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Analysis

Learning from the Ancient Maya: Exploring the Impact of Drought on Population Dynamics

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ABSTRACT

Understanding the relationship between drought and population dynamics is increasingly important, particularly in areas where high population growth corresponds with increasing drought risk due to climate change. We examine the relationship between drought events and population dynamics using a stylized hydrology-demography model that has been calibrated to simulate plausible feedbacks for the population decline of the Ancient Maya of Central America. We employ a deterministic and a stochastic approach.

We find that the impact of drought increases abruptly once a critical threshold of population density is exceeded. The critical threshold depends on the intensity and duration of the drought as well as on the level of technology adopted by society, the extent of markets and societal behavior. The simulations show that, for a society to be as food secure post-climate change as they are pre-climate change, strategies would have to be adopted to not only increase the region's capacity to provide sufficient resources for its growing population, but also to buffer the impact of a drier climate on productivity. This study provides suggestions on how technological, societal and economic development can modify the system to mitigate the impacts of climate change on the human population.

1. Introduction

While the development and management of water resources is able to foster the growth and wealth of societies, the absence of water security can have severe consequences (Grey and Sadoff, 2007). In some cases, when water is insufficient to satisfy agricultural, industrial, energy or transport demands, the consequences are merely economic. In other instances, drought forces people to temporarily reduce dependency on local resources or to relocate to a different location (Black et al., 2011; McLeman, 2011). It may also initiate or exacerbate conflict (Kelley et al., 2015). For several ancient societies, such as the Indus civilization in India (Pande and Ertsen, 2014), the Khmer society in modern day Cambodia (Buckley et al., 2010) or the Ancient Maya civilization of central America (Douglas et al., 2015) it is thought that drought contributed to their collapse. But also in modern history and present times, examples can be found in which drought has contributed to social disruption. Drought, in combination with mismanagement, triggered dust storms on the American Plains in the 1930s leading to a reduction in the value of agricultural land and population decline (Hornbeck, 2012). Dry season migration is a common adaptation strategy for pastoral and sedentary communities in the West African Sahel (McLeman and Hunter, 2010) and drought conditions have affected millions of people in Asia and Africa in the past years, although interlocking factors make it difficult to attribute drought as the sole reason for displacement in the majority of cases (NRC/IDMC, 2017).

Recent projections of drought occurrence under future climate scenarios show decreases in soil moisture globally and increases in the frequency of short-term (4–6 months) and long-term droughts (Sheffield and Wood, 2008). Reductions in rainfall are the primary cause for drought increases. At the same time, population growth puts pressure on local ecosystems and resources (Renaud et al., 2007; Vörösmarty et al., 2010; Hugo, 2011). Gaining insight in the relationship between rainfall decreases and population dynamics is therefore valuable to cope with environmental challenges such as droughts.

The relation between population and the earth's resources is generally constructed on the basis of two related concepts, i.e. the existence of a subsistence minimum and the concept of carrying capacity (Malthus, 1798; Odum (1953) in Sayre, 2008). Both concepts are based

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on the assumption that resources are limited, and that a maximum number of people can be supported indefinitely and sustainably. Despite its complexity, the concept has been widely applied. Over the years, several authors have used basic assumptions regarding average food needs to provide estimates of global carrying capacity (Cohen, 1995; Daily and Ehrlich, 1992). Others have developed concepts that account for variations in affluence or technology in determining the environmental impact (e.g. the IPAT-model) or ecological footprint (Chertow, 2000; Wackernagel, 1994). As part of the ecological footprint approach, the carrying capacity concept has been reinterpreted as a land per capita necessary to sustain an individual's throughput including consumption and waste discharge ("demand on nature") rather than as capita per land ("supply of nature") (Wackernagel, 1994; Rees, 1996). Similarly, the water footprint has been developed to provide estimates of the amount of water used to produce single goods or services, or to estimate the amount of water on which an individual or country depends (Hoekstra and Hung, 2005). Given the extensive role trade plays in current societies, this dependence is no longer local, but extends to the global scale and carrying capacity is essentially linked to the global supply of water (Konar et al., 2011; Lutter et al., 2016).

Moreover, scholars have attempted to provide a dynamic representation of resource and population interactions. The aim of such models is to provide insight in the underlying variables and mechanisms that drive the observed dynamics and to provide a learning tool through which the impact of, for example, policy interventions can be tested. Inspired by ecological predator-prey models (Holling, 1973; Arditi and Ginzburg, 1989), Brander and Taylor (1998) developed the Ricardo-Malthus model of renewable resource use. Here, humans are assumed the predator and the resource base the prey. The authors show how endogenous resource degradation could have led to population decline on Easter Island. Resource growth is modeled using a simple logistic function, determined by an intrinsic growth rate (r) and carrying capacity (K). Several related models have been developed over the years (Nagase and Uehara, 2011). Scholars have explored the role of institutions, such as property rights or population controls on population and resource dynamics, the impact of technological progress or alternative production functions, conflict or the impact of inequality (Anderies, 2000; Dalton and Coats, 2000; Dalton et al., 2005; Erickson and Gowdy, 2000; Good and Reuveny, 2006; Pezzey and Anderies, 2003; Reuveny and Decker, 2000; D'Alessandro, 2007; Maxwell and Reuveny, 2000; Prskawetz et al., 2003; Motesharrei et al., 2014). The basic logistic equation for resource growth has been kept in all of these models. This equation is however less suitable for faster growing agricultural resources as the resource stock is not a major input in production (Maxwell and Reuveny, 2000). Also the impact of a changing climate cannot be explicitly evaluated as it is not an input to the model frameworks.

Scholars that have attempted to dynamically represent rainfall, resource and population dynamics include Pande and Savenije (2016), Ginnetti and Franck (2014) and Kuil et al. (2016). Pande and Savenije (2016) explored the climatic and socio-economic conditions that result in low capital stock of farmers and attempted to relate this to farmer suicide rates. They were motivated by a region in India that witnessed many suicides of farmers who could not extricate themselves out of the depth trap, especially during periods of low rainfall. Ginnetti and Franck (2014) present an initial attempt to model displacements of pastoralists as a result of droughts. They conceptualize the system as a causal sequence between rainfall, pasture productivity and livestock growth in connection to a subsistence threshold above which pastoralists can continue their lifestyle and below which pastoralists become displaced. They find, for example, that displacement can occur even if rainfall is close to its mean, but also that displacement is delayed relative to reductions in rainfall. Kuil et al. (2016) developed a stylized, socio-hydrological model to investigate the feedbacks between water stress and a society mainly dependent on agriculture. Rainfall determines crop growth, which determines food production, which ensures population growth as long as food availability is sufficient. When food availability is insufficient, the community becomes vulnerable which results in reduced or negative population growth, unless the community is able to adapt. In Kuil et al. (2016), the model has been applied to the Ancient Maya, a flourishing civilization in northern Central America that experienced a large population decline starting at the end of the Classic Period. It was shown that a modest reduction in rainfall, as derived from paleo-climatic data, can lead to an 80% reduction of the Maya population as was suggested by Medina-Elizalde et al. (2010). At the same time, it was acknowledged that uncertainty is associated with the precipitation series used to drive the model in addition to uncertainties in the model's structure.

In this study, we aim to examine the relationship between drought and population dynamics in further detail. By doing so, this study aims to shed light on the mechanism that leads to a population decline. We investigate the role of technological advances, which include the construction of reservoirs, on population dynamics. We also explore the impact of changes in rainfall on the likelihood of population decline occurring for the Ancient Maya. We do this by using the stylized dynamic model developed in Kuil et al. (2016) in which the interactions between an agricultural society with its environment are conceptualized using insights from the hydrological, socio-economic, and vulnerability literatures.

Through the study of socio-hydrological relationships in the context of an ancient civilization like the Maya, we expect to find important implications for the drought prone societies of today. The paper develops as follows. First, the model is introduced, then an outline of the approach taken to investigate the relationship between drought and population dynamics is given. We subsequently present the results and discuss the implications of the findings.

2. Socio-hydrological Drought Processes Conceptualized

The field of socio-hydrology is built on the premises that human and water systems are coupled and coevolve (Troy et al., 2015). Humans contribute to and subsequently adapt to water security problems (Levy et al., 2016). Accordingly, a new approach is proposed to study the two-way interactions and dynamic relationships between water and social processes (Sivapalan et al., 2012; Sivapalan and Blöschl, 2015). The model used in this study is built within the spirit of socio-hydrology, as well as within the spirit of models like Brander and Taylor (1998). The model assumes Malthusian population dynamics, but differs from a typical economic model by not explicitly modeling the production and consumption side of the economy and instead highlighting the socio-hydrological dynamics present within a complex socio-environmental system.

Based on Kuil et al. (2016) we assume a community who produces food to sustain itself. Hereto, the community cultivates land, whereby per area food production depends on crop characteristics and on the amount of precipitation that falls. The society can grow as long as food supply is sufficient. This positive feedback loop can be interrupted in two ways. Firstly, the population is limited by the amount of resources, e.g. land and water, it can utilize given their level of knowhow and skills. Thus, when food supply can no longer be increased despite food demand remaining high, the community becomes vulnerable. Secondly, it could happen that precipitation deviates from what is considered normal and the community faces reduced harvests as a consequence of drought. Here, the community can become vulnerable and in the absence of any adaptive measures, a reduction in population will occur due to reduced births, increased mortality or forced emigration. Adaption is possible through the construction of reservoirs. In line with the theory of agricultural intensification (Boserup, 2011), but also with the theory of endogenous change (Pande and Ertsen, 2014), it is likely that scarcity triggered technological and institutional change. While this can take many forms, the model only considers structural measures in the form of reservoir building. A reservoir affects the hydrological system by capturing more water, allowing for an increase in food production per area that restores food supply and demand, allowing renewed population growth. This feedback continues until the society recognizes reservoir capacity is sufficient to capture available precipitation.

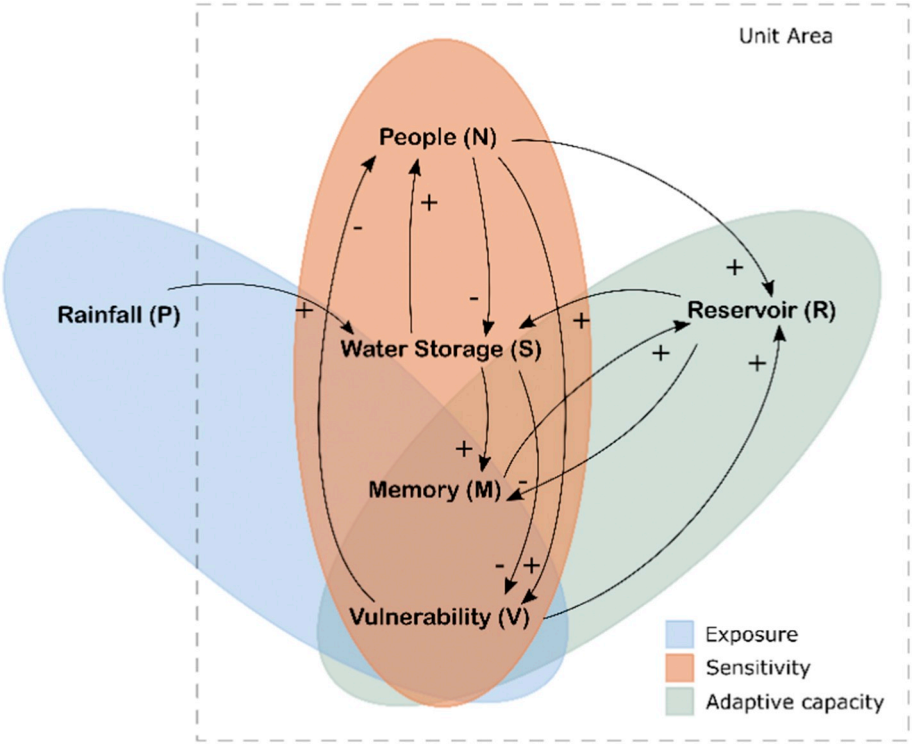


Fig. 1. Flow diagram showing the state variables of the model and how they interact. When rainfall P increases, water storage S increases (+), resulting in a higher yield and positive growth of population density N (+). The use of water by the society leads in turn to a decrease in storage (−). If population density increases this could potentially lead to a higher vulnerability V of the system (+), although increased water storage S counteracts this (−). Increased vulnerability V motivates society to construct reservoirs R (+), provided that there are enough people (labor) to do so (+). More reservoirs allow increased water storage (+). If storage is high relative to the storage capacity, memory M is high and reservoir construction R continues, but by creating more storage, M decreases (−). Lastly, when the system is vulnerable (i.e., close to 1) and a threshold is reached, population density N is impacted negatively (−).
From Kuil et al. (2016)

An overview of the model's conceptualization can be seen in Fig. 1. An example of model results can be found in Fig. 2. Five state variables are used to conceptualize the society's dynamics, i.e. water storage (S), population density (N), reservoir capacity (R), memory (M) and vulnerability (V). Precipitation (P), which includes drought events, drives the model. A detailed description of the model's equations can be found in Kuil et al. (2016). A summary of the model framework is included in the Appendix A.

3. Approach

To investigate the relationship between drought and population density, we use model parameters corresponding to the simulation in Fig. 2 (see Appendix A) and systematically vary rainfall exposure. In Kuil et al. (2016), the precipitation series used from 487 to 1000 CE were based on the derived precipitation data by Medina-Elizalde et al. (2010). In order to create monthly rain data and a distinct rain season in which around 80% of the rain falls within six months, the annual precipitation values were first upscaled to match the annual rainfall found at Tikal and subsequently downscaled to monthly values by applying a sine function with an amplitude of 0.9 times the monthly mean to mimic the strong seasonality of the area. Throughout this paper, the precipitation series in Kuil et al. (2016) is used as a baseline.

First, several droughts of varying duration and intensity are defined deterministically. The society is systematically exposed to these droughts and the impact on society is examined. Subsequently, statistical distributions are fitted to the baseline annual rainfall record and the society is subjected to a series of stochastically generated rainfall series. As it turns out (Section 3.4) the rainfall record derived by Medina-Elizalde et al. (2010) shows a shift in precipitation around 830 CE. We use this shift in precipitation to illustrate the impact of a change in climate on population dynamics. We also examine the effect of alternative adaptation strategies, other than reservoirs, on long term population dynamics.

3.1. Drought Definition

We adopt a threshold level method to define when a drought is occurring (Van Loon, 2015). We create a yearly duration curve for precipitation (P) based on the baseline annual rainfall record and consider rainfall years beyond the 80th percentile as drought years in line with commonly adopted thresholds ranging between the 70th and 95th percentile (Sheffield and Wood, 2008; Van Loon et al., 2014; Van Loon, 2015). Annual precipitation of 1542 mm per year or less is defined as a drought year (≥14% below mean annual rainfall of 1800 mm per year). We convert the yearly threshold to a monthly variable threshold using the approach as described before. We adopt the statistics introduced in Sheffield and Wood (2008) to characterize a drought, such that 'duration' is represented by the length of the period precipitation is below the threshold (measured in years), 'intensity' is based on the mean rainfall over the duration of the drought and measured as the share of time (%) when rainfall is below the mean. Finally 'severity' is measured by the time integrated deficit below the threshold, which in fact equals the product of intensity and the duration of the drought and has units of % years.

3.2. Assessing Drought Impact

We quantify the impact of a drought by considering the difference between the population density level at the beginning of the drought and the minimum population density level after the drought (see Fig. 3: impact). We define the recovery time as the time it takes for society to recover from the minimum population density level after the drought to the initial population density level at the beginning of a drought (see Fig. 3: recovery). If no recovery takes place within the simulation period, we record NA. In today's world, emergency aid to provide water and food, can contribute to mitigating the effect of drought on population dynamics. Given the model's assumptions, i.e. as a closed system with the exception of precipitation, actions that alleviate the impact are not taken into account. The model's results can therefore be seen as a proxy for the amount of external aid that is needed versus the amount of resilience that remains within the system.

3.3. Deterministic Drought Analysis

3.3.1. Exposure to an Individual Drought Event

For each simulation, the model is run for a period of 50 years at a

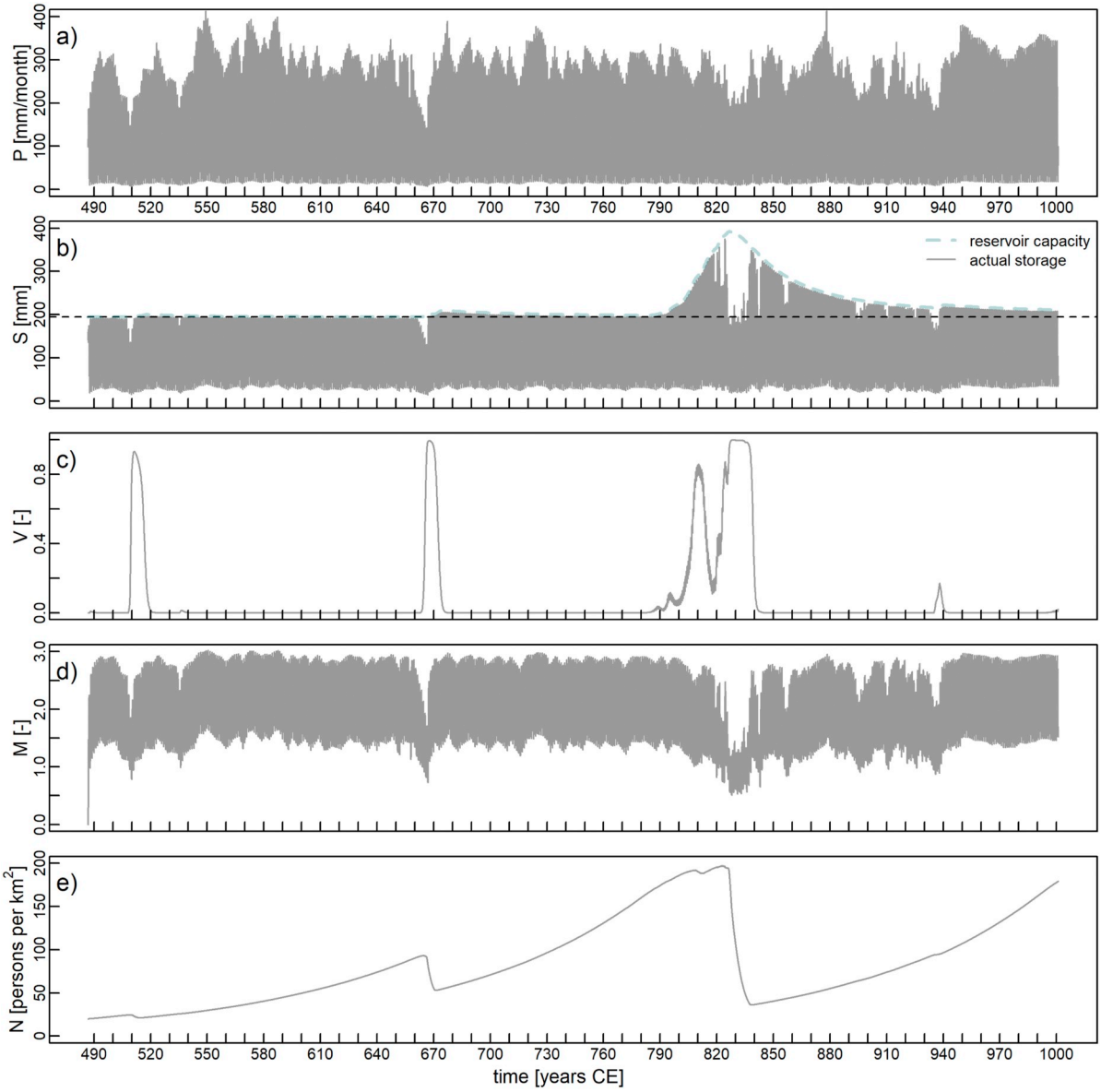


Fig. 2. Model results when the model is parameterized (see Table 1) in line with our knowledge on the Ancient Maya civilization. Initially, population density is low, natural resources are sufficient and population growth is exponential. A period of reduced rainfall around 665 CE (panel a) has a substantial impact on society (panel e), as harvests fail due to insufficient soil moisture (panel b) and the population becomes vulnerable (panel c). The population density is however insufficient to initiate large scale reservoir construction (dashed blue line, panel b). After a period of increased vulnerability leading to reservoir construction and continued population growth, several droughts at the end of the Late Classic (towards 830 CE) cause reservoirs to dry up, and result in failed harvests and severe population decline. Throughout Ancient Maya area, archeological evidence indicates that around this time the heyday of the Ancient Maya civilization was over. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
Adapted from Kuil et al. (2016)

monthly time step with a constant annual precipitation equal to mean annual precipitation (1800 mm/year) and considering seasonality. At t = 50, a drought of varying intensity and duration is introduced. Afterwards, precipitation values return to mean annual values for the remaining simulation time until a total simulation time of 200 years is reached. We select five different intensity levels, i.e. 1542, 1440, 1260, 1080 and 896 mm/year, such that the values cover the range between the 80th and 100th percentile of the yearly precipitation duration curve. These values correspond respectively to 14, 20, 30, 40 and 50% below mean annual rainfall. We also select five different drought durations, i.e. 1, 2, 5, 10 and 20 years. In total, we thus have 25 different drought exposures.

Based on initial model simulations, we expect that the impact of a drought is a results of the system's exposure, sensitivity and adaptive capacity. We therefore assess the impact of a drought for different levels of population density (N) and take reservoir construction (R) into account. We run the model for a society that is able to build reservoirs and for a society that does not have this technology, and for 21 different initial population density levels, i.e. 10, 20, 30, … up until 210 persons per unit area. This maximum initial population density of 210 persons per unit area equals the equilibrium population density under constant mean annual rainfall of 1800 mm per year and model parameterization including reservoir construction.

3.3.2. *Exposure to Two Consecutive Drought Events*

When two droughts occur one after another, it could be that both, one or neither of the droughts have an impact on population dynamics. To gain insights into the conditions leading to each situation, we run the following experiment. After a drought with 1440 mm/year (−20%)

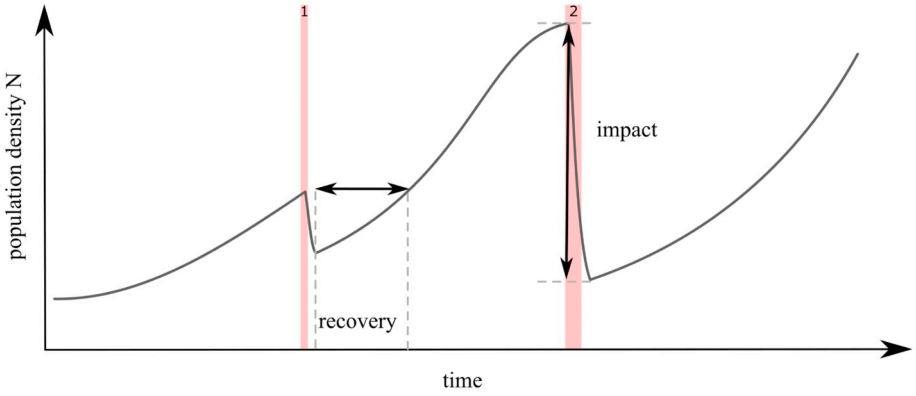


Fig. 3. Schematic that illustrates how the impact of a drought as well as the recovery time of society is assessed. Droughts are marked by red panels numbered 1 and 2. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

precipitation of one year in duration, we assume that a second one-year drought occurs that varies in intensity, i.e. 1542, 1440, or 1260 mm/year, respectively. We repeat the experiment for an overall higher drought intensity level, i.e. we assume an initial drought of one year in duration with an intensity level of 1260 mm/year (−30%), after which a second one-year drought occurs of 1440, 1260 or 1080 mm/year, respectively. We analyze the effects on a society with and without reservoirs and for 21 different initial population density levels, similar to the case of an individual drought event.

3.4. Stochastic Drought Analysis

3.4.1. Fitting Statistical Distributions to Capture General Rainfall Characteristics

To generate rainfall series stochastically we aim to reproduce the statistical properties of the rainfall record, including possible changes in these properties within the time period of interest. The package 'changepoint' in software R (Killick and Eckley, 2014) is used to identify whether periods with a significantly distinct mean and variance can be identified within the rainfall series available. Fig. 4a presents the outcome of the 'changepoint' analysis when five break points are adopted.

From Fig. 4a, it can be concluded that a period of reduced rainfall occurs after 819 CE. This coincides roughly with the end of the Classic Period and the start of the decline of the Maya civilization. Also, when the number of break points is increased or decreased, this point in time turns out to be robust. We therefore divide the record in to two periods: one period that includes data before 819 CE and a second period that includes data after 819 CE. Fig. 4b shows the two density plots of annual precipitation as described, i.e. for the period before 819 CE (blue) and for the period after 819 CE (red).

We simulate annual rainfall with a lag-1 autoregressive model (Markov Process). We assume that annual precipitation sums are normally distributed. The mean, variance, and the autoregressive parameter of the Markov process are calibrated for each period independently. We use these characteristics to generate the synthetic precipitation time series. The generated rainfall representative of the period 487–818 CE is characterized by a mean annual rainfall of 1842 mm/year (σ = 310 mm/year), while the generated rainfall representative for the period 819–1000 CE is characterized by a mean annual rainfall of 1752 mm/year (σ = 309 mm/year). The sample estimates of the standard deviation for the two periods are not significantly different, which indicates that the breakpoint of 819 CE refers only to a change in the mean annual rainfall, and not in its variance. Possibly, the fact that the standard deviation is period-independent could be an artifact of the rainfall reconstruction method used by Medina-Elizalde et al. (2010). Additional analysis comparing the generated rainfall of the period 819–1000 CE with the generated rainfall of 487–818 CE shows that mean drought duration increased from 2 to 3 years, mean intensity increased slightly from 21.4 to 21.7% below mean annual rainfall, and mean severity increased from 53% years to 75% years (see for definitions Section 3.1).

3.4.2. Exposure to Different Rainfall Series

To gain insight in what could have happened when the Ancient Maya society had faced a drier climate, we perform two experiments. For the first experiment, we analyze the population dynamics when the Ancient Maya are exposed to rainfall with characteristics similar to the period 487–818 CE (from here on indicated as 'the 'normal' climate'). For the second experiment, we analyze the population dynamics when the Ancient Maya are exposed to rainfall with characteristics similar to the period 819–1000 CE (from here on indicated as 'the drier climate').

We start each model simulation at the year 768 CE, whereby we extract the initial values for the state variables S, N, V, M and R, from the original model simulation at t = 768 (Fig. 2). We then expose the society to the original baseline precipitation data for the next 50 years. From 819 CE onwards, we expose the society to 200 years of generated rainfall, which either represents the 'normal' or the 'drier climate'. We repeat the procedure 100 times for each climate, in order to acknowledge the stochasticity in the rainfall input.

3.4.3. Exposure to Different Rainfall Series Under Various Adaptation Strategies

Lastly, we are interested in what could have happened had the Maya adopted additional strategies to mitigate water scarcity. Characteristic for the Classic period (600 to 830 CE) is the sharp rise in population (Culbert, 1988), resulting in a rapid increase in resource use before population decline occurred. Possibly, a more proactive approach towards resource scarcity, for example by reducing water demand by slowing down population growth, could have prevented a collapse. In the model this can be simulated by adjusting parameter β_N, which effectively regulates the population growth rate for a given food availability.

In present times, failed local harvests due to below average rainfall can be mitigated through the existence of global food networks (Konar et al., 2011, 2013). If such a global food network would have existed during the time of the Maya, their situation might have looked very different. To simulate the effect of today's virtual water networks on population dynamics, the per capita local water demand, parameter γ_N, can be lowered. This setting reflects a situation in which part of the food is imported, i.e. comparable to a person's or a country's external water footprint in addition to their internal footprint (Hoekstra and Hung, 2005).

We repeat the simulations as described in Section 3.4.2, but assume proactive behavior to slowdown population growth (β_N is set to 0 instead of −0.1) and/or reduced dependence on local water resources as a consequence of virtual water trading (γ_N is set to 0.15 instead of 0.6). The latter is a possible assumption given the range of external water footprints found across the world (Mekonnen and Hoekstra, 2011).

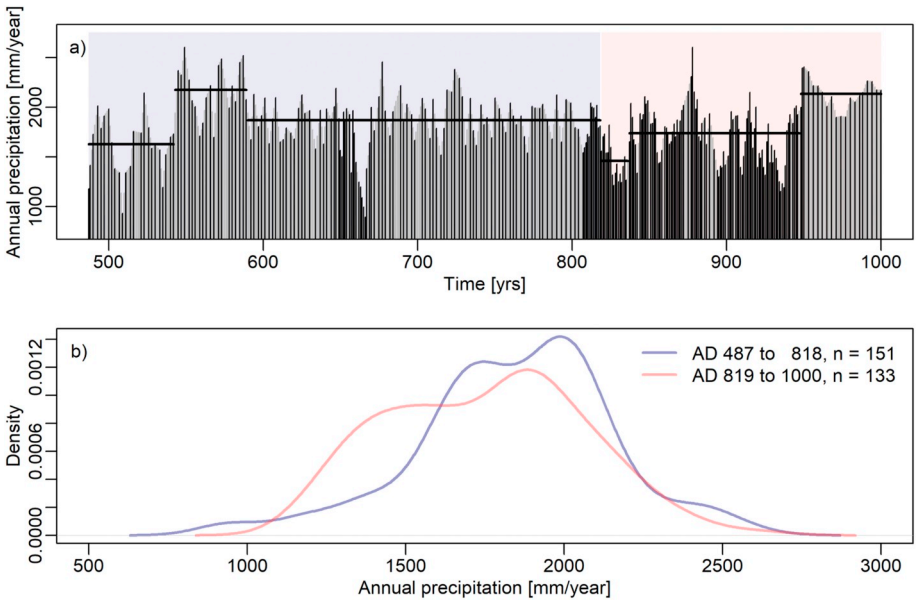


Fig. 4. Rainfall characteristics a) Changepoint analysis of the baseline precipitation series. The year 819 CE seems a critical change point, robust to changes of the number of breakpoints. Gray lines represent interpolated data, black lines years for which isotope data is available. b) Density plots for the rainfall record before 819 CE (blue) and for the rainfall record after 819 CE. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

4. Results

4.1. Deterministic Drought Exposure

4.1.1. The Impact of an Individual Drought Event

Fig. 5 shows the impact of the different droughts on population density. Each panel shows the reduction in population density (y-axis) versus the population density level at the time of drought (x-axis) with reservoirs (blue) and without reservoirs (red). Individual points are the outcomes of the 21 simulations obtained by running the model with the 21 different initial population density values. When the reduction in population density reaches the dotted gray diagonal line, the population is reduced to zero. Drought intensity increases from the bottom to top row and drought duration increases from the left to right column.

From Fig. 5 we may conclude that the society is able to cope with droughts of low intensity at low population densities. The initially horizontal lines along the x-axis indicate that no reduction in population takes place. Only when initial population density levels approach maximum levels (and hence come close to the carrying capacity), droughts start to show an impact on population growth. The panels clearly show that reservoirs allow society to prolong growth as higher initial population density levels (blue) are reached (the blue horizontal lines along the x-axis are stretched to the right). The maximum population density level for the society without reservoirs (red) lies around 15% below the population density levels of a society with reservoirs (blue). When this effect seems small, please note that dynamics are simulated for a unit area. The figure also shows that reservoirs mitigate the impact of droughts. This is most clearly visible for short duration (1 to 5 years), low to medium intensity (−14 to −20%) droughts. For these cases, a society with reservoirs (blue) that has reached the same initial population density as a society without reservoirs (red) experiences a lower reduction in population density or no impact at all. The mitigating effect of reservoirs dissipates when the society that builds reservoirs grows to higher population density levels compared to the society without reservoirs. Neither is the mitigating effect of the reservoirs present for long-term, severe reductions in precipitation. The impact on population is devastating for all levels of population in case of high-intensity droughts lasting 5 to 20 years and high intensities of droughts (exceeding −30%) (Panels on the top, right corner).

Fig. 6 shows the recovery time in years (y-axis) for each reduction in normalized population density (x-axis). Drought intensity increases again from the bottom to top row and drought duration increases from the left to right column. When recovery does not take place within the total simulation time, points are not included. Overall, recovery time increases exponentially with increasing drought impact. Also, the advantage of reservoirs can be observed, albeit minimal. One reason for this observation is that population growth is responding logistically to food availability. Once enough food is available, population grows at a constant rate, exogenously determined by factors other than water. Moreover, it might be that population is too severely impacted after a drought to maintain the reservoirs. Labor is insufficient and the reservoirs are assumed to silt up or degrade over time.

4.1.2. The Impact of Two Consecutive Drought Events

To illustrate what happens when a society is exposed to two consecutive droughts, we present the development of population density N over time ($N_{initial}$ = 120 persons per km^2) for a society without reservoirs (Fig. 7a, b) and for a society with reservoirs (Fig. 7c, d). In addition, we present the actual development of reservoir capacity R (Fig. 7e, f). The gray vertical lines indicate the times at which drought 1 and 2 take place. In the left column, the first drought has an intensity of −20%; in the right column, the first drought has an intensity of −30%. The intensity of the second drought is indicated by the color of the line. Green represents a drought of −14%, blue of −20%, yellow of −30% and red of −40% intensity.

Considering Fig. 7a and c, we observe that the first drought of −20% intensity causes stagnation of population growth, but does not lead to a significant reduction. Subsequently, for the society without reservoirs (Fig. 7a), the second drought does lead to a significant impact that increases with increasing drought intensity. A society that builds reservoirs (Fig. 7c, e) on the other hand, escapes the drought impact in case of a second drought of equal (blue) or lesser intensity (green), and experiences a reduced impact as a consequence of the higher intensity (yellow) second drought.

Considering Fig. 7b and d, we observe that the first drought of −30% intensity leads to a reduction in population density. As population density levels after the first drought remain higher for Fig. 7d compared to Fig. 7b we may conclude that reservoirs mitigate the impact. Fig. 7f confirms this. Subsequently, the second drought of the same intensity (yellow) has a lower impact for both societies. On the other hand, the higher intensity drought (red) results in a slightly higher impact for the society with reservoirs (Fig. 7d) compared to the society without reservoirs (Fig. 7b).

The impact of each drought is thus the result of the interplay between the intensity of the drought and the initial level of population. This is

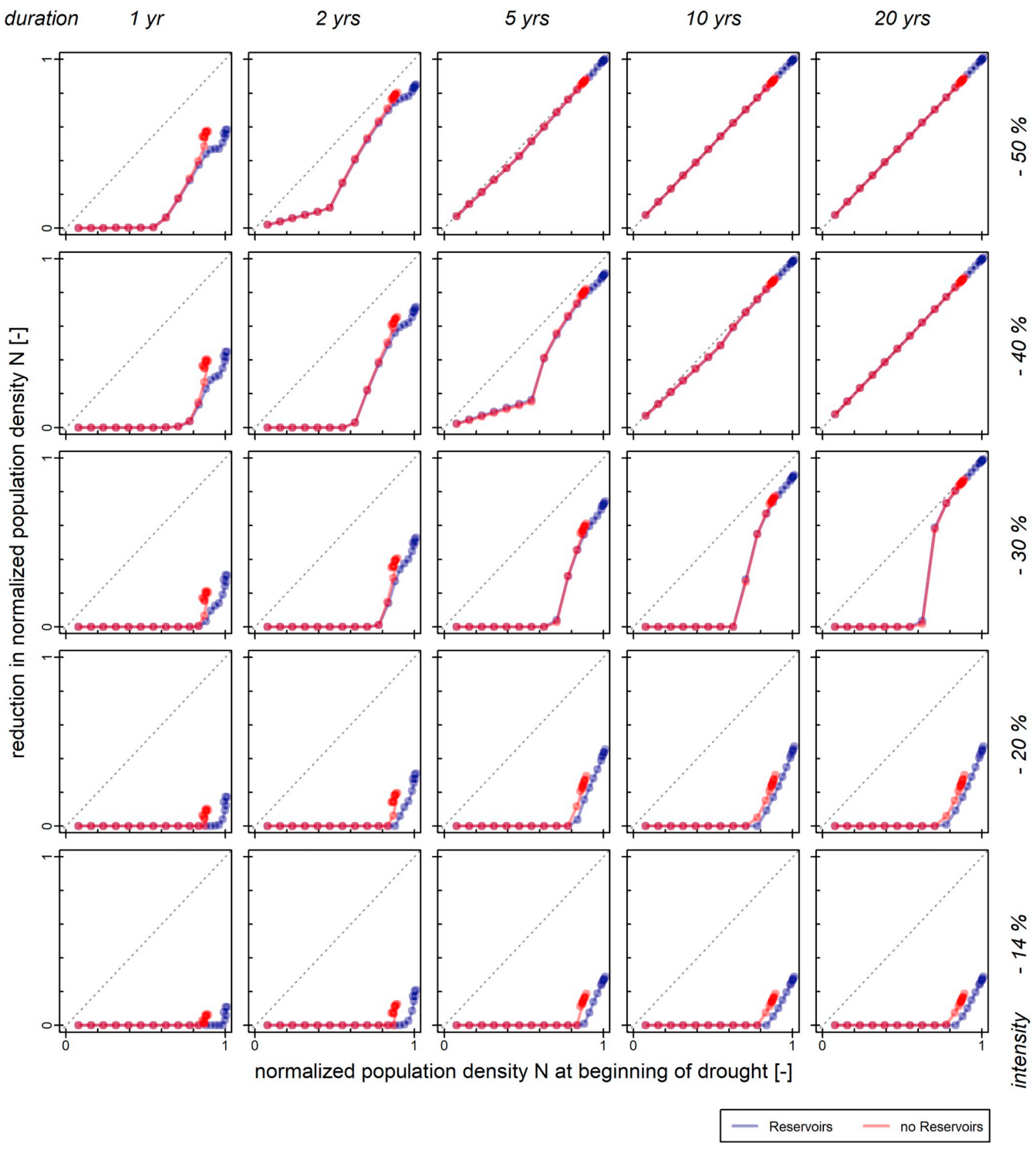


Fig. 5. The impact of the different droughts on the society without (red) and with reservoirs (blue). The x-axis depicts the normalized population density N [−] the society has reached at the beginning of a drought, calculated as $\frac{N_{t=1}}{K}$, where t = 1 represents the onset of the drought and K is carrying capacity. The y-axis depicts the reduction in normalized population density as a consequence of the drought, calculated as $\frac{N_{t=1}-N_{t=2}}{K}$, where t = 1 represents the onset of the drought and t = 2 represents the instance the minimum population level is reached directly after the drought. Drought duration increases when moving from left to right across the figure, while drought intensity increases from bottom to top. The carrying capacity population density level K is set at 210 persons per km^2 and represents a society making use of reservoirs at mean annual rainfall of 1800 mm/year. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

clearly illustrated by the two droughts of −20% (blue) in Fig. 7a and the two droughts of −30% (yellow) in Fig. 7b. A similar drought has a larger impact if population density is higher, while if society has reduced its water demands as a consequence of the first drought, the impact of the second drought is less severe. Secondly, society can mitigate the impact of a drought through adaptation, as shown in Fig. 7c. At the same time, the figure illustrates that there are limits to the adaptive measure. If the water surplus is insufficient to overcome the drought, its impact will be

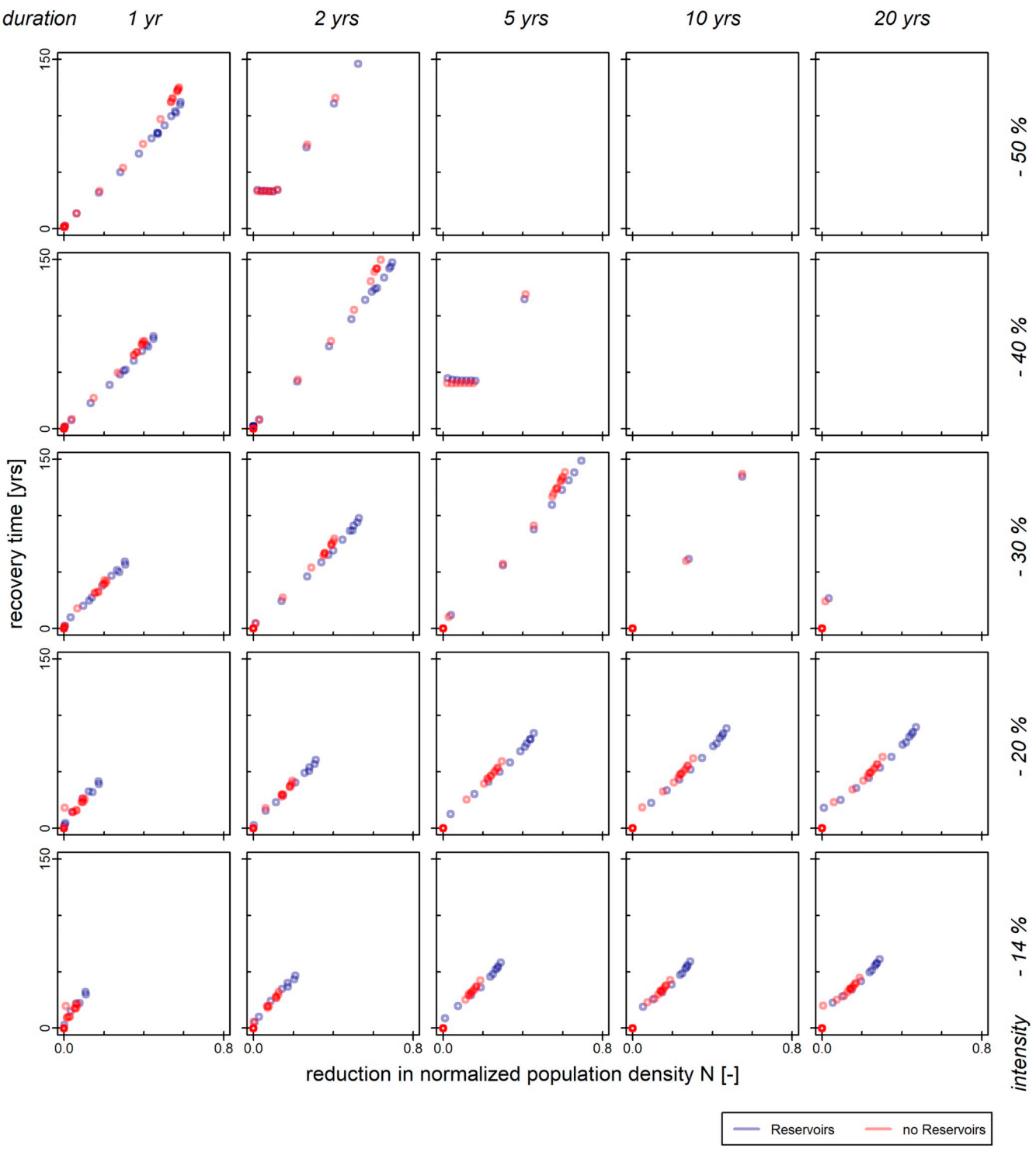


Fig. 6. The time it takes to recover to pre-drought population levels for the society without (red) and with reservoirs (blue), for different droughts. The x-axis depicts the reduction in normalized population density (equal to the y-axis of Fig. 5 and calculated as $\frac{N_{t=1}-N_{t=2}}{K}$). The y-axis depicts the time in years it takes to recover. Similarly to the previous figure, drought duration increases when moving from left to right across the figure, while drought intensity increases from bottom to top. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

felt equally or even more severely. A higher impact is felt if, due to reservoir construction, society has grown to higher population densities at the time of the drought. This can be seen in Fig. 7d (red).

Model dynamics are further illustrated in Fig. 8, which shows food ability (FA), vulnerability (V), normalized population density N (N_n) and normalized carrying capacity K (K_n) for the case in which a first drought of −20% intensity is followed by a second drought of −30% intensity (Fig. 8a without reservoirs, Fig. 8c with reservoirs) and the case in which a first drought of −30% intensity is followed by a second drought of −30% intensity (Fig. 8b without reservoirs, Fig. 8d with reservoirs). The cases are the same as the yellow simulations in Fig. 7.

In all panels it can be seen that food availability (yellow) is at a comfortable level (FA > 0 indicates a food surplus) at the start of the simulation, but starts to decrease after a period of population growth.

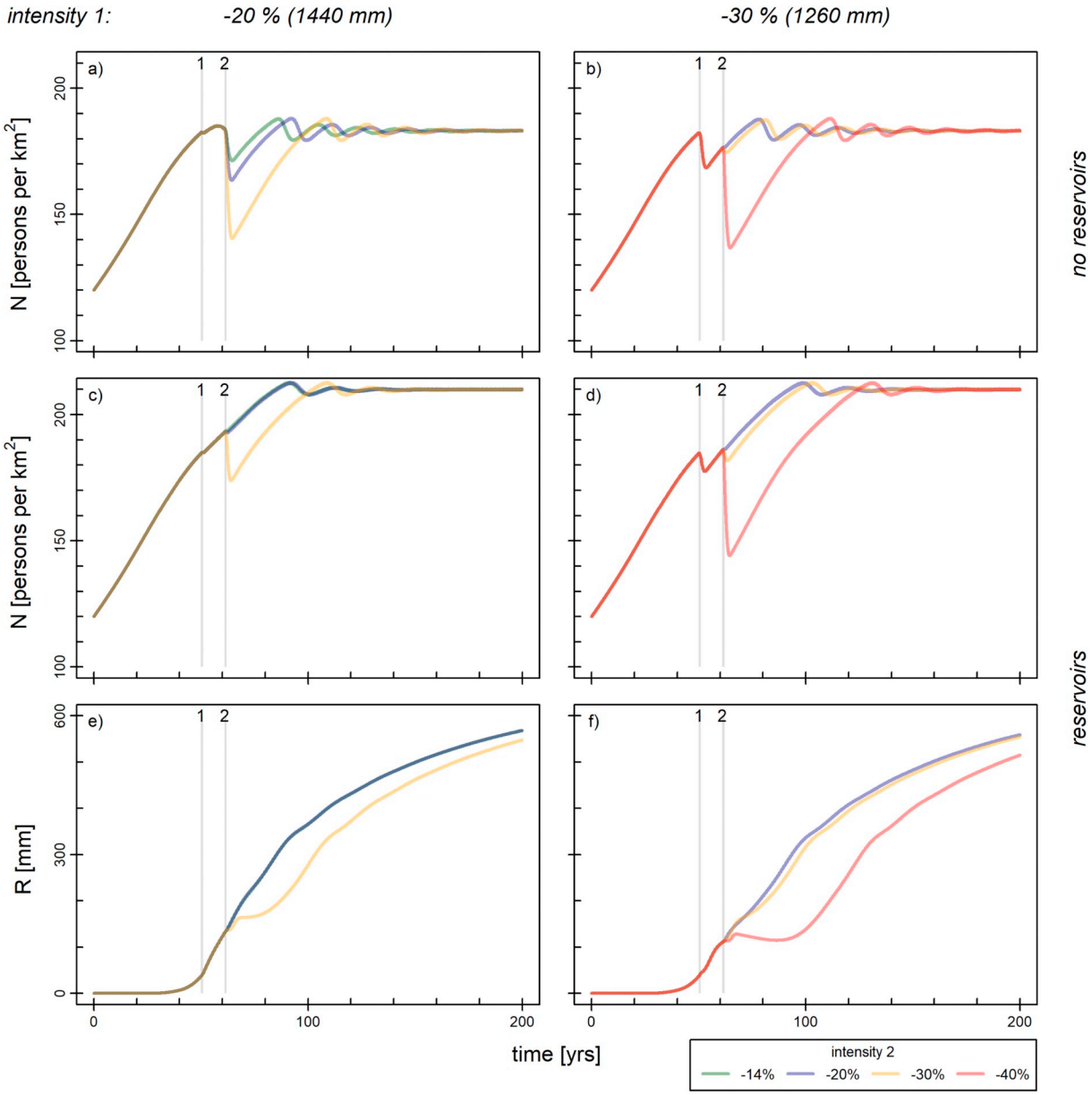


Fig. 7. The impact of two consecutive droughts. In the left column the intensity of the first drought is −20%, in the right column the intensity of the first drought is −30%. The colors represent the intensity of the second drought (see legend). The times at which each drought occurs are indicated by the gray vertical lines. Panels a to d show the development of N during a 200 year period, where a and b represent a society without reservoirs and c and d a society with reservoirs. Panels e and f show reservoir development corresponding to c and d, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Consequently, a slight rise in vulnerability (red) occurs before the onset of the drought (which also motivates the society with the technology to build reservoirs to start constructing them). When a drought occurs, crops experience water stress and food production goes down, causing food availability (yellow) to fall below 0 indicating a food shortage. This is reflected by a decrease in carrying capacity during the drought (gray). Consequently, vulnerability V (red) rises sharply. Now, the resulting dynamics depend on the drought duration and intensity that determines the magnitude of water shortage, on the actual population density levels that determine the dependence of the society on the water resources and on reservoir storage that determines to what extent the society can mitigate the water shortage. In Fig. 7a and c the first drought results in a rise in vulnerability, but not to such extent that a crisis breaks out. At the onset of the following drought more people depend on the water resources and the drought is more intense, causing V to approach 1. Consequently, people start to actively leave the area (or starve due to increased mortality), especially in case of a. In case of c, one can observe that reservoir construction has lessened the impact of the drought and that carrying capacity levels have slightly increased. The crisis is therefore less severe. For Fig. 7b, the first drought of −30% intensity has caused a decline in population density. Hence, when the next drought occurs, the food shortage is less severe, population density levels do not significantly exceed carrying capacity and a crisis can largely be avoided. Fig. 7d shows that the impact of both droughts is mitigated (both impacts are small) due to the continued reservoir construction that is still resulting in an increase in carrying capacity levels (gray).

4.2. Stochastic Drought Exposure

4.2.1. The Impact of a Drier Climate

Fig. 9 shows a summary of model simulations when the society is, from 829 CE onwards, subject to the 'normal' climate (blue), and when

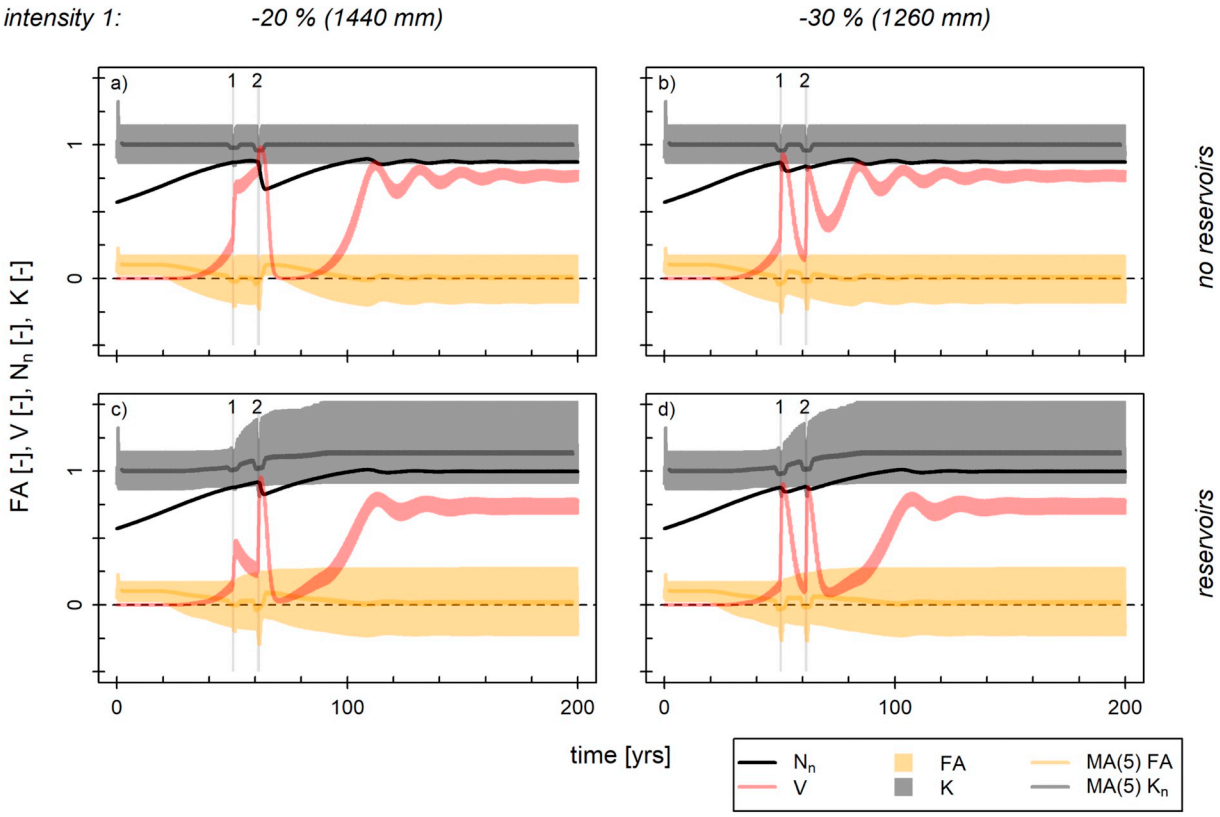


Fig. 8. Development of food availability FA, vulnerability V and normalized carrying capacity K (K_n), in addition to normalized population density N (i.e. N_n) for the two concecutive droughts that were presented in yellow in Fig. 7. The gray vertical lines (1,2) indicate the timing of the droughts. Panels a and c show the impact of a drought of −20% intensity followed by a drought of −30% intensity for a society without (a) and with reservoirs (c). Similarly, panels b and c show the impact of two droughts of −30% intensity for a society without (b) and with reservoirs (d). The widths of FA, K_n and V represent seasonal variability. For clarity, a 5 year moving average is presented for FA (MA5 FA) and K_n (MA5 K_n) as well. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the society is subject to the drier climate (red). When population density level N is plotted over time (Fig. 9a), we can observe that in both climates population levels of > 200 persons per km^2 can be reached. When comparing the median population density levels of the two climates (bold lines), population density drops by almost 30% for the drier climate indicating that it is less likely for the area to be able to sustain the original population densities. This also becomes apparent from Fig. 9b. For each of the 100 simulations we selected the maximum decline in population density during the period between 829 and 1020 CE. Subsequently, we divided these population declines by the population density level at the start of the drought, such that a decline of 100% implies that the initial population has been reduced to 0. We then estimated the probability density for the selected 100 declines experienced during the normal climate (blue), and for the selected 100 declines experienced during the drier climate (red). Considering the relatively high probability density values for reductions in population of > 50%, Fig. 9b shows that a severe population decrease within the 200 year period was already likely under the prevailing climatic conditions and becomes even more likely when the society is facing a drier climate.

4.2.2. The Impact of a Drier Climate Under Various Adaptation Strategies

Fig. 10 shows a summary of population density levels for different adaptation strategies when the society is, from 829 CE onwards, subject to the 'normal' climate (left column) and when the society is subject to a drier climate characterized by a lower mean annual precipitation and an increase in drought duration and severity (right column).

Fig. 10a and b present population dynamics when the society would have behaved proactively to reduce resource pressure by slowing down its population growth. From panels a and b it can be concluded that the overall dynamics with the adoption of more proactive behavior do not substantially change. While it is possible for society to reach densities of 200 people per km^2 or more, the medians indicate that these levels are generally unsustainable in the long run. Also here, median population density levels are lower for the drier climate than for the 'normal' climate. Thus, unless the adoption of proactive behavior leads to a substantial reduction in population density from the population density level reached around 829 CE to a population level comparable to the median, it is still likely that the society will be impacted by one or more drought events.

The presence of a global food network, which effectively reduces the local per capita water demand by 75%, alias 75% virtual water, (Fig. 10c, d) has a much higher influence on population dynamics. Under the 'normal' climate, it is likely that the society would have been able to grow for another 100 years (counting from 829 CE) experiencing minimal resource pressure. Hereby, it is able to triple its population density. Under the drier climate, society is also able to grow but experiences resource pressure already after 50 years as the widening of the quartiles illustrates. For both climates, however, overshoot and collapse behavior is visible before society settles at a more sustainable population density level.

The introduction of virtual water in combination with reduced population growth seems most effective in reaching stable population density levels (Fig. 10e, f). Also here the effect of a drier climate is noticeable, as resource pressure impacts population earlier and population density levels are lower, when panel f is compared to e. The overshoot and collapse behavior seems to be largely avoided as is shown by the more stable median in Fig. 9f compared to Fig. 9d.

To analyze the impact of the adaptation strategies on the chance that the society would have experienced a major population decline, we

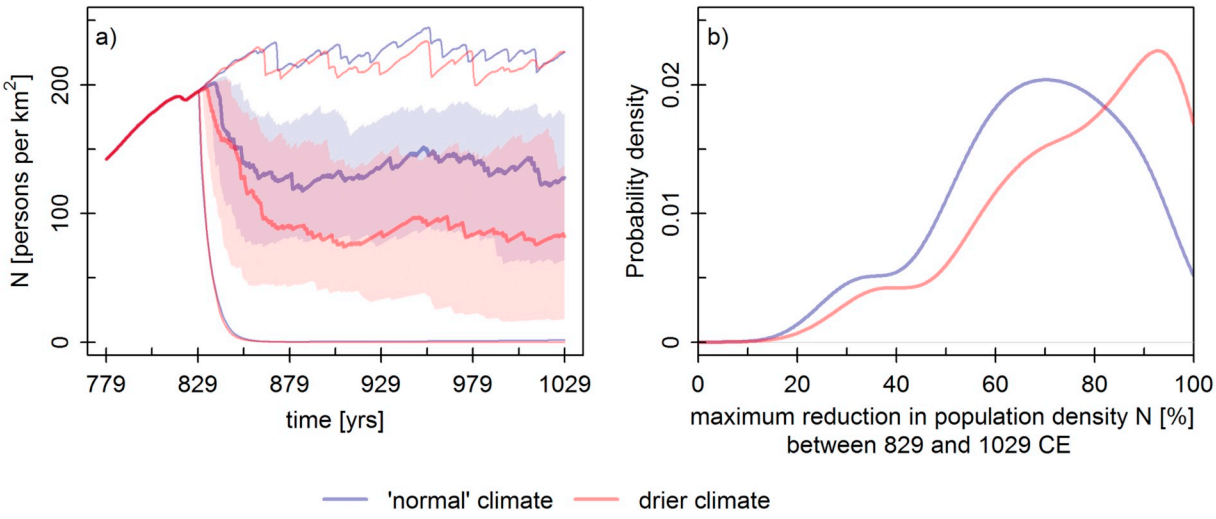


Fig. 9. The impact of different precipitation series on population dynamics. Panel a shows a summary of population density levels N during 779 to 1029 CE based on the 100 simulations for each climate. Blue respresents a society subjected to stochastically generated rainfall corresponding to the 'normal' climate, red to the 'drier' climate. For the first 50 years, original precipitation levels have been used. The panel shows the median of the generated population density levels (bold line), the quartiles (outlines of the shaded area) and the min and maximum values (plain lines). Panel b shows the distribution of the maximum population declines experienced within the 200 year period from 829 to 1029 CE based on the 100 simulations corresponding to the normal climate (blue), and similarly corresponding to the drier climate (red). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

estimate, based on the same approach as in Section 4.2.1, the probability density of maximum population declines between 829 and 1029 CE when society is exposed to the 'normal' climate and to the drier climate. Fig. 11 shows, similarly to Fig. 9b, each of these distributions, i.e. for the base scenario (gray, dashed), for the society that proactively reduces population growth (red), for the society that effectively imports water through trade (blue), and for the society that is able to import virtual water through trade as well as manage its population (black). While we observe that the chance of experiencing a major environmental shock is reduced with each of the adaptation strategies adopted, the pattern is not truly reversed until the society is able to rely on virtual water for 75% of its demand and adopts a more pro-active approach to scarcity by reducing its population growth rate (black). Still, the risk of a major impact from the onset of a drier climate is increased, as in the left panel (the 'normal' climate) the highest densities are found for around a 0 to 10% reduction in population density, while for the right panel (the drier climate) the density is more equally spread. Measures that are highly effective in mitigating water scarcity under a 'normal climate' are still effective under a drier climate, but less so, as the additional climate burden needs to be overcome as well.

5. Discussion

The aim of this paper was to examine the relationship between drought and population dynamics. We used a socio-hydrological model in which hydrology and demography are coupled that has been calibrated to simulate plausible dynamics for the Ancient Maya civilization (Kuil et al., 2016). We presented societal responses when subject to droughts of different intensities and durations, and gave insight into possible long-term dynamics of the society when subject to stochastically generated rainfall series to represent conditions before and after 819 CE, respectively. The rainfall series differ in mean annual rainfall and in the intensity and severity of droughts that occur.

We find that a society is impacted by a drought as soon as a critical threshold or population density is exceeded. Before this threshold, the society is relatively unaffected by droughts, while, after crossing this threshold, the society becomes vulnerable. To what extent increased vulnerability results in crisis and population decline is, among others, dependent on the intensity and duration of a drought. We have demonstrated societal response for droughts of selected durations and intensities, but in principle the observed dynamics may occur at any resource level at which direct and indirect water demands exceed water supply. The model results therefore underline the observation of Ginnetti and Franck (2014), who concluded that displacement of people can occur even if rainfall is close to mean rainfall.

The socio-hydrological feedback loop present in this model can also be compared to the feedback loop present in general population resources models for a slow growing resource stock, such as forests (Brander and Taylor, 1998; Nagase and Uehara, 2011). In these models, conservation of the environment will occur if a society's ability or willingness to harvest is low and the region is scarcely populated (Anderies, 2000). On the other hand, high population levels in combination with a high harvesting rate, might lead to more resources being harvested than the resource stock can regenerate within a given time period, ultimately resulting in resource scarcity leading to population decline. In our socio-hydrological model, socio-environmental functioning is guaranteed as long as a society's direct and indirect water demands (in the model captured by water dependent agricultural production) are lower than that which nature is able to provide, also in case of a drought. When, however, a drought causes agricultural yields to fall below demand, a crisis might break out. An additional feature of the model presented here is that the primary resource directly depends on rainfall, which is highly variable. Consequently, simulated behavior is more volatile and may include more abrupt transitions from a seemingly non-vulnerable society to one that is vulnerable.

The model results show that humans can interact with the system in such a way that they alter the timing of a resource crisis or its impact. By storing water in reservoirs and releasing it during a drought, we have demonstrated that reservoirs are able to temporarily mitigate the loss in carrying capacity that would have occurred without additional storage. Consequently, a drought may not affect society. Results also show that benefits decrease rapidly when the drought becomes too severe, or when the population has grown too large so that it relies on the reservoir water not as an emergency resource, but on a permanent basis. In this case, reservoirs make the society more vulnerable to droughts instead of less vulnerable, which may result in more severe population declines. This has been hypothesized by Lucero (2002), highlighted in Kuil et al. (2016) and has been analyzed more generally by Pande et al. (2014). When we considered global food trade, model results changed significantly. Effectively importing virtual water

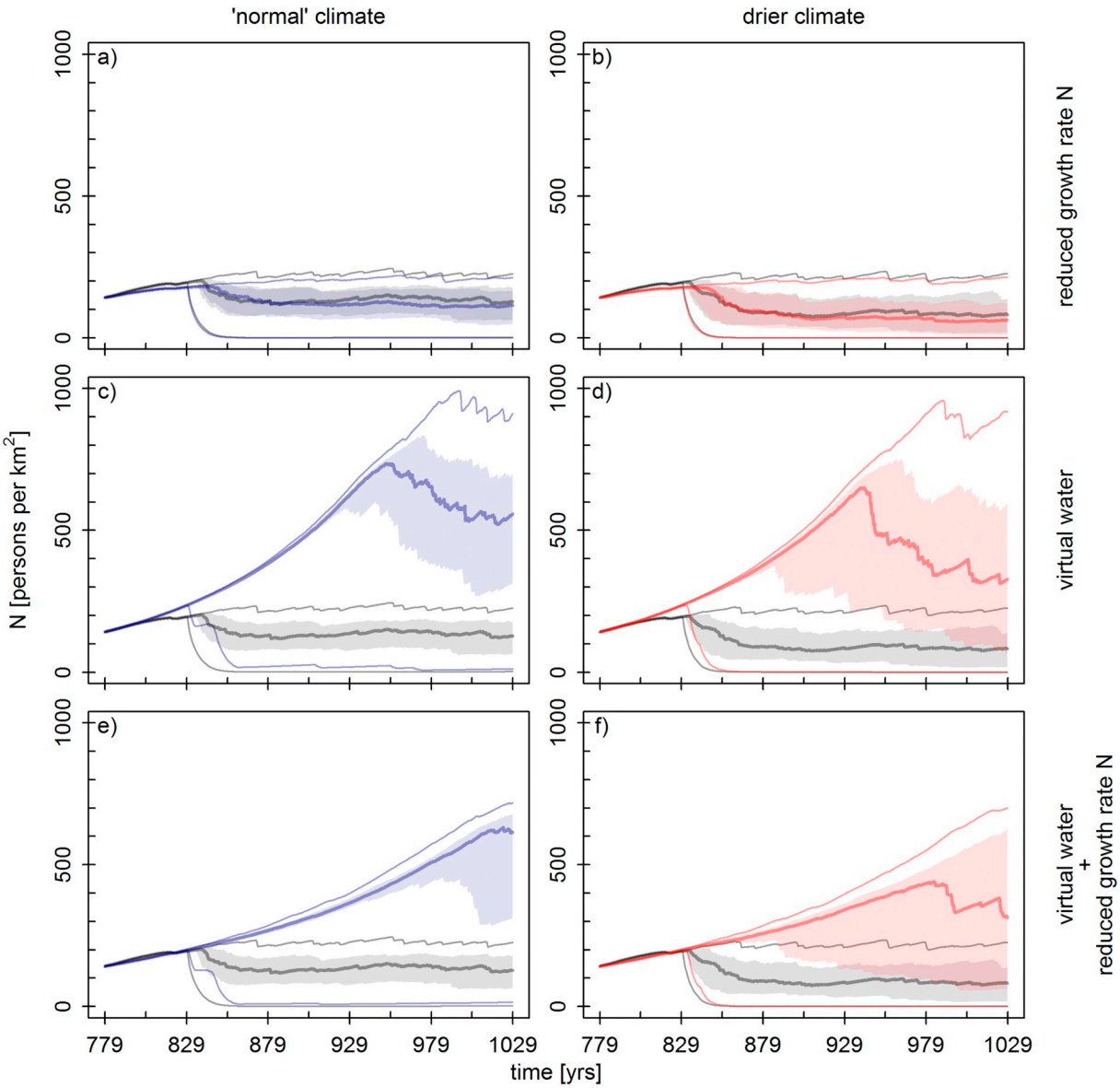


Fig. 10. The influence of alternative adaptation strategies, i.e. reduced population growth rate, virtual water, and reduced population growth rate and virtual water combined, on population development for a society experiencing a 'normal' climate (left column) and a drier climate (right column). Each of the panels shows the median (bold), quartiles, and minimum and maximum population densities reached summarized for 100 simulations. All panels include the baseline dynamics as presented in Fig. 9 for comparison in gray. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

(Hoekstra and Chapagain, 2006), the Maya civilization could have extended its period of growth another 50 to 100 years, ceteris paribus, in which it was relatively unaffected by droughts and scarcity. Local population density levels could have continued to increase at an (near-) exponential rate. Model results also showed, however, that boom and bust behavior would have been delayed and not prevented. Only for a more pro-active society, which acknowledges that there are limits to water resources and is able to slow down its population growth in time, overshoot and collapse behavior is less likely. These findings are in line with the qualitative behavior reported by Anderies (2000) and by Reuveny and Decker (2000). They also underline the findings of Pande et al. (2014), who demonstrate through a simple model of endogenous technological change that technological change in fact delays a society's response to change under increasing water scarcity, as it may give a (false) impression that it is in control of nature.

Lastly, the simulations showed that for a society to be as food secure at the level of pre-climate change population density, increased efforts would have to be undertaken to not only increase the region's carrying capacity to match its population growth, but also to overcome the additional loss of resilience due to climate change. If the Ancient Maya indeed faced such a change in climate, their chances to overcome water scarcity decreased significantly. Since the primary resource in our model directly depends on highly variable rainfall, simulated behavior is volatile and may include abrupt transitions from a seemingly non-vulnerable society to one that is vulnerable.

We recognize that the model is stylized and that the full complexity of the world has not been captured. Water stress within agricultural systems is not only determined by precipitation, but also by crop responses to temperature and CO_2 levels (Wiltshire et al., 2013). In practice, water use and management will be influenced by the political, social, economic and administrative system in place. Thus while the effect of reducing population growth or a net virtual water import can be illustrated through the modeling framework, the actual success of these measures will depend on how well a society is able to adapt and accommodate the proposed solutions. For example, in absence of compulsory birth control, fertility behavior would have to change

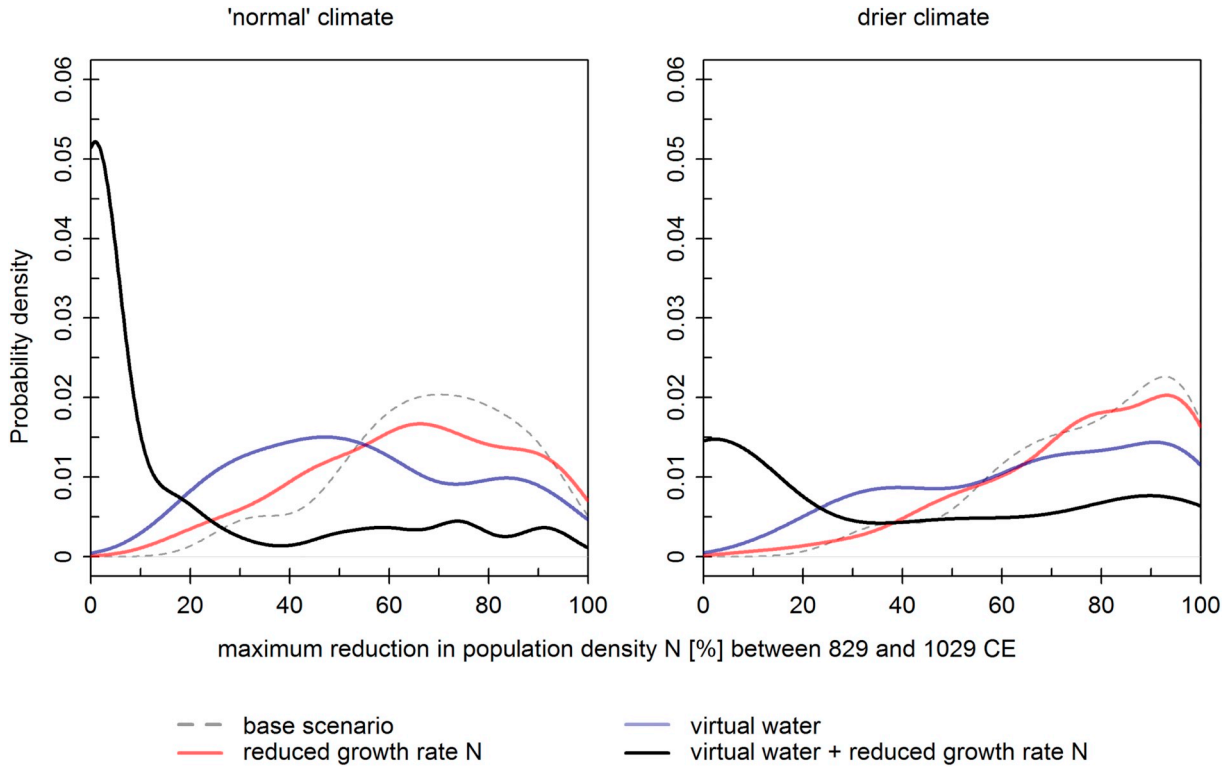


Fig. 11. Distributions of the maximum reduction in population density experienced within the 200 year period from 829 to 1029 CE for each of the adaptation strategies (reduced growth rate N, virtual water and virtual water + reduced growth rate N) when society is exposed to a 'normal' climate (left) and to a drier climate (right). The maximum population decline within the 200 year period has been selected for each simulation, such that one probability density is estimated based on 100 values. The decline in population is expressed relative to the initial population level at the onset of the drought. At a reduction of 100% the population fully collapses.

autonomously. In practice, this decision depends on many factors including the costs and benefits children bring, broad economic factors, but also the norms and values an individual or society adheres to (Joëlle, 2003). In order to be able to sustain net water import, the Maya would have to have an alternative resource or product that could be traded as well as the means to support trade across large distances. Also, in order for trade linkages to emerge, water scarcity conditions would have to be profoundly different between the trading partners (Pande and Ertsen, 2014). While it is known that the Ancient Maya participated in trade, no evidence is found for large scale food trade and likely transport constraints have played a role (Dahlin et al., 2007; Turner, 2000, p. 252). Nevertheless, the conclusions of this work are highly relevant for today's society.

At present, a number of countries have external water footprints larger than 70% (Mekonnen and Hoekstra, 2011). For some countries, like the Netherlands or the UK, this dependency is not by necessity. For other countries like Malta, Jordan or Israel domestic freshwater availability is scarce and large populations are only possible because the majority of food is imported (Mekonnen and Hoekstra, 2011). The stability of these trade relations is thus important to ensure development and stability of these countries. Similarly, for countries that are highly dependent on their own water resources for agricultural productivity, fluctuations in rainfall can have major impacts. While for some regions changes in temperature and precipitation are likely resulting in higher productivity, declines in food yield have been projected for other regions, including many developing countries (Lobell et al., 2008; Parry et al., 2004). It is likely that climate variability and change will exacerbate food insecurity in areas currently vulnerable to undernutrition (McLeman, 2011; Wheeler and Von Braun, 2013). Models like the one presented in this paper may thus help to illustrate the possible effects from changes in climate and explore the pathways to alternative, sustainable trajectories of population development. Analogous to the work by Ginnetti and Franck (2014) for parts of Africa, the model may provide a basis to understand the mechanisms behind environmentally induced migration related to drought events. In this regard, one should not only look at a region's internal economy but also at the economy of the destination region, as migration will be affected by the difference in attractiveness between the two regions (Roobavannan et al., 2017). Further development and testing of the model is necessary, as actual impacts will be modified by food access, utilization and stability dimensions of food security in addition to the actual availability of food (Wheeler and Von Braun, 2013).

6. Conclusions

The relationship between drought events and population dynamics has been examined using a stylized hydrology-demography model that has been calibrated to simulate plausible feedbacks for the Ancient Maya. We find that the impact of a drought on society increases abruptly as soon as a critical threshold or population density is exceeded. The critical level of this threshold depends on the intensity and duration of the drought as well as on technology adopted by society, markets, norms and institutional arrangements. In particular we explored the impact of reservoirs, the influence of virtual water and proactive behavior towards resource scarcity. Although technological progress may move the threshold upwards, it will not disappear. Model simulations show that for a society to be as food secure post-climate change as they are pre-climate change, strategies would have to be adopted to not only increase the region's capacity to provide sufficient resources for its growing population, but also to buffer the impact of a drier climate on productivity. If the Maya would have had access to virtual water trading at the scale that occurs today and would have combined this with a more proactive response aimed at reducing the population growth rate, the chance of a severe impact occurring would have been reduced, ceteris paribus.

Acknowledgements

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Appendix A

Table 1
Socio-hydrological drought processes conceptualized. The table presents an overview of model equations and parameters. The parameter values correspond to Fig. 2. A detailed explanation can be found in Kuil et al. (2016).

State var.	Equation	Ref	Parameter (Unit, Meaning, Value)
Hydrology			
S [L] water storage	$\frac{dS}{dt} = \frac{d(S_S+S_R)}{dt} = P - ET_{crops} - ET_{native} - E_R - Q$	1a	α_H [L T^{-1}] max ET rate 200 β_H [L T^{-1}] max ET rate 200 γ_H [T^{-1}] evaporation rate R 0.04 ϕ_H [L] field capacity 195 δ_H [-] runoff coeff. 0.5 ε_H [-] runoff coeff. 10 η_H [-] overflow R 500 ζ_H [-] overflow R 0.98 μ_N [-] land to person ratio 1.25
	$ET_{crops} = \alpha_H \frac{S_S}{\varphi_H} \min\left[1, \frac{\mu_N N}{K}\right]$	1b	
	$ET_{native} = \beta_H \frac{S_S}{\varphi_H}\left(1 - \min\left[1, \frac{\mu_N N}{K}\right]\right)$	1c	
	$K = \overline{S_S}/\gamma_N = 0.5\left(S_S + S_{S,t-c}\right)/\gamma_N$	1d	
	$E_R = \gamma_H S_R$		
	$Q = P \frac{1}{1+e^{-\varepsilon_H\left(\frac{S_S}{\varphi_H}-\delta_H\right)}} \frac{1}{1+e^{-\eta_H\left(\frac{S}{\varphi_H+R}-\zeta_H\right)}}$	1e	
Demography			
N [persons L^{-2}] population density	$\frac{dN}{dt} = (b-d)N$	2a	α_N [T^{-1}] base growth rate 0.003 θ_N [T^{-1}] birth rate 0.00095 ε_N [T^{-1}] mortality rate 0.0012 β_N [-] behavioral threshold -0.1 δ_N [-] adjustment speed 0.5 γ_N [L T^{-1} person^{-1}] water demand per person 0.6 η_N [-] response to V 15 ζ_N [-] response to V 4.5 θ_H [-] yield response factor 1.25
	$b = \alpha_N + \frac{\theta_N}{1+e^{-\delta_N(FA-\beta_N)}}$	2b	
	$d = \left(\alpha_N + \frac{\varepsilon_N}{1+e^{\delta_N(FA-\beta_N)}}\right)(1+\zeta_N)V^{\eta_N}$	2c	
	$FA = -\frac{\alpha_H\left(\left(\left(1-\frac{S_S}{\varphi_H}\right)\theta_H\right)-1\right)\min\left[1,\frac{\mu_N N}{K}\right]}{\gamma_N N + \alpha_R N M V(1-V)} - 1$	2d	
Vulnerability			
V [-]	$\frac{dV}{dt} = -FA\,(V - min[0, FA])(1-V)$	3	
Supply management			
R [L] reservoir capacity	$\frac{dR}{dt} = \alpha_R N M V(1-V) - \frac{\beta_R}{N} R$	4	α_R [L T^{-1} person^{-1}] building rate per person 0.01 β_R [person T^{-1}] degradation rate 0.1
Societal knowledge			
M [-] memory	$\frac{dM}{dt} = \frac{S}{\varphi_H + R} - \alpha_M M$	5	α_M [T^{-1}] forgetting rate 0.3

Model summary

Hydrology is conceptualized by a simple water balance equation for a unit area (Table 1, Eq. (1)). Total water storage per unit area, S [L], is the outcome of inflow, i.e. precipitation (P), and outflows, i.e. evapotranspiration from the cultivated area ET_{crops}, evapotranspiration from the natural vegetated area ET_{native}, evaporation from the reservoir E_R, and runoff Q, which is the sum of runoff from the land Q_R and spillovers from the reservoir Q_S. S is composed of the soil moisture storage per unit area, S_S [L], and the water that is stored in the reservoir, S_R [L]. Both storage capacities are essentially limited by a maximum, respectively field capacity, φ_H [L], and reservoir storage, R [L]. Evapotranspiration rates, as well as runoff, are maximum when soil moisture is at field capacity and decrease when water stress occurs. The simplifying assumption is made that water moves from

the reservoir to the soil, as long as the soil is below field capacity, i.e. irrigation takes places in order to keep the water content optimal. Only when water storage is larger than field capacity, water is stored in the reservoirs. Lastly, it is assumed that the community cultivates the land proportionally to their inhabitants, expressed by the fraction min[1, $\mu_N N/K$]. If the area is densely populated and population N ≥ carrying capacity K, the unit area is fully cultivated and the fraction equals 1. If population N ≪ carrying capacity K, the fraction of land that is cultivated equals $\mu_N N/K$, whereby a higher land to person ratio (μ_N) increases the availability food (surplus). Carrying capacity K is dynamic and depends on the average soil moisture available and the water demand needed per person.

Population dynamics are represented by N and measured as the number of people per unit area [persons L^{-2}] (Table 1, Eq. (2)). b is the per capita birth rate and d the per capita death rate. Both rates vary depending on food availability FA, which is calculated as the ratio between the food produced (yield, determined by ET_{crops}) and the food need of the community (determined by the average food need per person times the number of people and the additional costs needed when building reservoirs) (Eq. (2)d). Overall, in line with Malthus' theory (Malthus, 1798), the population equation allows for both a preventing check and a positive check to occur. The preventive check occurs when society gradually adjusts its net growth rate in response to food shortage. In case of long-term food shortage and/or gradual, preventive adaptation occurring to slow, the vulnerability V of the community increases (Table 1, Eq. (3)). The increase in vulnerability may lead to a positive check, which could be famine, conflict and/or emigration. The value of V varies between 0 and 1, where 0 represents a nonvulnerable community (that can easily cope with a sudden change in precipitation) and 1 a vulnerable community (that experiences a shock and possibly collapse, for the same drop in precipitation) (Füssel and Klein, 2006; Downing et al., 2005).

Reservoirs, referred to in this context, are structures that are built off-stream and capture water through harvesting rainwater (Table 1, Eq. (4)). We aim to capture that for the construction of reservoirs, R, labor (N) is needed (Boserup, 2011) and that reservoirs are constructed in response to a crisis (V), creating a window of opportunity (Birkmann et al., 2010). Lastly, reservoir construction will slow down when the community becomes aware (M) that additional reservoir capacity is no longer filled. Memory (M), as used here, represents local knowledge on the average water availability in the area and is represented by the ratio of actual storage to storage capacity (Table 1, Eq. (5)).

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