2020; Hipkiss, 2023).

The central part of the conceptual model in Fig. 2 is the socio-environmental interface where physical environmental components that are internal and local are impacted upon or driven by the external environmental and internal social components (Kuil et al., 2016). Here environmental degradation is classed as a decline in the relative environmental condition of the island in comparison to the island's condition just prior to the arrival of humans. In many Pacific islands including Mangaia, human arrival is followed by deforestation, extinction of island fauna, erosion of topsoil and nutrient depletion and introduction of commensal such as pigs, food crops (taro) and rats (Ellison, 1994; Prebble, Anderson and Kennett, 2013; Gosling et al., 2020; Strandberg et al., 2023). Though it should be considered that on other islands, the clearing of native forest and replacing it with tree crops such as coconut and breadfruit or croplands like on Tikopia means the environment was modified, but not necessarily degraded (Kirch, 2007). The food resources component includes marine, wild and agricultural resources - but for the purposes of the scenarios examined below it is assumed that the island community depended mainly on subsistence farming and some marine resources for most of their food requirements, which is reflected in archaeological records across the Pacific (Kinaston et al., 2014; Kirch, 2017; Herrscher et al., 2018). In our conceptual model, the water component refers to any potable water resource including but not limited to groundwater, rivers and lakes.

Within the social components of our conceptual model, the main physical parameter is the total population of the island. The interaction with other components is based on changing population size. In addition, the model includes social components including memory/indigenous knowledge, vulnerability and adaptive capacity. Adaptive capacity here refers to a community's ability to adapt to adverse conditions, such as an extreme event (Carpenter and Brock, 2008). Whilst it is appreciated that memory/indigenous knowledge and adaptive capacity are inter-related, here they are expressed separately. This is because there is a scenario in which an island community has a high-level of indigenous knowledge, but other variables may impact on their ability to utilise that knowledge to adapt to a changing environment, although we recognise that a high level of indigenous knowledge would increase their chances

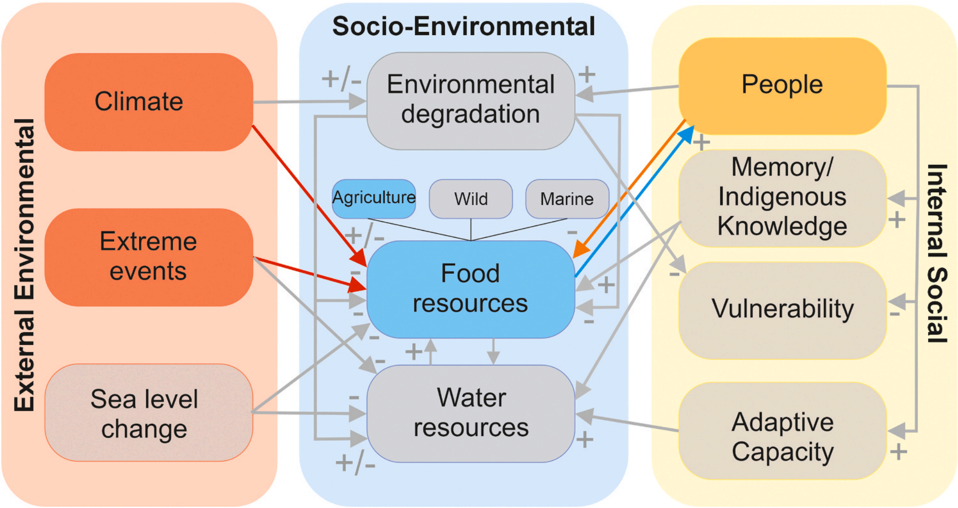

Fig. 2. Conceptual model of the Mangaia socio-ecological system split into external environmental (left), internal social (right) and the socio-environmental interface (centre). Coloured components denote the components that were selected as part of the final socio-ecological model. The plus and minus symbols indicate whether the starting variable had a positive or negative influence on the end variable.

of doing so. Finally, the vulnerability component is included to represent how changes in water and food resources impact upon the vulnerability of the community to extreme events through time.

3.1.2. *Creating the Model*

Based on the conceptual model, a computational systems dynamics model was developed to simulate the climatic, agricultural and population dynamics of the Mangaian island socio-ecological system. The aim here is to focus on those components that a) reflect the impact of hydroclimate change on island life, b) are considered to be the most sensitive to hydroclimate change, and c) are amenable to mathematical representation and parameterisation. We intentionally kept our model relatively simple because the more complex a model becomes, the higher the uncertainty associated with the outputs (Brandt and Merico, 2015). System dynamics models have the capacity to easily become overly complex (Kelly et al., 2013; Elsawah et al., 2017) and difficult to interpret or test (Brandt and Merico, 2015). Whilst limiting the model to a few key components will also include uncertainty, we argue it is preferable to focus on the elements where there is more complete understanding of the parameters and their relationships. Fig. 2 shows a revised conceptual model with the essential components in colour and the non-essential components in grey. Based on the ethnohistoric and archaeological evidence examined in Section 2, these three elements were chosen to represent the fundamental aspects of the Mangaian prehistoric socio-ecological system. The non-essential components have been removed as there is not the data to parametrise them or due to the uncertainty in their relationships to the key components. The remaining components were quantified using a set of differential equations that were built to represent the relationships between variables. The model is adapted from the Brandt and Merico (2015) Rapa Nui (Easter Island) model and the Kuil et al (2016) socio-hydrological model of the classic Maya. The equations and relationships were implemented using the Vensim system dynamics modelling software (Ventana Systems inc, 2024).

3.2. *Model parameterisation*

The model uses ordinary differential equations to represent the relationship between Rainfall (*P*), population (*N*) and food availability (*FA*). Parameters for the differential equations are listed in Table 1. Selection of these values is discussed within subsequent subsections. Fig. 3 shows the structure of the Vensim model and shows the relationship between components. Their constituent variables and how the relationships are represented in the model are discussed below.

Table 1
List of parameters, stocks and outputs used within the Mangaia socio-ecological model.

Symbol	Name	Starting or constant value	Units
Parameters			
μ_N	Max human growth rate	0.03	Year^{-1}
δ_N	Labour required	106	People/km^2
F_N	Food requirement per person	912,500	Kcal/year
C_{max}	Maximum crop yield	100	%
θ_c	Adjustment parameter	2.0e+ 5/200000	-
δ_C	Adjustment speed	0.007	-
γ_c	Crop calorie availability	1664510400	Kcal/km^2
m_C	Crop mortality rate	10	%
L_t	Total available land	19.9	Km^2
Stocks			
N	Population	50	N^{-1}
Outputs			
Θ_N	Available Labour	-	N^{-1}
γ_N	Population food requirement	-	Kcal^{-1}
r_N	Population growth rate	-	-
K_A	Agricultural Carrying Capacity	-	N^{-1}
C	Total crop calorie production	-	Kcal/year
FA	Food Availability	-	Kcal^{-1}
L	Available land	-	Km^2
External Data			
P	Rainfall	-	mm/year

3.3. *Population*

Population (N) is calculated as the current population multiplied by the population growth rate (r_N). r_N is determined by multiplying the maximum human growth rate by the ratio of the population over agricultural carrying capacity. The growth rate is constrained by how close the population is to the agricultural carrying capacity, such that it decreases as resources become strained. This equation is adapted from the Brandt and Merico (2015) model and uses their suggested value of 0.03 for the maximum growth rate, which was originally proposed by Birdsell (1957) for ancient societies. The model was given an initial starting population of 50 people as per existing models of Pacific societies (Brandt and Merico, 2015), which is the assumed size of a migrating community. There is currently no estimate of the absolute maximum population size or population dynamics (temporal changes of population size) pre-contact. The earliest population estimate of 2000–3000 people was provided by Williams (1837) in 1832 though this estimate followed an epidemic caused by diseases introduced by the first missionaries to the island that was “exceedingly fatal” (Williams, 1837, p.81). The total population over a time step, t, is:

$$\frac{N}{t} = \quad (r_N N) + N \tag{1}$$

where N is the total population and r_N is the population growth rate, which in turn is calculated as:

$$r_N \ = \ \mu N(1 - \left(\frac{N}{KA}\right)) \tag{2}$$

where μ_N is the maximum population growth rate and K_A is the total agricultural carrying capacity, which is described in more detail in the next section.

3.4. *Carrying Capacity*

The agricultural carrying capacity value is a function of the amount of food available (specifically staple starch, i.e. taro) from the cultivable land and the population size that could be sustained by this, considering the food required by the population (Hamilton and Kahn, 2007). The carrying capacity of the island is determined by the availability of food and is limited by the amount of land available for cultivation. The equation is derived from the carrying capacity component of Brandt and Merico’s (2015) population equation but adapted to represent agricultural carrying capacity:

$$K_A = N(1 - \frac{Y_N - C}{Y_N}) \tag{3}$$

Where Y_N is the population food requirement, which is calculated as the number of calories required per year for the total island population and C is the total crop calorie production, which is the total calories produced by the amount of land cultivated for crops (Brandt and Merico, 2015).

3.5. *Food Availability*

Food availability is modelled as the ratio between food produced (C) and food required by the population of the island (γ_N) both measured in calories per year. This is expressed as:

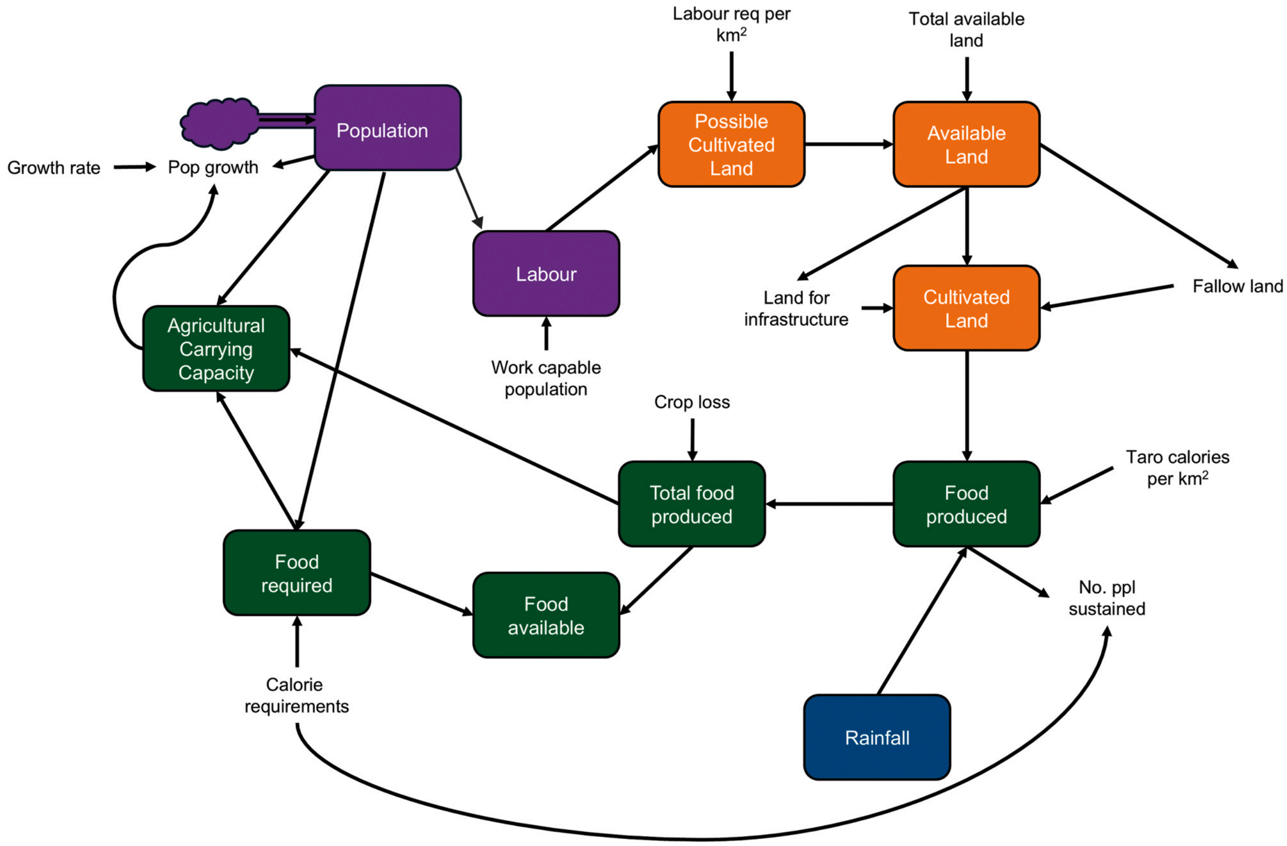

Fig. 3. Visualisation of the Vensim model structure. Population is represented as a stock within the model with population growth provided as an input into that stock. The colours denote the different components of the system, with purple representing the human population, orange denoting variables related to land availability, green for agricultural variables and blue for the rainfall input that drives the model.

$$FA = \frac{C}{Y_N} \tag{4}$$

C is the crop yield per km^2 multiplied by the amount of land cleared. The available land is initially controlled by labour availability to physically clear and work the land and later is limited by the total available land on the island suitable for taro, which is estimated at 19.9 km^2 by Kirch (2017). This is noted as an important factor especially in the early stages of colonisation where limited population dictates the amount of land that can be cleared and worked for agricultural purposes (Kirch, 2017). The food required is calculated by multiplying the total current population (N) by the food calorie requirement per person (F_N), which is expressed as:

$$Y_N = NF_N \tag{5}$$

The values for available labour and the number of people required to work the land are both taken from Lee and Tuljapurkar (2008) and Puleston and Tuljapurkar (2008) who assume that 50 % of the population is available for agricultural work. They suggest that a single adult can manage 0.94 ha of agricultural land over a year, which equates to 0.0094 km^2 when utilising traditional methods over the course of a traditional working day. Available land is calculated as the fraction of the available labour (θ_N) relative to the labour required per km^2 (δ_N) up to a maximum value of 19.9 km^2, which is the total available land that is suitable for taro production (L_t). This is expressed as:

$$L = MIN(\left(\frac{\theta_N}{\delta_N}\right), L_t \tag{6}$$

Pondfield systems require some fallowing to maintain soil fertility (Kirch, 1994) with both Kirch (1994) and Hamilton and Kahn (2007) suggesting that approximately 20 % of land is left fallow at any one time. γ_C represents the calorie production per km^2 of taro. There are several values suggested for the yield of wetland taro based on modern observations of pondfield systems using traditional methods of cultivation. These values range from 13.3 to 20 t/ha/yr for Futunan pondfield systems (Kirch, 1994), mid-range values of 20.2 t/ha/yr for modern Hawaiian values (Huang, 1979) to high range of 25.1–58.1 t/ha/yr for traditional pondfield techniques in Maewo, Vanuatu (Spriggs, 1984). For our model, this value is constant and uses a mid-range value taken from Huang's (1979) estimate of 20.2 t/ha/year which was then adapted to reflect values per km^2. Alternative yields were considered as part of the sensitivity analysis. Hamilton and Kahn (2007) similarly adopted a mid- range value of 25 t/ha/yr for their model based on values from Kirch (1994) and Spriggs (1984) and so a comparable approach is adopted here too. To calculate changing crop yields in response to rainfall a logistic growth equation was used to reflect the conditions required for the production of taro as per the values provided by the FAO (1996). Total crop calorie production is calculated as:

$$C_C = C - m_C \tag{7}$$

Where C_C is total crop calorie production, C is maximum crop calorie production and m_C is crop mortality. Total crop calorie production in turn is calculated as:

$$C = \quad L(\gamma_C \frac{C_{\max}}{1 + \theta_c e^{-\delta_c P}}) \tag{8}$$

Where L is the available cultivable land, γ_C *is* the crop calorie availability, C_{max} is the maximum crop yield and P represents rainfall, which is the external driver and is provided as an input data set. Finally, Θ_c and δ_c are parameters that define the shape of the logistic growth curve, which represents the relationship between rainfall and taro yields. This relationship was defined by the minimum (1000 mm/yr) and optimum rainfall values (1800–2700 mm/yr) for taro, which were taken from the FAO (1996) published values.

3.6. Model Inputs

3.6.1. Contemporary Rainfall Scenarios

To test the behaviour of the model and understand the reaction of the Mangaian socio-ecological system to changing hydrological conditions a series of rainfall data sets mimicking the rainfall of Mangaia were created. Rainfall data sets of 1000 years were generated in R code using a first order autoregressive model (AR(1) model), that utilised the statistical characteristics of the observed rainfall from Mangaia over the past century taken from the monthly station data portal of the KNMI Climate Explorer (KNMI, 2022). Table 2 shows the four rainfall scenarios and their characteristics. The rationale for using these values is that scenarios 1 and 2 are based on the range of observed rainfall data from Mangaia with different autocorrelation values (Rho) that alter the duration and frequency of drought events. A lower value of Rho corresponds to lower autocorrelation between one data point and the next generating a more random series and therefore drought events are frequent but short-lived. A higher Rho value increases the autocorrelation and generates a lower frequency of drought events but of longer duration. The available rainfall data for Mangaia only covers approximately 40 years and likely does not represent the true range of values so to account for a higher range of variability, scenarios 3 and 4 used an increased range of rainfall values. For each scenario, 10 iterations of the rainfall time series were generated to represent the variability in the stochastic generation of rainfall data in the AR(1) model, which were then used to test the sensitivity of population to drought events.

Based on the rainfall data sets for each scenario, the R package ‘drought’ (Hao et al., 2017) was used to calculate the drought duration, frequency and severity. The impact of drought events upon population dynamics was calculated as per Kuil et al (2019) using two metrics. The first is the rate of recovery, which measures the time it takes for the population value to return to its pre-drought value – see Fig. 4. The second is the maximum population change - referred to as impact in Fig. 4 - which identifies the percentage drop in the population from the start of the drought to the lowest population value within the duration of the drought. Drought duration is calculated in a similar manner to that of McGree et al (2016) with the drought starting when rainfall drops below a specified drought threshold. Drought severity is the sum of the rainfall deficit below the threshold for every year of the drought duration (Hao et al., 2017). The end of the drought period is when the rainfall returns to above the drought threshold. Typically, a threshold for drought is set at the lowest 20 % of rainfall values for the scenario data as per Kuil et al (2019) and is used within the hydrology literature (Sheffield and Wood, 2008; Van Loon et al., 2014; Van Loon, 2015). However, as there is no quantitative reconstruction for rainfall, the modern data for Mangaia has only 40 years of complete data and the rainfall datasets generated have different ranges and characteristics, a statistically based threshold for meteorological drought is not appropriate. Instead, an absolute drought threshold is used based on the level of rainfall (1000 mm/year) at which the model starts to exhibit impacts upon the agricultural carrying capacity and the population, specifically on the yields of taro. The threshold is physically based (i.e., it relates to agricultural impacts) but is based on the parameters of the model, which are uncertain. This could be improved in the future if quantitative palaeo data sets can be developed that allow for a better understanding of meteorological drought locally or potentially the use of the longer rainfall record from the near-by island of Rarotonga though for the purposes of this study it was decided to use the Mangaia record to keep the model as true a representation of Mangaia as possible.

Table 2
The statistical and drought characteristics of the different rainfall scenarios.

Scenario	Magnitude	Duration	Frequency	Rho (-1–1)	Range (mm)
1	Low	Low	Low	0.4	1000–2800
2	Low	High	High	0.9	1000–2800
3	High	Low	Low	0.4	250–3000
4	High	High	High	0.9	250–3000

3.6.2. Palaeo Reconstruction Rainfall Data Set

For the rainfall datasets, it was decided to use contemporary and palaeo rainfall data to build over Earth System model outputs for two reasons. Firstly, the resolution of Earth System models is typically relatively coarse. For example, the Coupled Model Intercomparison Project (CMIP) models have a resolution ranging from 11 to 400 km depending on the model chosen (Soares et al., 2024). Secondly, the South Pacific Convergence Zone (SPCZ) – the primary source of precipitation in the tropical South Pacific – is poorly represented in Earth System models including the models produced by Coupled Model Intercomparison Project due to biases that have improved over time but still have issues reproducing rainfall patterns in this region (Brown et al., 2020). We argue the use of contemporary and palaeo rainfall datasets provides a more representative dataset particularly when focusing on one island system.

This study, like the Kuil et al (2016) classic Maya model study, uses palaeoclimatological rainfall reconstructions for the Late Holocene. Currently, there are no annually resolved rainfall records that go back c.1000 years in the Pacific, which may explain why there has been little modelling of drought in the region. The Toomey et al. (2016) record from Apu Bay in the Society islands utilises a Ti/Ca ratio that is sub-annually resolved and a continuous 3,000-year record but is clearly impacted by humans with the upward shift in mean values at the start of the MCA around Polynesian expansion. Furthermore, Ti is – at best - an erosion proxy rather than a direct rainfall proxy. Alternatively, a number of biomarker and dinosterol hydrogen isotope records have been developed across the Pacific region (Smittenberg et al., 2011; Atwood and Sachs, 2014; Hassall, 2017; Sachs et al., 2018; Sear et al., 2020; Maloney et al., 2022), including one from Samoa and another from the Southern Cook Islands (Hassall, 2017; Sear et al., 2020). The dinosterol data from Lake Lanoto’o - located on the island of ‘Upolu in Samoa - is a more direct rainfall proxy and can be converted into mm/day values using a calibration set developed from tropical South Pacific sediments (Maloney et al., 2019). It is also the physically closest quantitatively reconstructed rainfall record to Mangaia. However, these records are not annually resolved. Instead, they represent the rate of change over multiple decades to centuries with snapshots of values that cover approximately a decade of sedimentation. The resolution of the data set varies between 21 and 368 years (Sear et al., 2020).

The two islands of ‘Upolu and Mangaia are quite different in terms of elevation and location in relation to the SPCZ which in turn influences the amount of rainfall each island receives. Lake Lanoto’o is a highland site that sits at 760 masl (Sear et al., 2020) whereas the island of Mangaia has a maximum elevation of 168 m (Ellison, 1994). Historical measured data show that there is a difference of approximately 1000 mm/year between the average modern rainfall from Samoa and Mangaia. As the model is designed to represent the Mangaian island system – the reconstruction was corrected to account for the difference between the rainfall profiles for the two islands to provide a representative rainfall profile for Mangaia for this period.

To produce annual precipitation values, the available palaeo data were smoothed using a loess smoother to generate a mean rainfall dataset over the past 1000 years (see Fig. 5). To account for the error associated with the dinosterol reconstruction, a set of scenarios - across the scope of the dinosterol analytical error from Sear et al. (2020)- were used to represent the range of possible rainfall profiles during this period. In Fig. 5, the P + % scenarios are the mean value plus a certain percentage of the total error and the P-% scenarios are the mean value minus a certain percentage of the total error to assess the uncertainty in

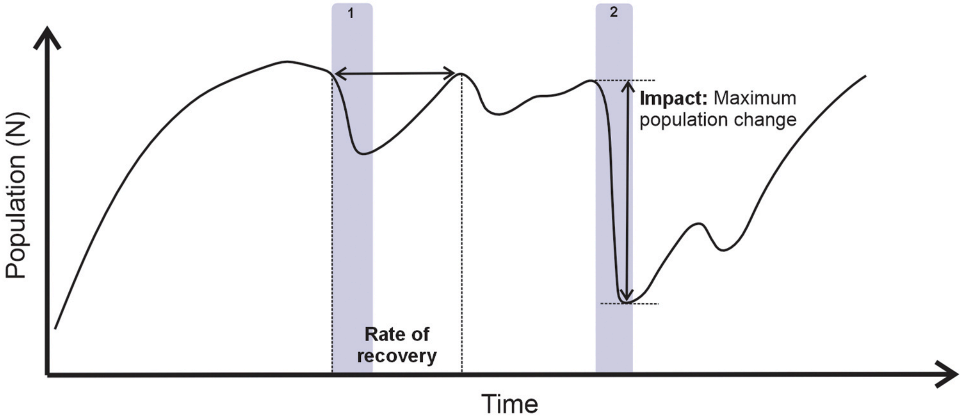

Fig. 4. Graph of population over time identifying how the metrics of impact and recovery are measured. Blue boxes denote drought events. This has been elaborated based on the hypothesis proposed by Kuil et al., (2019).

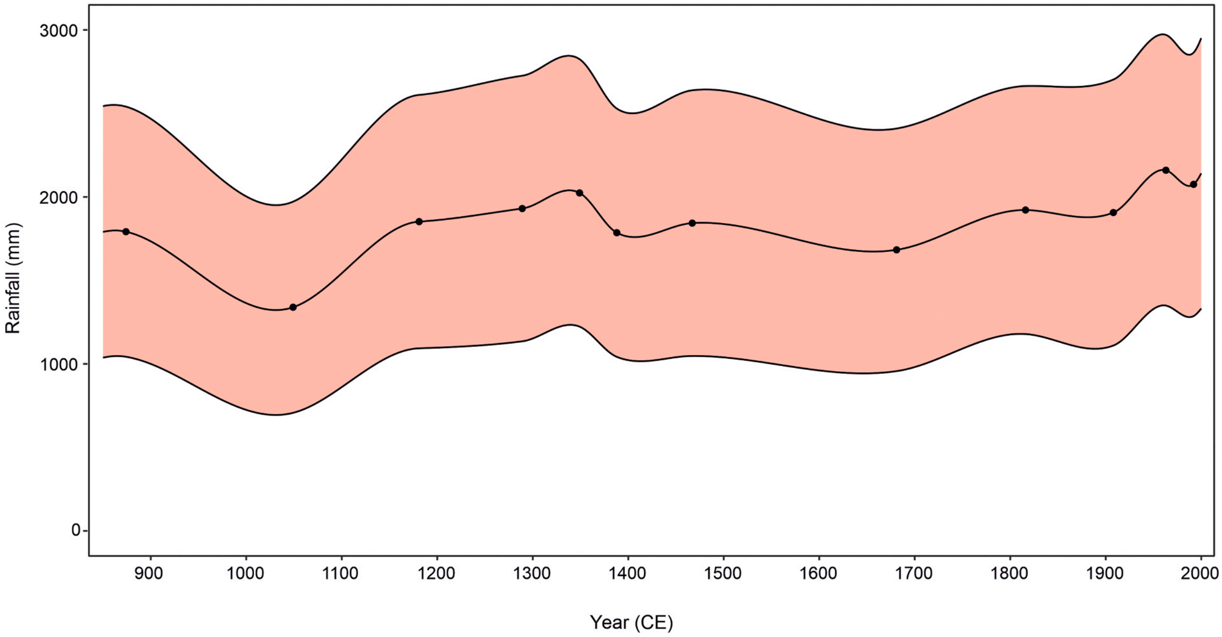

Fig. 5. The quantitative rainfall reconstruction covering the past 1000 years from Lake Lanoto'o in Samoa to cover period of human arrival into Eastern Polynesia - taken from Sear et al (2020) with a loess smoother running through the points giving the running mean rainfall value. The red area denotes the minimum and maximum error associated with the dinosterol reconstruction.

the reconstructed rainfall values from dinosterols. The palaeo data set is reconstructed for Mangaia as a 1000-year subset that starts at the arrival of humans to Mangaia in approximately 1000 CE (Kirch, 2017; Sear et al., 2020) to 2000 CE. The standard deviation value is set at 436.1 and was taken from the modern observed data from Mangaia and the Rho value was set at 0.9 to mimic inter-annual rainfall variation. As with most palaeo records, there is uncertainty in the values, but we suggest, as shown by Kuil et al. (2016), these records can still provide realistic ranges in rainfall values that can be used to assess the impact of droughts on agriculture and population dynamics in the region.

3.7. Sensitivity Analysis and Model Validation

The model parameters are uncertain as they are not directly measurable for an archaeological system (Brandt and Merico, 2015) or there is not a modern-day equivalent system that the parameters can be derived from. Uncertainty in parameters including maximum human growth rate (μN), labour required (δN) and crop calorie availability (γc) were evaluated using sensitivity tests. Parameter values were altered by + /- 10, 25 and 50 % and run through the model to show the impact on the model outputs. The sensitivity ranges are reasonable to reflect the uncertainties in these parameters, and changes of 10–25 % encompass the uncertainty suggested within the wider literature as discussed in Section 3.2. A change of 50 % would indicate that there are large uncertainties in the parameter values and this allows us to test whether significant uncertainties would result in changes in model behaviour. Fig. 6 shows the results from the sensitivity tests of μN, δN and γc. Parameters such as food requirement per person (FN) and total available land (Lt) are not considered as part of the analysis as these have known values or very small uncertainties. The sensitivity of the model to the rainfall input is tested as part of the model scenarios presented within the results section below, so is not included here. Fig. 6 shows the food availability output as this is influenced by each of the parameters tested. The sensitivity tests show that despite the alterations to parameter values, the model still displays the same behaviour over time, but the speed of those changes increases or decreases in response to different parameter values, as would be expected. This offers confidence that the model is not producing certain behaviours because of a particular

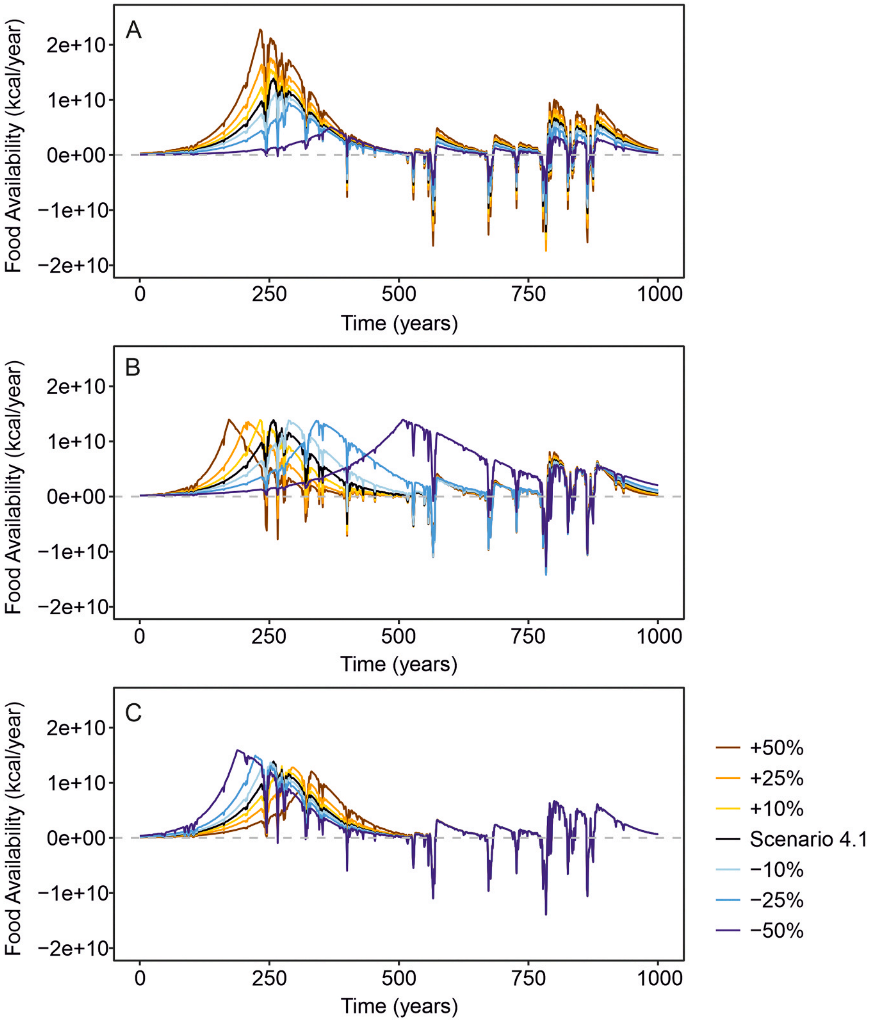

Fig. 6. Sensitivity test outputs showing a 10–50 % change in values for A - crop calorie availability, B - maximum population growth and C - Labour required and how it changes the baseline of food availability output from contemporary scenario 4.1 over 1000 years.

parameter value choice, providing confidence in the robustness of the model formulation and its outputs.

4. Results

4.1. Contemporary Scenario model outputs

Table 3 and Fig. 7, summarise some of the key outputs – drought characteristics, population and agricultural carrying capacity as well as the rainfall input for each iteration of each contemporary scenario, where the rainfall dataset was built on statistics from the contemporary rainfall data.

Table 3
Drought characteristics of the contemporary model scenarios.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Drought Frequency(per 1000 years)	106.80	47.10	107.20	43.80
Drought Intensity - Average	0.78	1.72	0.78	1.91
Drought Intensity - Maximum	4.31	20.88	4.61	13.80
Drought Duration – Average (Years)	1.49	3.39	1.47	3.79
Drought Duration – Maximum (Years)	5.00	19.70	5.50	17.30

For contemporary scenario 1, there are few fluctuations in the population curve, indicating that little change occurs under this scenario. This is due to the low magnitude and duration of drought events in this series. The droughts are more frequent than in contemporary scenario 2 as per Table 3, but this clearly does not have a notable impact on agricultural and population dynamics if the drought events are low in magnitude and duration.

In scenario 2, the dips in population and in the agricultural carrying capacity are noticeably larger than in contemporary scenario 1. The length of time that the agricultural carrying capacity remains below the maximum capacity is also longer in contemporary scenario 2 due to the longer duration of droughts compared to contemporary scenario 1 (Table 2 and Table 3).

As summarised in Table 2 and shown in Fig. 7, contemporary scenarios 3 and 4 have a larger range of rainfall than contemporary scenarios 1 & 2. This shows the response of the model to a higher value of rainfall variability as it is unlikely that 40 years of recorded rainfall is representative of the full range of Mangaian rainfall. This range of rainfall also results in droughts that significantly affect the taro yields and in turn agricultural carrying capacity.

In scenarios 3 and 4, there are clearly larger fluctuations in the agricultural carrying capacity and population in comparison to scenarios 1 and 2 due to the increase in the magnitude of change in rainfall. The biggest fluctuations in the population and agricultural carrying capacity occur following a relatively stable and smooth initial growth

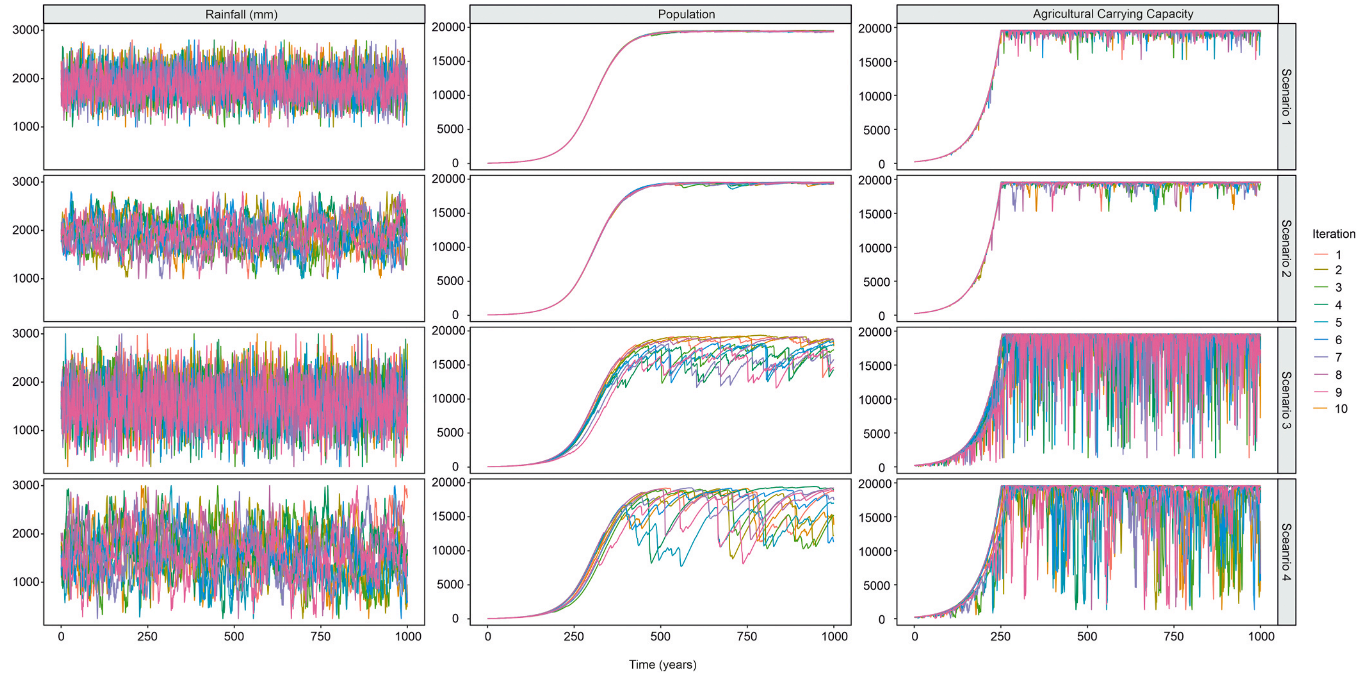

Fig. 7. Outputs from the system dynamics Vensim contemporary model for Mangaia including rainfall (mm), population (N) and agricultural carrying capacity (N). The outputs are broken down into the four contemporary drought scenarios: scenario 1 – low magnitude, duration and frequency, scenario 2 – low magnitude but high duration/frequency, scenario 3 – high magnitude but low duration/frequency and scenario 4 – high magnitude, duration and frequency Within each panel the colours represent the 10 iterations of each scenario.

period for approximately 300 years. There is, however, a wider spread in the initial exponential growth of the population in both contemporary scenarios 3 and 4. This indicates that whilst drought events may not cause a notable decrease in population, they do slow the rate of growth for the early stages of colonisation. The fluctuations in population become larger as it grows closer to the absolute maximum carrying capacity of the island. The number of people needing to be supported per km^2 of taro pondfields increases to the point at which no excess food is produced. Therefore, when a reduction in rainfall occurs there is no redundancy for crop loss and so there is a greater impact on the population. It is clear from Fig. 7, that the rainfall dataset for contemporary scenario 4, which has less frequent but more severe droughts than scenario 3, has the biggest impact on the yield and thus population out of all the scenarios.

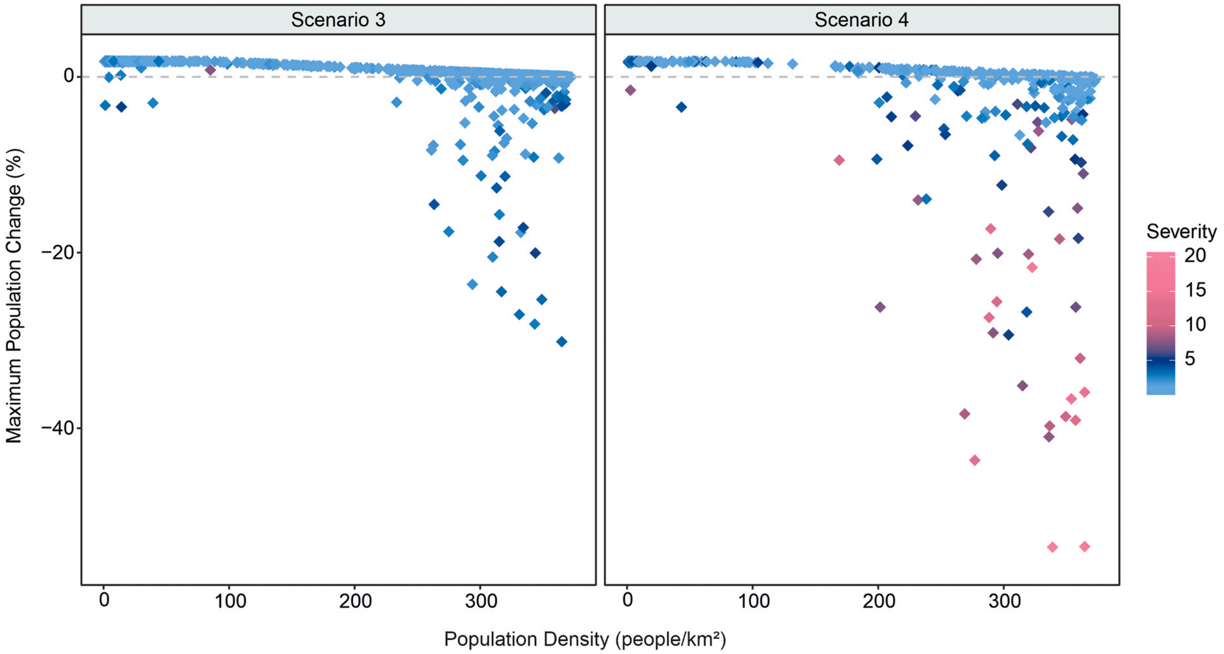

Fig. 8. Graph plotting the population density against the maximum population change at each drought events produced from the rainfall data for contemporary scenarios 3 – high magnitude but low duration/frequency and contemporary scenario 4 – high magnitude, duration and frequency and the colour denotes the severity of the drought event.

4.2. Contemporary scenario drought and population metrics

Fig. 8 presents the results from contemporary scenario 3 and 4, which compares the population density against the maximum population change for each individual drought event for the two scenarios. As the lower rainfall limit for contemporary scenarios 1 and 2 was 1000 mm, which is the drought threshold, these scenarios are not considered in the drought and population dynamic metric analysis.

The severity of each drought event is calculated using a combination of the intensity and duration and then indicated by the colour of the individual event point. It was clear from the scenario data presented in the previous section that the population density and the drought duration both play a role in the impact of droughts on population dynamics. Fig. 8 shows that with population density values below approximately 100 people/km^2 across Mangaia droughts will typically not drive a negative population change, indicating that droughts have a lower impact on smaller populations.

In terms of the impact on food availability, Fig. 9 shows the modelled total available food for contemporary scenario 4, as it represents the most variable rainfall dataset. Across all iterations, after approximately 250 years, the amount of food available per person starts to decrease and large food deficits start from 320 years. Following this, food availability fluctuates with large shifts between food surplus and food deficit.

4.3. 1000-year Palaeo Scenario

This sequence is derived from the Lake Lanoto'o palaeo record and represents the likely climatic changes that occurred on Mangaia as humans arrived on the island in c.1000 AD. The full 2000-year time series was cropped so human arrival coincides with the rainfall record at 1000 AD. Fig. 10 shows some of the key outputs – population and agricultural carrying capacity - of the socio-ecological model as well as the rainfall input for each palaeo scenario.

Palaeo scenario P + 100 %, which is at the upper limit of the dinosterol error, shows a similar pattern to the model scenarios with rainfall levels higher than 1000 mm so there is little to no stress on the population through time. The data show that by 250 years into the sequence the population shifts toward exponential growth. Palaeo scenario P + 50 % similarly shows rapid population growth and supports a population throughout, although the time to exponential growth is slowed and there are fluctuations in population once it reaches close to its maximum carrying capacity as the rainfall varies affecting crop yields.

For palaeo scenarios P + 5 % through P + 25 %, compared to P + 100 %, the start of exponential population growth is delayed by several hundred years. After 1500 AD, population growth slowed due to a downward shift in the rainfall records at around 1400 AD that persisted for around 300 years. Towards the end of the series, rainfall values start to rise again and this is reflected in the slow but steadily growing population values through the latter half of the record. Some of the model outputs show intersecting lines between scenarios despite the difference in mean value due to the randomness in the generation of the annual rainfall data - which may cause large droughts to be generated.

4.4. Palaeo drought and population metrics

Fig. 11 shows the drought and population metrics for each of the palaeo scenarios. For palaeo scenarios P-100 % and P-50 %, the whole rainfall sequence is characterised as one large drought event as the rainfall sequence does not reach above 1000 mm and the population collapses almost immediately after arrival. All the other palaeo scenarios include this large drought event that has a large impact on the population early on when the population density is very low. This indicates how prominent this drought period likely was and the impact it would have had on the island population.

Palaeo scenarios P + 15 %, + 20 %, + 25 % and + 50 % show more of a similar pattern to the drought metrics from the earlier model scenario outputs whereby, once the population density is high enough drought events start to have a bigger impact on population dynamics. However, as population density increases, the impact of low severity drought events causes the population growth to drop until the start of a decline in population from around 150 people/km^2 for palaeo scenario P + 25 % to around 200 people/km^2 for palaeo scenario P + 15 % and P + 20 %. Scenario P + 50 % with the highest rainfall levels has a higher population density of close to 300 people per km^2 due to the good taro yield provided by higher and more consistent rainfall.

Fig. 12 shows the food availability for each of the palaeo scenarios. It is clear that a majority of the palaeo scenarios indicate a much later peak in food availability than suggested by Kirch (2017) and they peak much lower than those in the model scenario outputs with the exception of the palaeo scenarios P + 50 % and P + 100 %.

Only the palaeo scenarios P + 50 % and P + 100 %, which sit at the higher end of the dinosterol error, show a similar peak height to the contemporary scenario data. Palaeo scenario P + 100 %, which reflects the absolute dinosterol error maximum, hits the peak in food availability at around 250 years, whereas the food availability peak in palaeo scenario P + 50 % is at least 50 years later. In palaeo scenario P + 25 %, the food availability peak occurs at around 400 years post-colonisation

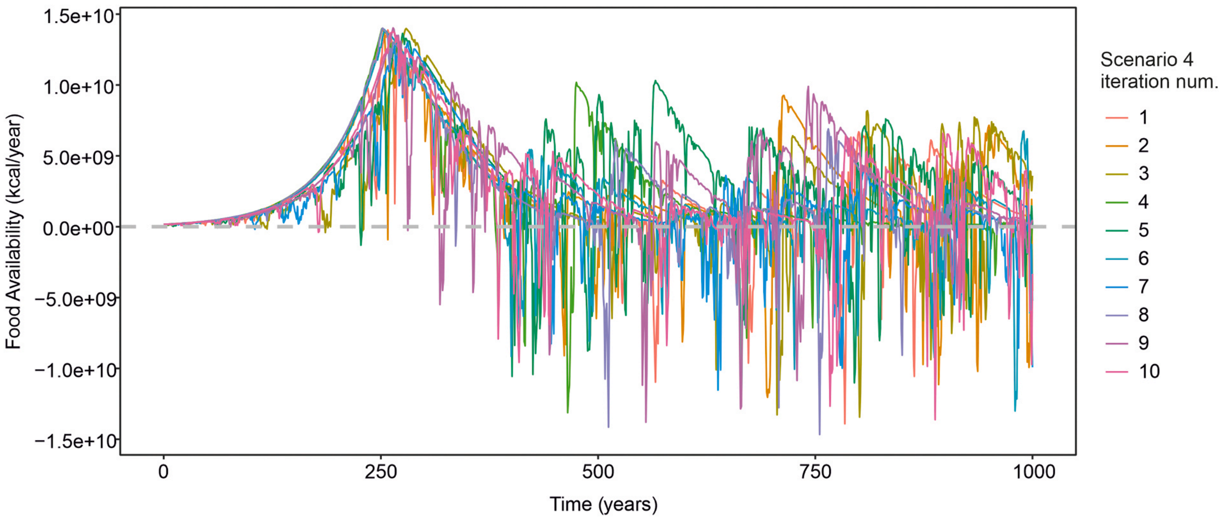

Fig. 9. Total food availability output from the 10 iterations of the contemporary-model scenario 4.

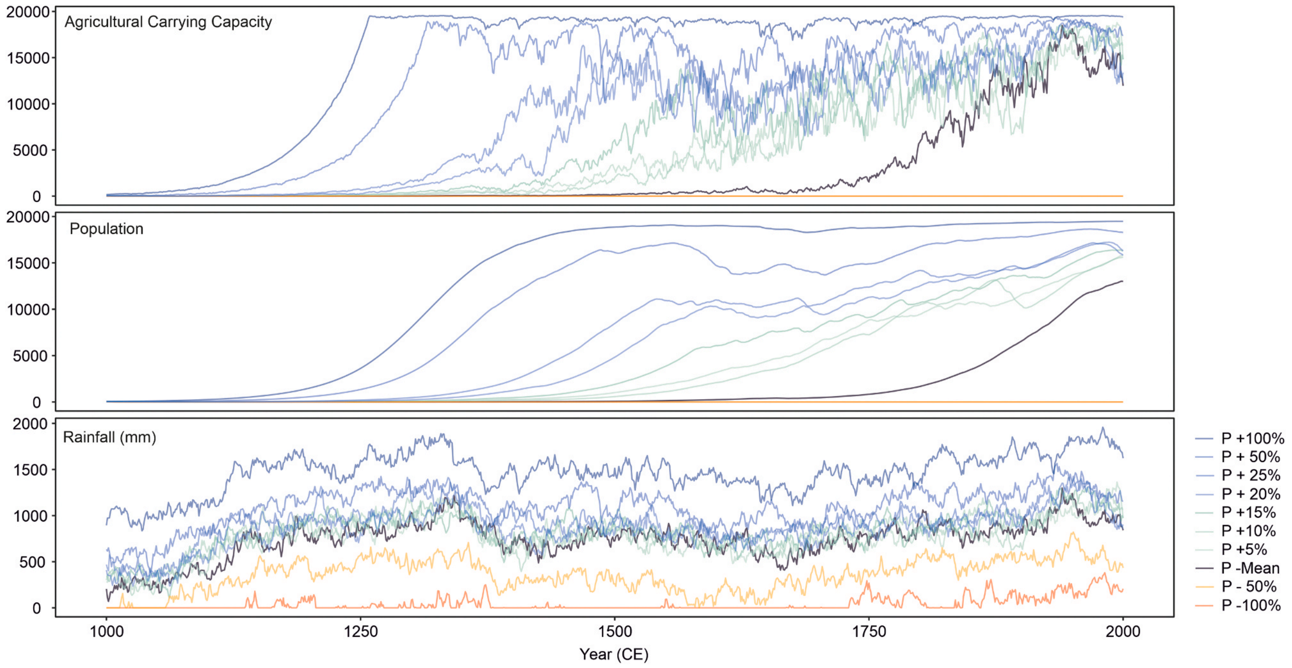

Fig. 10. Graphs showing the agricultural carrying capacity (ACC), population and rainfall outputs for the palaeo scenarios covering the period 1000 – 2000 CE.

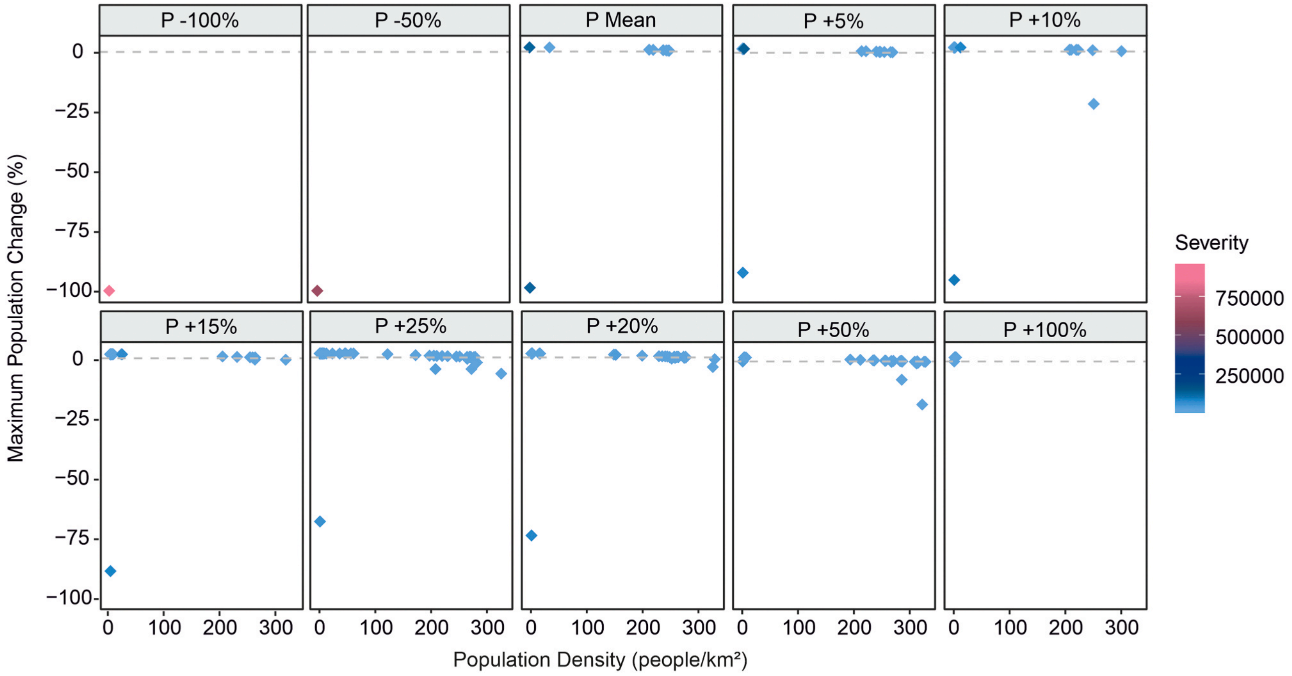

Fig. 11. Graph plotting the population density against the maximum population change at each drought event produced from the 1000-year palaeo scenarios, which include the mean dinosterol value (P mean) and scenarios that represent the mean + /- a percentage of the total dinosterol analytical error. The colour denotes the severity of the drought events.

and other palaeo scenarios subsequently peak later in the sequence after this point. This suggests that on Mangaia the food availability in relation to the key horticultural crop taro occurred later than normal due to adverse climatic conditions. The dinosterol mean value, represented by palaeo scenario P-Mean, does not peak until 500 years post-human arrival.

5. Discussion

5.1. *The Impact of Drought on Island Systems*

The modelling results reveal several key findings on drought variability and how it impacts on island socio-ecological systems. Firstly, with population density values below approximately 100 people/km^2 droughts will typically not drive a negative population change, indicating that droughts have a lower impact on smaller populations. This is

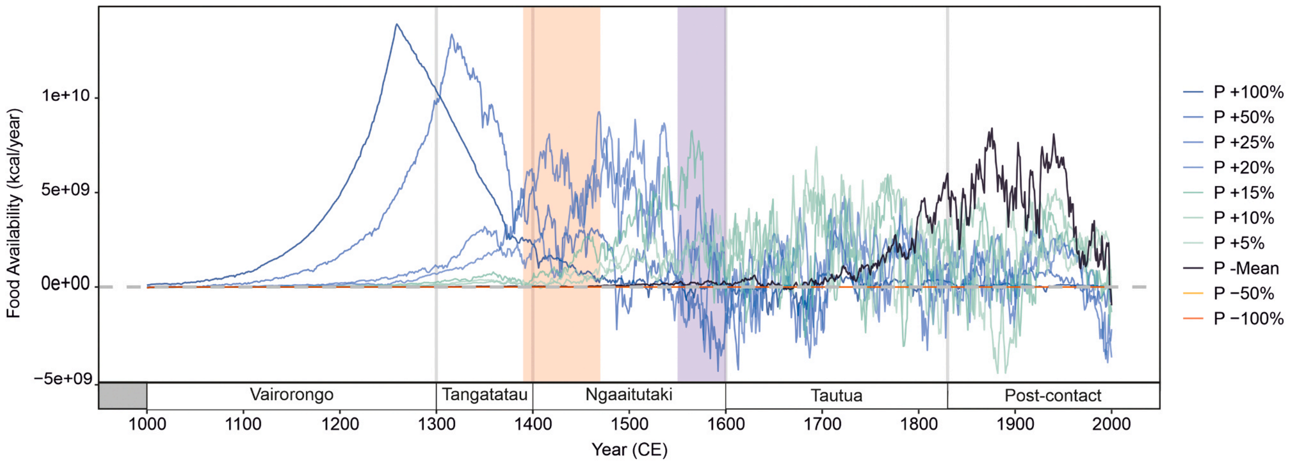

Fig. 12. Graph showing the total food availability output from the palaeo scenarios. The red box highlights a period of conflict in Mangaian history and the purple box highlights a period where food production improved as per Kirch (2017). Grey lines denote the breaks between different periods of Mangaian history with the name of each period labelled as per Kirch (2017).

because there is more food available per person when there is a lower population density, which creates a buffer in times of drought. However, drought events in times of lower population density values, can result in negative population change if they are severe enough. Over time, the average population change that occurs with low-level severity droughts drops. Initially, the population change remains positive, that is, population growth continues as the more frequent but lower severity droughts have a low level of impact on agricultural carrying capacity and thus population dynamics. As the population density increases so does the impact of the drought as measured by maximum population change during each drought event. The population density threshold where drought events start to have a notable impact is different for each scenario. For contemporary scenario 3, which represents the more frequent but less intense drought sequence, the threshold is about 250 people/km^2. For contemporary scenario 4, which represents the less frequent but more intense drought sequence, the threshold is about 150 people/km^2. The difference between these two scenarios is the longer duration of droughts in contemporary scenario 4 indicated by overall higher severity drought events as illustrated in Fig. 7. After the population hits these density thresholds, droughts – whether they are low or high severity – have a greater impact on the population. This is because there is less food available per person when the population is living at the limits of the island carrying capacity and so there is no buffer against the impacts of drought, assuming there is no water storage and everything else stays the same. This also indicates that a longer duration event has more impact than more frequent shorter duration events upon agricultural carrying capacity and population dynamics. The exponential rise in population seen in the contemporary scenarios interacts back with other parameters such as labour and food required, both of which increase with the population and spurs on an intensification in agriculture until the available land is used up as islands are finite resources so limits the total population. The population density values simulated by the palaeo model are comparable to existing estimates. Whilst the maximum population density of Mangaia from the literature is lower than the model suggests at 58 people/km^2 across the island this is using the post-contact estimate from 1833 and there was likely a larger population prior to European contact (Stevenson et al., 2015; Kirch, 2017). However, a recent estimate of the population of Rapa Nui (Easter Island) by Puleston et al. (2017) would equate to a population density of 107 people/km^2 and another by Rallu (2024) for Tahiti suggests a population density of 148 people/km^2 – both values are like the estimates provided by the Mangaia model.

When this is taken into consideration with the palaeo scenarios it implies that the Mangaia population could have reached this density threshold from around 300 years post-colonisation putting the island under stress from over-population. Reaching the carrying capacity level also makes the population more vulnerable to other pressures such as drought. Kuil (2016) found similar patterns where vulnerability of the population significantly increased, and food shortages started to occur once they reached close to the maximum capacity though the impacts were mitigated somewhat with the use of reservoirs by the Classic Maya.

The palaeo model suggests that the initial drought or dry period that potentially occurred concurrently with the second pulse of human migration in the tropical Pacific (c.950 CE) (Sear et al., 2020) would have slowed the growth of the population of Mangaia following initial colonisation. This is evident in Fig. 10 from the flattening of the population curves as the rainfall drops incrementally through the scenarios. The lower the rainfall values, the slower the population grows. The agricultural carrying capacity shows a similar pattern as people are required to clear the land for agriculture and keep it productive. The results for rainfall palaeo scenario P-Mean indicates that Mangaia would not have been able to sustain a total population of even 100 people (<2 people/km^2) using taro for at least 500 years following initial human arrival. The population does not reach maximum carrying capacity before the end of the time sequence. The low levels of rainfall as humans arrive into Eastern Polynesia meant that agriculture would not be able to sustain the initial colonists. This does not mean they did not or could not be supported by other food sources. For example, we know early Mangaians had birds, flying fox and rats as part of their diet (Kirch, 2017) and would make use of marine resources (Butler, 2017) and forest arboriculture (Kirch, 2017). However, taro would have been important for sustaining large populations. There is a noticeable step up in agricultural carrying capacity values between scenario P-mean and scenario P + 5 %. This represents a threshold change between a rainfall scenario that can produce a good taro yield and a rainfall scenario that sees notable slowdown in the growth of the population due to lower taro yields.

5.2. *Model Evaluation and Palaeo Context Interpretation*

Behavioural and structural testing involves determining whether the model adequately represents the observed system behaviour and to understand whether the model provides a reasonable representation of the real system (Elsawah et al., 2017). This is difficult to do when modelling a prehistoric system, as there are no observed data available to compare with the model outputs and the modern-day system itself likely no longer functions in the same way. To evaluate the structure and outputs of this model, the alternative is to compare the model outputs with existing archaeological records. Another way to evaluate the model is to compare it to other models from the literature to see whether it produces similar behaviours. This allows us to see whether the outputs are plausible and how useful the model is for understanding the socio-ecological system of Mangaia.

Kirch (2017) looked at the relationship between population and food availability in Hawaii and states that there are parallels to be drawn between the Hawaiian and Mangaian examples. From this, he postulated several theories on the population and agricultural dynamics:

1) Initially the limit on food production following colonisation was a shortage in available labour.
2) Over time, the population of the island would have rapidly increased and eventually reached the total carrying capacity of the island causing a negative shift in food availability. The drop in food availability would have limited fertility and increased mortality leading to an overall decline or upper limit on population numbers.
3) Environmental degradation – specifically deforestation and the associated erosion - would impact on the agricultural productivity of the island and the amount of suitable land
4) The shift from agricultural productivity being limited by labour to being limited by land availability would have taken approximately 250 years.

These theories were developed out of work done by the Hawai'i Biocomplexity project (Kirch et al., 2012) and built especially on work done by Puleston and Tuljapurkar (2008). Kirch (2017) drew parallels between the socio-ecological dynamics of Mangaia and the outputs of the modelling used to reconstruct the impact of agricultural intensification in Hawai'i (Kirch et al., 2012). However, these observations were not followed through with an attempt to model the Mangaian system. The model presented in this study offers an opportunity to test some of the hypotheses Kirch (2017) set out in his monograph on Mangaian archaeology.

As discussed in Section 3, as per Kirch's theory, agricultural production is explicitly linked to population size in the model, as is common in socio-ecological model studies (Axtell et al., 2002; Hamilton and Kahn, 2007; Heckbert, 2013; Brandt and Merico, 2015; Kuil et al., 2016; Lima et al., 2020). As the population grows, so does the amount of food produced until the population hits the maximum amount of land that can be cultivated for, in this instance, wetland taro. When compared to the Kohala model (Kirch et al., 2012), the outputs of the contemporary model scenarios 3 and 4 in Section 4 show a similar pattern of population growth with the smoother exponential rise following initial colonisation, before levelling out when the population reaches the carrying capacity of the island or area, after which, the population fluctuates based on environmental factors. The fluctuations in contemporary scenarios 3 and 4 are notably larger than those from the Hawai'i model that considers other food sources. The Mangaia model focuses specifically on taro production and if other food sources were considered then the outputs would likely be more similar in terms of the lower rate of variability in the population numbers once they plateau at around the carrying capacity.

Fig. 9 shows that the amount of food available per person in contemporary scenario 4 starts to decrease after 250 years. This is because the population reaches the agricultural carrying capacity at around 250 years post-arrival. This is consistent with Kirch's theories on population growth and food availability and the timeline for reaching those thresholds. The model developed by Kirch et al (2012) utilised a modified nutrient cycling model, a demographic model and was more complex as it included marine resources, hierarchical social organisation and a more diverse agricultural system. Despite the two models being significantly different and representing different levels of complexity, they both show similar responses, providing confidence in the Mangaia model outputs and indicating that this simplified model captures the main dynamics of the system. Kirch (2017) suggests that there was a period of stress on Mangaia toward the end of the Tangatatau phase (1300 – 1400 CE) between approximately 1250 CE and 1450 CE. During this time, there was a rise in conflict and a decline in the number of pig bones in the archaeological horizon with evidence of cannibalism from 1390 to 1470 CE – this is highlighted by the red box in Fig. 12. The population had started living around the wetlands and developing horticulture during this period. An explanation for this based on the model is that there is a gap between the start of exponential population growth and the peak in food availability (thanks to agricultural intensification of taro production) due to unfavourable conditions for taro production in the first century or so following human arrival. The models suggest that had conditions been more favourable in the first century following human arrival then the ramp up to agricultural intensification could have occurred at least a century earlier perhaps preventing this period of stress at the end of the Tangatatau phase. By 1300 CE, all the islands of the Pacific had been colonised (Wilmshurst et al., 2011; Ioannidis et al., 2021). It has been suggested that this period of compounding impacts from climate and over-population on the Mangaian system around 1300 CE led to outbreaks of conflict and cannibalism during the Tangatatau phase (Kirch, 2017) as a mechanism to relieve stress on the system as it was no longer possible to relieve pressure by migration (Hipkiss, 2023).

Nevertheless, conditions appeared to improve on Mangaia following this period of stress with an increase of pig bones in the archaeological sequence within the Ngaaitutaki phase (1400 – 1600 CE). It is believed that the population peaked in Mangaia in this phase (Kirch, 2017). Kirch (2017) believes this improvement in food availability conditions were likely due to the intensification of agriculture and the introduction of the sweet potato. Sweet potato is a dryland crop (Kirch, 2017) so can deal with lower levels of rainfall making it an important addition to Polynesian cultigens as it enables people to adapt to variable rainfall. Palaeo scenarios P + 15 %, P + 20 % and P + 25 % show food availability increasing just prior to and over this period as taro agriculture expands which corresponds with the narrative from the archaeological record.

Following this, several animals become extirpated in this period including some that were important food sources in previous phases and there is a higher level of violence – these indicate stress on food availability again (Kirch, 2017). In the palaeo models, around 550–600 years post-human arrival, which would equate to approximately 1550–1600 CE, the food availability drops down rapidly as the population grows.

The model findings are consistent in several ways with what we currently know about Mangaian prehistory but add the novelty of climate as a possible driver. Kirch (2017) did not consider the role of climate on the human colonisation of Mangaia, likely due to scarcity of data on past climate in the region. However, in the model, periods of population stress were caused by the slowing of the intensification of agriculture due to adverse climatic conditions for the growth of taro. In the palaeo scenarios, the recovery of the population in the beginning of the Ngaaitutaki phase could be due to the late blooming of the taro agricultural intensification, which was delayed due to adverse climatic conditions around the time of colonisation.

A space-limited environment model based on the 'Opunohu Valley on Moorea, French Polynesia was introduced by Hamilton and Kahn (2007). Their model relates to this study in terms of the representation of a maximum carrying capacity. The difference is that Hamilton and Kahn's (2007) carrying capacity is an absolute maximum value whereas the value in the Mangaia model is a dynamic value through time similar to the Brandt and Merico (2015) Rapa Nui (Easter Island) model. Their absolute carrying capacity was a population of 58,435, which comes out at a population density of 436 people per km^2. The Mangaia model gave an absolute carrying capacity of 19,548, which gives a population density of 377 people per km^2. This offers some confidence that the model is providing a relatively realistic output when compared to other similar models. This suggests that the model captures the main relationships and their magnitudes, considering that the Mo'orea model takes into account a wider range of agricultural crops and soil properties. Hamilton and Kahn (2007) note that their maximum carrying capacity value is much higher than their population estimate based on the house-count method and instead suggest that this number is potentially twice what the valley would have produced so it represents an absolute maximum assuming optimum outputs. Similarly, a population of 19,548 is much higher than the estimated 3000 in 1833 even if they had been decimated by an epidemic. Whilst there is not currently any evidence to support a value of ~400 people/km^2, there is also no estimate for population size of Mangaia precontact. In a number of the palaeo scenarios however, the population does not reach the absolute maximum carrying capacity as it does in the model scenarios. This indicates that perhaps the model scenarios represent a more optimised system whereas the palaeo scenarios present a more realistic estimate.

The sensitivity tests showed the model appears robust to the parameterisation as it displayed similar behaviour over time despite varying parameter values, offering confidence that the model is not producing certain behaviours because of a particular parameter value choice. The results presented from the model outputs also provided a sensitivity test for the rainfall input. There is however evidence of thresholds of change particularly with the changes in rainfall data, as shown in palaeo scenarios P-50 % and P-100 % in Fig. 6, suggesting the model is sensitive to rainfall below 75 % of the mean for which the population essentially collapses. This suggests that the scenarios that represent the extremes of possible rainfall profiles should be considered with care as these are not consistent with what we know about time of colonisation, i.e. no collapse is documented in the archaeological evidence (Kirch, 2017). However, those scenarios do suggest extreme changes in the rainfall amount. The range in rainfall values for the palaeo scenarios is high due to the uncertainty from palaeo data sets, which is a limitation that can only be overcome with new local quantitative palaeo records with lower uncertainties in the calibration profile.

5.3. Limitations and Further Development

As per the sentiments expressed by Brandt and Merico (2015), this model is a simplified representation of the key components and feedbacks of the Mangaian island socio-ecological system. Therefore, when compared to the conceptual model described earlier, there are some aspects of the system that have not been represented.

An example of this is that the model represents a mono-crop society by focusing on taro as it was a key staple crop. However, Polynesians were a multi-cropping society with food adaptation strategies to deal with extreme conditions (Kirch, 2017; Hamilton and Kahn, 2007). The introduction of multi-cropping and simulating the switch between resources during times of hardship would likely reduce the magnitude of the fluctuations seen in some of the population outputs in palaeo scenarios (see Fig. 10) to become something more like the Kirch et al. (2012) outputs and increase the overall carrying capacity. For example, the introduction of sweet potato to Mangaia would have been an important change to agricultural practices as it is a dryland crop that was capable of growing in the agriculturally poor makatea and uplands areas (Hiroa, 1934) so could provide an additional source of food when puna lands were under stress during dry conditions. In addition, early settlers to the island and founding settlements would have initially utilised wild and marine resources as primary food sources including bats, birds, fish and wild growing vegetation. In other parts of the Pacific, isotopic studies have shown that first settlers depended on foraging and wild animals for sources of food prior to the establishment of agricultural crops (Kinaston et al., 2014). Marine resources have also been excluded but were part of the diet on Mangaia throughout human occupation as evidenced by fish remains in the Tangatatau Rockshelter (Butler, 2017). Though fish may not have been as extensive a part of the diet as on other Polynesian island due to the limited reef habitat present around Mangaia and a lack of a true lagoon (Butler, 2017). Nevertheless, the inclusion of wild and marine resources would have allowed for a higher carrying capacity for the island and perhaps a buffering of the impact of drought by switching to alternative sources of food. However, it is difficult to identify and quantify the wild resources available during this time and how they were used in the early stages of settlement in Mangaia. Very little is known about the first arrival of humans and their diet on this island (Kirch, 2017).

This model also does not consider other controls on population numbers. For example, on the Rapa Nui (Easter Island) model developed by Brandt and Merico (2015) they included an epidemic component to their model to represent the introduction of diseases by Europeans. In the palaeo scenarios explored in this study, the population continues to grow through to the year 2000 CE. Whereas we know that the population of Mangaia was decimated by illness following the arrival of Europeans in 1824 (Williams, 1837). Though the focus of this model was specifically to understand the prehistoric socio-ecological system rather than reconstruct the population dynamics through to the post-contact period there are other controls on population that are not explored such as the periods of conflict on Mangaia and the start of cannibalism (Kirch, 2017), which would have acted as another type of control on population numbers beyond agricultural productivity or climate.

Other features of the socio-ecological system that were described in Section 2, such as water resources, resource management, environmental degradation and a more complex population were also not included. These and the others described above would potentially have implications on carrying capacity and ultimately the ’real’ output would depart from that predicted purely based on rainfall. Whilst there are a number of these elements that could be introduced and built into the socio-ecological model, the aim was to maintain simplicity and therefore interpretability by representing the key components and feedbacks to understand the broader socio-ecological processes during the periods of human migration in the tropical South Pacific. Where there was insufficient information or data available in the archaeological and ethnohistorical record for these components, there is no justification to add further complexity. Each island in the tropical South Pacific is unique but there is scope to adapt this model so that it could be applied with updated parameters to represent other island systems. Future work may look to develop this simple model to better represent some of the elements described here but for the purposes of this paper the model has provided insights into how changing hydrological conditions may have impacted on key aspects of prehistoric island life.

6. Conclusions

Using a range of drought scenarios based around current knowledge of the Mangaian rainfall patterns, the socio-ecological model has enabled an assessment of the impact of drought on agricultural productivity and population dynamics. The key findings were that as the population density of the island increases, the impact of drought events on the population increases across all levels of severity. The threshold of the population density where there is a significant shift in the impact of drought varies depending on the rainfall patterns but typically is around 165–230 people per km^2. The contemporary scenarios based upon the modern day Mangaian rainfall data also indicate that the severity of the drought rather than the return frequency drove the bigger changes in carrying capacity and population dynamics for Mangaia over a 1000-year period. Based on the palaeo scenarios that utilise a corrected version of a quantitative rainfall data set from Lake Lanoto’o in Samoa, changing rainfall levels impact on the timing and rate of population growth due to its role as a limiting factor of agricultural productivity. This then can hasten or delay the rate at which a population reaches the island’s maximum carrying capacity and the rate of agricultural intensification. This shows that the dry period concurrent with human arrival on Mangaia would have slowed the growth of the population as rainfall levels were low enough to impact upon taro yields during initial colonisation. This is the first model of prehistoric Pacific island life that utilises rainfall palaeo data to understand how changing hydrological conditions affects agricultural productivity and population dynamics.

CRediT authorship contribution statement

David Sear: Writing – review & editing, Supervision, Project administration, Methodology, Conceptualization. **Peter Langdon:** Writing – review & editing, Supervision, Methodology. **Justin Sheffield:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Hipkiss Charlotte Victoria:** Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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