

Agent-based simulation of Holocene monsoon precipitation patterns and hunter-gatherer population dynamics in semi-arid environments

A. L. Balbo^{a,*}, X. Rubio-Campillo^b, B. Rondelli^a, M. Ramírez^c, C. Lancelotti^a, A. Torrano^b, M. Salpeteur^d, N. Lipovetzky^e, V. Reyes-García^{f,d}, C. Montañola^{g,b}, M. Madella^{f,a}

(a) Complexity and Socio-Ecological dynamics (CaSEs, www.cases-bcn.net), Istitució Milà i Fontanals, Spanish National Research Council (IMF-CSIC), C/Egipcíacs 15, 08001 Barcelona, Spain

(b) Barcelona Supercomputing Centre (BSC), Nexus II Building, C/Jordi Girona, 29, 08034 Barcelona, Spain

(c) School of CS & ITRMIT, University of Melbourne 3001 Victoria Australia

(d) Institut de Ciència i Tecnologia Ambientals, Universitat Autònoma de Barcelona (ICTA-UAB), Edifici C Campus de la UAB, 08193 Bellaterra (Cerdanyola del Vallès), Barcelona, Spain

(e) Dept. of Computer Sci. & Software Eng., University of Melbourne, Victoria, Australia

(f) Catalan Institute of Research and Advanced Studies (ICREA)

(g) Departament d'Estadística i Investigació Operativa, Universitat Politècnica de Catalunya (EIO-UPC), C/Jordi Girona, 1-3, 08034 Barcelona

*Contacts: balbo@imf.csic.es, Telephone: +34 617 138 396, Fax: +34 934 430 071

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Abstract

Based on archaeological evidence from Kutch-Saurashtra (N Gujarat, NW India), we use Agent-Based Modelling (ABM) to explore the persistence of hunter-gatherer (HG) groups in semi-arid environments in the mid and late Holocene. Agents interact within a realistic semi-arid environment dominated by the monsoon. Precipitation trends are modelled from instrumental records (1871 - 2008) calibrated with existing models for the Asian monsoon in the Holocene (c. 12 ka - present). Experiments aim at exploring dependencies between population dynamics and climate-driven environmental change (in terms of resource availability) for precipitation patterns at the local, regional and continental scales. Resources are distributed across a simplified ground-model. Average yearly precipitation (AYP, i.e. mean) and variance in yearly precipitation (VYP, i.e. standard deviation) are the main parameters affecting resource availability in the simulations. We assess the effects of environmental change on HG populations at different time-scales: (1) Patterns of seasonal (inter-annual) resource availability, (2) Effects of changes in mean precipitation trends over the long (Pleistocene-Holocene) and the mid (Holocene, millennial) periods, and (3) Effects of intra-annual precipitation variability, i.e. changes in standard deviation from mean precipitation trends over the short period (annual to decadal). Simulations show that: (1) Strong seasonality is coherent with the persistence of HG populations in India, independently of the geographical scale of the precipitation models, (2) Changes in AYP over the mid period (Holocene) are not sufficient to explain the disappearance of HG populations in Kutch-Saurashtra (K-S) 4 ka, (3) Precipitation variability (VYP) over the short period (annual to decadal) is the main parameter affecting population performance and overall ecosystem dynamics. To date, sufficiently refined palaeo-climatic records do not exist for the study area, but higher VYP values 4 ka do not exclude the possibility that other factors may have driven the disappearance of HG populations in Kutch-Saurashtra.

1. Introduction

A recent report of the Intergovernmental Panel on Climate Change defines two of the main processes affecting climate change: (a) a shift of the entire distribution of a given parameter towards a different mean and (b) a change in the overall variability of a given parameter (i.e. standard deviation) with no shift in the mean (IPCC 2012). The same report highlights that such changes in the intensity and frequency of extreme weather and climate events have the potential to contribute to the vulnerability of any given socio-ecological system (SES). Based on such assessment, we explore the persistence of hunter-gatherer (HG) groups in semi-arid environments in the mid and late Holocene in relation to climate-driven environmental change, i.e. variation in precipitation in terms of mean and standard deviation. Monsoon climate is studied here as a multi-scalar perturbation affecting hunter-gatherer (HG) communities in N Gujarat during the Holocene. Simulation is used to explore the boundaries of Holocene monsoon variability within which a HG society is likely to thrive. For example, Late Pleistocene/Early Holocene Levantine foraging (i.e. HG) groups (Kebaran) reveal a potential for sustainability and resilience even under adverse climatic conditions (Rosen and Rivera-Collazo 2012). It has been suggested that transitional ecological areas show features of species composition, structure, and function representative of the ecosystems they transcend and that indigenous peoples whose living territories traverse ecological edges have a correspondingly increased access to important resources and therefore have a greater capacity for adaptation (Turner et al. 2003: 439). Social and environmental processes are linked by complex feedbacks on different spatial and temporal scales. Social-ecological systems (SESs) show different degrees of resilience, i.e. ability to adjust to perturbations without collapsing into a qualitatively different state that is controlled by a different set of social or ecological processes (Widlök et al. 2012). The agent-based simulation we propose explores the potential for persistence of HG communities relative to climate-driven environmental change during the mid and late Holocene in N Gujarat, a semi-arid region in NW India.

In our starting model Holocene HG groups in N Gujarat are adapted to marked seasonality (represented by the monsoon) in a semi-arid environment (at the margin of the Thar Desert). The main aim of this work is to define the minimum climatic (and environmental) conditions that could sustain this type of population. We use Agent-Based Modelling (ABM) and simulation to explore how climate variability may have affected this SES in terms of persistence, resilience and disappearance (Holling 2001; Folke et al. 2002; Folke 2006; Epstein 2008). Agents in our model aim at perpetuating/adapting their SES when facing changing environmental conditions (Meadow and Patel 2003). The proposed ABM is based on real-world data from the study area. The presence of HG communities during the Holocene is inferred from archaeological assemblages dominated by a combination of microlithic stone tools and game bones (Balbo et al. 2012). Long-term persistence of HG in the area is supported by radiocarbon dates from stratified open-air archaeological contexts. Loteshwar, Bagor, Nagwada and Langhnaj provide the chronological framework of reference for the present study, with HG occupation attested c. 10 to 4 ka (Misra 1973; Allchin et al. 1978; Patel 2009). Given the fragmentary character of archaeological and palaeoenvironmental records, agent behaviour is modelled integrating anthropological information (e.g. Tanaka and Sugawara 1996; Nagar 2008) and environmental conditions are modelled from historical climatic (www.tropmet.res.in with permission from the Indian Institute for Tropical Meteorology, Sontakke and Singh 1996; Sontakke et al. 2008; Attri and Tyagi 2010; Singh and Ranade 2010) and environmental (Kelly 1983) data.

N Gujarat represents a semi-arid marginal environment, between the hyper arid Thar Desert to the N and the more fertile area of Saurashtra to the S. This monsoon-dependent region may be defined as an ecotone, where contrasting ecological niches are in tension and small near-threshold climatic shifts can generate significant environmental changes, greatly affecting resource availability and human population (Byrne 1998). Palaeoclimatic models are used to frame simulation of past climatic and environmental conditions. Existing models for the Asian monsoon precipitation patterns suggest that the currently observed strong seasonality was established in the early phases of the Holocene, c. 12 ka onwards (Liu et al. 2003). The same models suggest Asian monsoon precipitation has decreased monotonically by about 7% through the Holocene, i.e. c. 0.6% every 1000 years over the past 12 ka (Liu et al. 2003: 2484). Overall, precipitation anomalies in Asian monsoon were low c. 12-10 ka, rising to maximum c. 8 ka and lowering until stabilization c. 5 ka (Liu et al. 2003: 2487). Palaeoclimatic records confirm this tendency, although some strengthening in precipitation has been observed at the regional scale over the past 1.5 ka (Anderson et al. 2010). Palaeoenvironmental studies suggest that increased precipitation in the first phases of the Holocene contributed to the stabilization of dunes in

the SW margin of the Thar Desert, with the Thar Desert SW boundary retiring to its present-day position c. 7 ka (Saini and Mujtaba 2012 and references therein).

2. Methods and model elements

The following entities are included in the model: climate (precipitation patterns), environment (ground model and resources) and agents (hunter-gatherers). A first model was elaborated using natural language to ease communication between specialists with different backgrounds. The Overview, Design concepts, Details protocol (ODD in Grimm et al. 2010) was used to specify the main components of the model in terms of aims and entities (SI1) and to implement a formal ABM.

2.1. Entities

Simulations are run to observe population dynamics relative to changes in resource availability. Agents interact within a ground model where resources available in each cell depend on (a) the type of land unit it represents, (b) precipitation patterns and (c) agents' use of available resources (Box 2002).

2.1.1. Ground model

The ground model supporting our simulation environment was derived from a supervised classification of Landsat satellite imagery (Balbo et al. 2012). Space is represented as a lattice, a regularly spaced grid of cells (raster map). The ground model extends over an area of 1600*1600 cells corresponding to a surface of c. 2500 km² (31.5 m per side cells). This area is considered representative of a broader semi-arid portion of N Gujarat for which we dispose of detailed archaeological information (Figure 1). Each cell carries topographic information, i.e. position and elevation as calculated from the Digital Elevation Model (DEM) derived from satellite imagery (Balbo et al. 2012).

Each cell is assigned to one of the following three land units:

1. Dune is the only unit where agents may settle.
2. Interdune is the unit representing depressions between dunes.
3. Water represents seasonal and permanent water points (lakes and rivers).

2.1.2. Climate

Climate is the cornerstone of the environmental model. The climate module determines the quantity of rain that precipitates on the ground model. Precipitation is calculated yearly and it is distributed evenly on the ground model. Precipitation values, in conjunction with the ground model, are used to calculate the amount of biomass available for each cell at each time-step. The precipitation models used in the simulations are multi-scalar, relative to the geographical distribution of the data used to build them: local, regional and continental. Precipitation patterns at the local (Kutch-Saurashtra, K-S), regional (NW India) and continental (whole India, wI) scales for 10 ka (arrival of Holocene HG in N Gujarat) and 4 ka (extinction of HG populations in N Gujarat) were modelled following a gamma distribution. The gamma distributions were derived from historical precipitation data for the period 1871 - 2008 (www.tropmet.res.in, Sontakke and Singh 1996; Sontakke et al. 2008; Attri and Tyagi 2010; Singh and Ranade 2010) calibrated using Holocene climatic models (Liu et al. 2003) (Figure 2). Two parameters were used to define the shape of the gamma distribution:

1. Average yearly precipitation (AYP), i.e. the total amount of rain in any given year.
2. Variance in yearly precipitation (VYP), i.e. the deviation from the AYP for any year within a given time-period.

Obtained values of AYP and VYP were used to adjust gamma distribution curves and feed the simulations (Table 1). Both parameters were kept constant within a given simulation run. Consistent sets of evenly spaced 50 year-long simulation runs were undertaken to explore the effects of climate over the short, mid and long periods to gain insight into the role played by these parameters on population dynamics for different precipitation patterns (local, regional and continental climatic settings) and temporal scales (millennial to annual).

Within any given year, the Indian monsoon generates a strong seasonality (asymmetrical precipitation pattern), defining three critical moments in simulation time, each corresponding to a four-month season:

- June to September (JJAS) or rainy season (monsoon): high precipitation, high temperature and low evapotranspiration).
- October to January (ONDJ) or post-monsoon: low precipitation, cool temperature and medium evapotranspiration.
- February to May (FMAM) or dry season: low precipitation, high temperature, high evapotranspiration.

Note that in the simulation any given year starts with the rainy season (JJAS), when the most significant part of yearly precipitation is discharged. At the beginning of the simulated year, the total value of the generated yearly precipitation is calculated and added to the system following the gamma distribution. No additional precipitation is considered for the remaining eight months of the year (ONDJ and FMAM).

2.1.3. Resources (biomass)

Resources in the ground are calculated every year. Resources are allocated as biomass to cells depending on yearly precipitation as from the gamma distribution. No resource is carried from one year to the following. The spatial density of resources decreases as distance from water increases and following a linear trend. In a given year, resource availability increases linearly to maximum through the rainy season (JJAS), then decreases linearly until the end of the dry season (FMAM). The temporal distribution of resources within a given year results from the combination of the temporal distribution of precipitation with the 'end-of-year minimum residual resources' parameter (EMR). The EMR is defined as a percentage of the overall biomass production for the corresponding year and represents seasonal variance in resource availability in the model (SI1). The EMR constitutes a threshold below which resources are not allowed to decrease at the end of the year. Variations in EMR have no effect on the overall yearly precipitation and on the total amount of biomass produced within a year. As a result, the higher the EMR, the lower the seasonal variation in the temporal distribution of precipitation and resources.

Overall biomass availability for dunes and interdunes is derived from present-day information on savanna biomass production (SI1, Kelly 1983). Yearly primary biomass production is estimated to 4000 g/m², efficiency to 23%, energy to 18400 KJ/m² and 4395 KCal (Percentage of accessible resources calculated according to Kelly 1983: Table 3, p. 284). Efficiency represents the biomass actually available to agents and it is calculated as the ratio of profitable versus total biomass (SI1).

2.1.4. Agents

Attributes and behavior of the agents are defined by the following principles. Agents within our HG population are conceived as 'nuclear families'. The composition of each agent was modelled from anthropological literature (e.g. Tanaka and Sugawara 1996; Nagar 2008). The agent is the minimum decisional unit of our model. However, some aspects are modeled at the individual level and computed at the agent level. For example, the probability of death is applied to the individual level but starvation rate is computed for the whole agent taking into account individual starvation rates (SI1). Specific aspects of agent behaviour were elaborated to represent individual components within each agent. In particular, we focused on agents' abilities to supply their own needs in terms of (a) resource consumption needs and (b) capability for resource gathering. Values for (a) and (b) depended on the age of the single components within each agent (e.g. metabolic needs and behavioural skills before adulthood).

Energetic requirements for agents were modelled based on FAO global reports (FAO/WHO/ONU 2005). For the purpose of this study, simulations were ran using agents whose behaviour is based on wired algorithms as in the classic ABM approach (Epstein 2007). According to the agent planning protocol (SI1), each day the agent will update its knowledge about environment and choose an action to execute. That is, agents will forage in a given direction within the home range or change the position of settlement if environmental conditions within home range are insufficient for covering their caloric needs. Realistic population dynamics were obtained without defining such parameter as fertility age

limit, maximum age or birth-control measures, by means of mortality rates, thus reducing the overall number of parameters in the model. Reproduction rates in our simulations are coherent with those observed in reality (Hewlett 1991).

2.2. Simulation tools

The software used to implement the model is the Pandora Library, created by the social simulation research group of the Barcelona Supercomputing Centre (Wittek and Rubio-Campillo 2012). This tool is designed to implement particularly demanding ABMs and to execute them in high-performance computing environments. This library allows the execution of several simulations by modifying initial parameters, as well as the distribution of particular executions with high computer costs by using a computer cluster.

2.3. Simulation experiments

Each simulation experiment aims at testing the role of one of the three relevant climate parameters (EMR, AYP, VYP) on population dynamics. The parameter under exploration varies between simulation runs while the other two parameters are kept constant. For each experiment, a separate set of simulations is run for each scale-related precipitation model (K-S, NWI, wI), starting with the same number of agents (100) and ground model. Consistent sets of 50 year-long simulation runs (18,000 days) are performed for parametric sweep to test minimum conditions for the widest possible range of precipitation variations in terms of mean and standard deviation. Each parameter configuration is executed ten times to account for stochasticity and results are averaged for consistency.

Simulation proceeded in three steps (Experiments 1-3):

1. Test the coherence of the model in relation to its components. In other words, variables in the model are calibrated to obtain a realistic result in terms of a HG population maintaining near-constant numbers of members in a semi-arid region dominated by the monsoon 10 ka, i.e. when first Holocene HG communities are first attested in the region.
2. Test the survival threshold of the HG population in terms of its resilience to changes in AYP over the mid and long periods. This step is subdivided into two stages:
 - a. Test the absolute thresholds for population extinction dependent on variability in AYP (i.e. full possible spectrum of change at the Pleistocene/Holocene time-scale).
 - b. Test whether the progressive reduction in AYP attested through the Holocene at the continental level is sufficient to explain the disappearance of HG in N Gujarat 4 ka.
3. Test the survival threshold of the HG population in terms of its resilience to precipitation variability over the short period (annual to decadal). In other terms, see whether higher VYP attested at the local rather than at the continental level, may be sufficient to explain the disappearance of HG in N Gujarat 4 ka.

Each experiment is run using precipitation models related to three different spatial scales (multi-scalar approach): (a) local (Kutch-Saurashtra), (b) regional (NW India) and (d) continental (whole India, wI). This approach aims at assessing scale-dependent differences in the expression of climate change and their impact on HG population dynamics.

2.3.1. Experiment 1 (exploring EMR)

The first experiment is set 10 ka and aims at building a sound realistic model of a population of HG living in equilibrium (maintaining a near-constant number) in a semi-arid region dominated by the Asian monsoon (Table 2). Several simulations were run using the parameters specified in the ODD (S11).

The underlying hypothesis for this experiment was that diminished seasonal variability (i.e. higher EMR) should improve population success by providing a more homogeneous intra-annual distribution of resources (i.e. reducing stress due to resource depletion during the dry-hot season).

The effects of variations in the 'end-of-year minimum residual resources' (EMR) parameter are explored in terms of population dynamics. This is done by sets of simulations where AYP and VYP are maintained constant and the EMR parameter increases from 0 to 1 by 0.1 increments. This amounts to 330 simulations (11 values x 10 executions x 3 climatic scenarios). In ecological terms, values of EMR near 0 represent strong seasonality (e.g. monsoon), values near 1 represent little seasonal variability (e.g. tropical climate) and values near 0.5 represent variability in temperate regions.

2.3.2. Experiment 2 (exploring AYP)

Based on Liu et al. (2003), it is estimated that precipitation has diminished linearly c. 0.6% every 1000 years over the past 12 ka (representing the Holocene). For the period c. 10-4 ka (i.e. the presumed period for the presence of HG population in N Gujarat) this would imply precipitations between c. 5.5% and 2.2% higher than those observed in the present-day.

The underlying hypothesis for this experiment was that progressive drying would have triggered HG population reduction and eventually disappearance 4 ka.

Experiment 2 starts from climatic conditions 4 ka and involves two different time-scales (scenarios) (Table 3). The effects of variations in the AYP parameter are explored in terms of population dynamics. This is done by sets of simulations where VYP and EMR are maintained constant:

1. In the first scenario (full possible spectrum of change at the Pleistocene-Holocene time-scale) we test changes in average yearly precipitation (AYP) over the long period. That is, we observe population dynamics under the broadest possible precipitation scenarios. This involves pushing the system beyond the variability attested for in Holocene climatic models to explore potential yearly average precipitation thresholds for population extinction. Variations in AYP from the 4 ka value are explored for climate trends at three different geographical scales (Table 3: 2aa, 2ba, 2ca). The sweep is done at intervals of 50 mm between -300 mm and +300 mm from AYP 4 ka. This amounts to 390 simulations (13 values x 10 executions x 3 climatic scenarios). In climatic terms, such variations in AYP go beyond the temporal scope of Holocene HG populations, but provide a first coarse approximation into the resilience of HG populations to climate change over the long period.
2. In the second scenario we test changes in AYP over the mid period (Holocene time-scale). That is, we observe population dynamics considering the linear decrease in precipitation accounted for in existing Holocene global climate models. The underlying hypothesis to be tested here was that more humid conditions in the early phases of the Holocene would have favoured HG persistence. Variations in AYP during the Holocene (12 ka - present) are explored at intervals of c. 1000 years (Table 3: 2ab, 2bb, 2cb). The precipitation interval changes depending on the geographic scale (2.5 mm for K-S, 3 mm for NWI, 6 mm for wI) to obtain a near-constant sweep of c. 1000 years independent of absolute precipitation values observed locally, regionally and continentally. This amounts to 450 simulations (15 values x 10 executions x 3 climatic scenarios).

2.3.3. Experiment 3 (exploring VYP)

The third experiment aims at testing population performance when confronted with increasing inter-annual variance in yearly precipitation (VYP). The goal is to explore the effects of the regional expression of global precipitation trends on the local HG community.

The underlying hypothesis was that increased VYP should affect population negatively (i.e. decrease the population's capability to foresee resource availability in consequent years). In other words, this experiment explores whether higher inter-annual variability recorded at the local/regional scale (as compared to the continental/global scale) contributed to the disappearance of the HG population in N Gujarat 4 ka.

Experiment 3 is set 4 ka (Table 4). The effects of variations in the VYP parameter are explored in terms of population dynamics. This is done by sets of simulations where AYP and EMR are maintained constant. For each geographical setting, VYP is allowed to vary between 1 and 300, with intervals of 20. This amounts to 480 simulations (16 values x 10 executions x 3 climatic scenarios).

3. Results

3.1. Experiment 1. Effects of EMR variation on HG population

Given the model parameters contained in the ODD (SI1), four significant population dynamic patterns emerge from Experiment 1 (Figure 3):

1. When EMR is set to 0 (i.e. resources at the end of the year are allowed to decrease to 0 due to strong seasonality) human population tends to collapse after few simulation years.
2. Starting from EMR values set to 0.1, human population becomes viable within the 50 y simulation period.
3. When EMR is set to 1 (i.e. resources are near-constant through the year), human population does not reach maximum numbers at the end of the simulation.
4. Middle EMR values (0.2-0.8) generate the steepest population increases and the largest populations at the end of the simulation.

A fifth result of this experiment is that the four findings above are consistent regardless of the climatic scenario (K-S, NWI and wI).

3.2. Experiment 2. Effects of variations in AYP on HG populations over the mid and long periods

Based on results from experiment 1, the EMR parameter is set constant to 0.1, as it is assumed to be the most representative of monsoon seasonality, also being the lowest EMR value providing viable HG populations. Two relevant patterns emerge from Experiment 2:

1. The threshold for HG population viability for different climatic scenarios is observed for the following AYP values:
 - a. Local (K-S): c. 300 mm/y
 - b. Regional (NWI): c. 250 mm/y
 - c. Continental (wI): no threshold observed.
2. Precipitation decrease, as derived from models of Holocene Asian monsoon evolution elaborated at the continental level, does not seem to significantly affect population dynamics at the local level (Figures 4 and 5). Population dynamics are virtually identical for average precipitation 10 ka, 4 ka and in the present-day.

3.3. Experiment 3. Effects of variations in VYP over the short period on HG populations

Based on results from experiment 1, the EMR parameter is kept constant to 0.1. The following outcomes in population dynamics are observed for Experiment 3 (Figure 6):

1. The threshold for HG population extinction 4 ka for different climatic scenarios is observed for the following VYP values:
 - a. Local (K-S): c. 200 mm.
 - b. Regional (NWI): c. 260 mm.
 - c. Continental (wI): no extinctions.
2. Population increases steadily for VYP values below c. 200 mm. Best population performance is observed for VYP = 1 (i.e. no VYP).

4. Discussion

4.1. Experiment 1. Defining viable HG populations

Independent of the scale of the climatic scenario, when resources are allowed to reach 0 at the end of the simulated year, human population tends to decrease and collapse. When simulation outcomes are observed in detail for 'end-of-year minimum residual resources' (EMR) = 0, we see that population tends to maintain initial agent numbers in years with high AYP. However, the recurrence of even few years of low AYP within 50-year long simulations seems to have dramatic effects on population dynamics, showing an overall tendency to population decrease.

A less intuitive result emerges when the whole range of values is explored for the EMR parameter. Increase in population is not proportional to increase in EMR. That is, maximum population growth is not observed when EMR is set to 1 (i.e. representing tropical climate with little seasonal differences). Instead, maximum population growth is observed for EMR values between 0.2 and 0.8 (i.e. temperate climate seasonality). Recall that total yearly biomass is constant based on precipitation in the corresponding year and that the EMR parameter affects how such biomass becomes available through the year. It seems then plausible that a non-extreme seasonal distribution of resources favours population performance. Seasonality provides access to a generous amount of resources at least during the rainy season, during which population can grow even in years of low overall precipitation, without allowing resources to reach 0 at the end of the year, which would cause starvation.

Finally, we observed that differences in population performance for EMR above 0.1 are far smaller than differences for EMR between 0 and 0.1. This trend becomes more pronounced as the geographical scale of the precipitation model used increases (Figure 3). We consider that EMR = 0.1 is the most representative value for a strong seasonal distribution of resources, as observed at the local level in the semi-arid environment of Kutch-Saurashtra. A similar, though less strong effect of seasonal precipitation on inter-annual resource distribution holds true for NW India and for India as a whole. On these bases the EMR parameter was set constant to 0.1 for all following experiments.

4.2. Experiment 2. Effects of AYP variability over the mid period (millennial) on HG populations

Variations in population dynamics are virtually insignificant for changes in AYP 10 ka (earliest evidence of Holocene HG populations in N Gujarat), 4 ka (latest evidence of HG populations) and in the present-day. This means that, solely based on continentally modelled patterns of Holocene precipitation change in Asian monsoon, HG populations should be observed in N Gujarat today. Variations in population dynamics are even less significant at the continental and regional scales, where absolute AYP values are systematically higher than at the local level (Table 1).

Consistent composite sets of 50 year-long simulations allow us to define the threshold in average yearly precipitation (AYP) for HG population persistence at c. 300 mm/y at the local level (K-S). At the regional level (NWI) some decrease in population is noted for AYP values c. 250 mm/y. No decrease is observed for simulations run based on precipitation data at the continental level (wI). AYP values simulated at the local level are not unrealistic. Years of similarly low, and even lower, precipitation have been documented in the historical record (i.e. the minimum AYP recorded for K-S in the 1871-2008 period was 71.1 mm in 1987). However, their consistent occurrence over more than two consecutive years has rarely been observed in Kutch-Saurashtra in the period covered by instrumental climate records, namely two times over three consecutive years in the 1871-2008 period (Grey area in Figure 2b). To our knowledge, a sufficiently refined palaeoclimatic proxy record indicating such low precipitation on consecutive years during the Holocene has not yet been published.

At present, results issued from our simulations can only be compared with broad palaeoclimatic reconstructions (e.g. Saini and Mujtaba 2012 and references therein). Significantly, Anderson et al. (2010: Figure 4 therein) have detected a sharp decrease in deposition frequencies of the planktic foraminifera *Globigerina bulloides* in the Arabian Sea starting 4 ka. Such decrease is attributed to reduced seasonal upwelling in the Arabian Sea and linked to weaker surface winds due to lower intensity in the monsoon. Climate events of intense drought have also been detected in speleothems for S Asia between 4.2 and 3.5 ka and for E Asia between 4.3 and 4.1 ka (Clift and Plumb 2008: Figure 6.2, p. 199 and references therein). However, considering the limits in the spatial and temporal definition provided by existing climatic records and models, it remains speculative to say whether the decrease in AYP detected in published climatic models for the Asian monsoon may have played any significant role in the disappearance of the HG mode of life in K-S 4 ka.

4.3. Experiment 3. Effects of VYP variability over the short period on local HG populations

Independent of the scale of the climatic scenario, human population increases as VYP decreases. That is, the lower the inter-annual (annual, decadal) variation in precipitation, the better human populations perform. This is somewhat expected as lower short-term variance means higher predictability of resource patterns and availability from one year to the following. The opposite context (high variance) reduces population's adaptive capabilities, as it requires a constant reconsideration of subsistence strategies that are dependent on resource availability and distribution. Decadal patterns of resource

availability affect reproductive strategies, i.e. the number of offspring any agents has depending on access to resources (SI1). Lower VYP means higher survival rate for newborns.

1. For local-scale precipitation scenarios (K-S), with VYP = c. 200 (i.e. the value recorded from historical instrumental records at the local level, K-S), HG population remains near-constant through the 50 y simulation time, although some simulation runs leading to population decrease appear. A more marked trend towards extinction emerges starting with VYP = c. 220.
2. For regional-scale precipitation scenarios (NWI), VYP threshold for the appearance of simulation runs leading to population decrease is c. 260. This corresponds to twice the VYP value recorded from historical instrumental records at the regional level (1365.17). For VYP = 1400, population tends to triple within a single simulation run (50 years).
3. For continental-scale precipitation scenarios (wI), no population decrease is observed within the explored VYP range (1 - 300 mm). For VYP = 100 (i.e. the VYP value recorded from historical instrumental records at the regional level), population increases four times within the 50 year simulation.

Overall, variations in population dynamics are less significant relative to precipitation trends at the continental and regional scales, where VYP values are systematically lower than at the local level (Table 1). The systematically higher AYP observed at regional and continental scales prevents overall yearly precipitation to near 0 using these climatic scenarios even in years where AYP is low and VYP is high. In sum, HG extinction for precipitation scenarios at the regional and continental levels cannot be related to changes in VYP. In contrast, for local-scale climatic scenarios, VYP is the main parameter affecting population performance.

At the local scale, VYP in the present-day is situated near the threshold of extinction for HG populations. This implies that if climatic events characterised by slightly higher VYP (+ 4 %) existed 4 ka, a slight increase in the variance in precipitation over the short period (annual, decadal) could have significantly contributed to the extinction of the HG mode of life in K-S.

Available palaeoclimatic records and models do not allow us to verify this hypothesis. The most refined existing records provide maximum palaeoclimatic definition at the decadal to centennial time scales (Clift and Plumb 2008), based among others on cave speleothems (Fleitmann et al. 2003), foraminifera from marine sediment successions (Anderson et al. 2010), pollen records (Lézine et al. 2007; Singh et al. 2007) and organic matter from lacustrine deposits (Yang et al. 2011). Likewise, due to the coarse grain of the underlying databases, the chronological definition of palaeoclimatic models at the global and continental levels do not go beyond the millennial timescale (Liu et al. 2003). They tend to provide a smoothed perception of inter-annual variation, under-representative of regional expressions of the same patterns. This dichotomy between the local and continental scales becomes sharper in case of marginal areas, such as K-S, located on the tail of the Indian monsoon trajectory. Meteorological instrumental records show higher inter-annual variability in precipitation at the local level (Kutch-Saurashtra) than at the regional (NW India) and continental (whole India) levels (Figure 2). In this sense, slight variations in VYP detected at regional and continental levels are likely to have a much stronger significance at the local level.

4.4. Further work

A better definition of the population trends observed in this first set of simulations is planned as a first development of the work presented here. This will be done by performing longer continuous simulations (100-1000 years) to observe the tail of extinction trajectories emerging near threshold for Experiment 3 at the local level (i.e. the effects of VYP variability on HG populations 4ka). Longer simulations will also allow us to better understand the effects of decadal to centennial time-scale variations not included in the present work.

Hunter-gatherer population performance explored in the present work will be evaluated at later stage (not presented here) in terms of settlement patterns. For example, simulations based on the Kalahari San foragers showed that increasing aridity in the dry season may lead to (a) fusion (with increased cooperation) where water points are few, but to (b) fission (with decreasing interaction) where water points are small but numerous (Widlök et al. 2012). Such processes have also been described in terms of 'population viscosity' (Hatchwell 2009).

As for agent design, future simulations will involve more sophisticated Model-Based Agents, whose actions are planned in relation to knowledge of specific goals and costs. Further work will also involve the emergence in the region of different SESs. Archaeological evidence shows agro-pastoral strategies gaining weight in the Late Holocene.

5. Conclusions

Computer simulation was used in this work as a tool for the integrated study of human behavioural traits (social and archaeological) and environmental change (climate, landscape and resources). The combination of such heterogeneous sets of data has been difficult in the past due to inherent differences in terms of temporal and geographical scales, granularity (i.e. definition) and continuity (i.e. completeness). Computer simulation has been used here as a virtual laboratory to fill such gaps and to propose a number of coherent realistic scenarios that help explaining the adaptive performance and environmental tolerance of specific SESs.

We have explored thresholds for Holocene HG populations in monsoon-dominated semi-arid environments in terms of adaptation to (1) strong seasonality and population dynamics relative to (2) precipitation trends over the mid and long periods (AYP parameter, Holocene time scale and greater) and to (3) variance in precipitations over the short period (VYP parameter, annual to decadal time scales).

1. The long-term persistence of HG populations in India is coherent with the strong seasonality characterising the Indian monsoon (EMR parameter = 0.1), independent of the geographic scale considered.
2. Changes in mean precipitation trends for the Asian monsoon over the mid period (Holocene), as derived from existing palaeoclimatic models are not sufficient to explain the disappearance of the HG mode of life in K-S 4 ka. However, palaeoclimatic reconstructions (Clift and Plumb 2008; Anderson et al. 2010) suggest dry episodes c. 4 ka (not detected in larger-scale palaeoclimatic models) could have contributed to the disappearance of HG in K-S.
3. At the local level, variance in precipitation over the short period (annual to decadal) is the main parameter affecting population performance and overall dynamics in our simulations. A sustained period of hypothetical higher VYP values 4 ka could have contributed significantly to the disappearance of HG in K-S, but higher VYP values 4 ka do not exclude the possibility of other factors affecting HG population performance.

In sum, global and continental models of precipitation for the Asian monsoon may not be representative of higher inter-annual variability recorded in regions found at the tail of the Asian monsoon trajectory, such as Kutch-Saurashtra. In these transitional areas the effects of higher inter-annual variance need to be taken into account to explain population dynamics relative to larger-scale climate trends.

Computer simulation has provided a valuable insight concerning the kind of data necessary to understand the persistence of specific SESs. High-definition palaeoclimatic records are needed to verify patterns of HG population extinction emerging from our simulations. Where available at the regional scale (e.g. Prasad et al. 2007), palaeoenvironmental records often lack the chronological definition needed to evaluate the effects of climate change for annual to decadal time-periods, i.e. those affecting people during their lifetime. More broadly, our perception is that refined palaeoclimate records at the local and regional scales are needed for a sound evaluation of climate-dependent changes in SESs (Madella and Fuller 2006).

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Bibliography

- Allchin B, Goudie A, Hedge K (1978) *The Prehistory and Palaeogeography of the Great Indian Desert*. Academic Press, London.
- Anderson DM, Baulcomb CK, Duvivier AK, Gupta AK (2010) Indian summer monsoon during the last two millennia. *Journal of Quaternary Science* 25:911–917. doi:10.1002/jqs.1369.
- Attri SD, Tyagi A (2010) *Climate Profile of India*. Contribution to the Indian Network of Climate Change Assessment. Environment Monitoring and Research Centre Indian Meteorological Department, New Delhi.
- Balbo AL, Rondelli B, Cecilia Conesa F, Lancelotti C, Madella M, Ajithprasad P (2012) Contributions of geoarchaeology and remote sensing to the study of Holocene hunter–gatherer and agropastoral groups in arid margins: The case of North Gujarat (Northwest India). *Quaternary International*:1–13. doi:10.1016/j.quaint.2012.12.016.
- Box P (2002) Spatial Units as Agents: Making the Landscape an Equal Player in Agent-Based Simulations. In: Gimblett HR (ed) *Integrating Geographic Information Systems and Agent-Based Modeling Techniques for Simulating Social and Ecological Processes*. Oxford University Press, Oxford, pp 59–82.
- Byrne D (1998) *Complexity Theory and the Social Sciences. An Introduction*. Routledge, London New York.
- Clift PD, Plumb RA (2008) *The Asian Monsoon: Causes, History, Effects*. Cambridge University Press, Cambridge.
- Epstein JM (2007) *Generative Social Science: Studies in Agent-Based Computational Modeling (Princeton Studies in Complexity)*. Princeton University Press, Princeton.
- Epstein J (2008) Why model? *Journal of Artificial Societies and Social* 11. <http://jasss.soc.surrey.ac.uk/11/4/12.html>.
- FAO/WHO/ONU (2005) *Human energy requirements. Scientific background papers from the Joint FAO/WHO/ONU Expert Consultation. October 17-24, 2001. Rome, Italy. Food and Nutrition Technical Report Series 1*. FAO. <http://www.ncbi.nlm.nih.gov/pubmed/19856424>.
- Fleitmann D, Burns SJ, Mudelsee M, Neff U, Kramers J, Mangini A, Matter A (2003) Holocene forcing of the Indian monsoon recorded in a stalagmite from southern Oman. *Science* 300:1737. doi:10.1126/science.1083130.
- Folke C (2006) Resilience: The emergence of a perspective for social–ecological systems analyses. *Global Environmental Change* 16:253–267. doi:10.1016/j.gloenvcha.2006.04.002.
- Folke C, Carpenter S, Elmqvist T, Gunderson L, Holling CS, Walker B (2002) Resilience and sustainable development: building adaptive capacity in a world of transformations. *Ambio* 31:437–40. <http://www.ncbi.nlm.nih.gov/pubmed/12374053>.
- Grimm V, Berger U, DeAngelis DL, Polhill JG, Giske J, Railsback SF (2010) The ODD protocol: A review and first update. *Ecological Modelling* 221:2760–2768. doi:10.1016/j.ecolmodel.2010.08.019.
- Hatchwell BJ (2009) The evolution of cooperative breeding in birds: kinship, dispersal and life history. *Phil Trans R Soc B* 364:3217–3227.
- Hewlett, B. S. (1991). *Demography and Childcare in Preindustrial Societies*. *Journal of Anthropological Research*, 47(1):1–37
- Holling CS (2001) Understanding the Complexity of Economic, Ecological, and Social Systems. *Ecosystems* 4:390–405. doi:10.1007/s10021-001-0101-5.
- Kelly RL (1983) Hunter-Gatherer Mobility Strategies. *Journal of Anthropological Research* 39:277–306.
- IPCC (2012) *Summary for Policymakers*. In: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, and New York, NY, USA, pp. 1–19
- Lézine A-M, Tiercelin J, Robert C, Saliège J, Cleuziou S, Inizan M, Braemer F (2007) Centennial to millennial-scale variability of the Indian monsoon during the early Holocene from a sediment, pollen and isotope record from the desert of Yemen. *Holocene* 243:235–249. doi:10.1016/j.palaeo.2006.05.019.

- Liu Z, Otto-Bliesner B, Kutzbach J, Li L, Shields C (2003) Coupled Climate Simulation of the Evolution of Global Monsoons in the Holocene. *Journal of Climate* 16:2472–2490. doi:10.1175/1520-0442(2003)016<2472:CCSOTE>2.0.CO;2.
- Madella M, Fuller DQ (2006) Palaeoecology and the Harappan Civilisation of South Asia: a reconsideration. *Quaternary Science Reviews* 25:1283–1301. doi:10.1016/j.quascirev.2005.10.012.
- Meadow RH, Patel AK (2003) Prehistoric pastoralism in Northwestern South Asia from the Neolithic through the Harappan Period. In: Weber S, Belcher W (eds) *Indus Ethnobiology: New Perspectives from the Field*. Lexington Books, Lanham, pp 65–93.
- Misra VN (1973) Bagor, a late Mesolithic settlement in north-west India. *World Archaeology* 5:92–110.
- Nagar M (2008) *Hunter-gatherers of North and Central India: an Ethnoarchaeological Study*. Archaeopress. BAR International Series 1749, Oxford.
- Patel AK (2009) Occupational Histories, Settlements and Subsistence in Western India : What Bones and Genes can tell us about the Origins and Spread of Pastoralism. *Anthropozoologica* 44:173–188.
- Prasad V, Phartiyal B, Sharma A (2007) Evidence of enhanced winter precipitation and the prevalence of a cool and dry climate during the mid to late Holocene in mainland Gujarat, India. *The Holocene* 17:889–896. doi:10.1177/0959683607082403.
- Rosen AM, Rivera-Collazo I (2012) Climate change, adaptive cycles, and the persistence of foraging economies during the late Pleistocene/Holocene transition in the Levant. *PNAS* 109:3640–3645.
- Saini HS, Mujtaba SAI (2012) Depositional history and palaeoclimatic variations at the northeastern fringe of Thar Desert, Haryana Plains, India. *Quaternary International* 250:37–48. doi:10.1016/j.quaint.2011.06.002.
- Singh V, Prasad V, Chakraborty S (2007) Phytoliths as indicators of monsoonal variability during mid-late Holocene in mainland Gujarat, western India. *Current Science* 92:8–13. http://www.pages-igbp.org/products/osmabstracts/Singh_Vartika.pdf.
- Singh N, Ranade A (2010) Global temperature and Indian Monsoon. *Geography and you*:41–43.
- Sontakke NA, Singh N (1996) Longest instrumental regional and all-India summer monsoon rainfall series using optimum observations: Reconstruction and update. *The Holocene* 6:315–331.
- Sontakke NA, Singh N, Singh HN (2008) Instrumental period rainfall series of the Indian region (AD 1813-2005): revised reconstruction, update and analysis. *The Holocene* 18:1055–1066. doi:10.1177/0959683608095576.
- Tanaka J, Sugawara K (1996) The /Gui and //Gana of Botswana. In: Lee RB, Daly R (eds) *The Cambridge Encyclopedia of Hunters and Gatherers*. Cambridge University Press, Cambridge, pp 195–199.
- Turner NJ, Davidson-Hunt IJ, Flaherty MO (2003) Living on the Edge: Ecological and Cultural Edges as Sources of Diversity for Social–Ecological Resilience. *Human Ecology* 31:439–461.
- Widlök T, Aufgebauer A, Bradtmöller M, Dikau R, Hoffmann T, Kretschmer I, Panagiotopoulos K, Pastoors A, Peters R, Schaebitz F, Schlummer M, Solich M, Wagner B, Weniger G-C, Zimmermann A (2012) Towards a theoretical framework for analyzing integrated socio-environmental systems. *Quaternary International* 274:259–272. doi:10.1016/j.quaint.2012.01.020.
- Wittek P, Rubio-Campillo X (2012) Scalable Agent-Based Modelling with Cloud HPC Resources for Social Simulations. In: 2012 IEEE 4th International Conference on Cloud Computing Technology and Science. pp 355–362.
- Yang T-N, Lee T-Q, Meyers P a., Song S-R, Kao S-J, Löwemark L, Chen R-F, Chen H-F, Wei K-Y, Fan C-W, Shiau L-J, Chiang H-W, Chen Y-G, Chen M-T (2011) Variations in monsoonal rainfall over the last 21 kyr inferred from sedimentary organic matter in Tung-Yuan Pond, southern Taiwan. *Quaternary Science Reviews* 30:3413–3422. doi:10.1016/j.quascirev.2011.08.017.

Tables

Table 1 Calibration of historical meteorological data (0 ka) for the Holocene period based on Liu et al 2003. K-S (Kutch-Saurashtra, local), NWI (NW India, regional), wI (whole India, continental), AYP = average yearly precipitation, VYP = variance in yearly precipitation

Table 2 Parameterisations for Experiment 1 (a to c). K-S (Kutch-Saurashtra, local), NWI (NW India, regional), wI (whole India, continental), AYP = average yearly precipitation, VYP = variance in yearly precipitation, EMR = end-of-year minimum residual resources

Table 3 Parameterisations for Experiment 2 (aa to cb). K-S (Kutch-Saurashtra, local), NWI (NW India, regional), wI (whole India, continental), AYP = average yearly precipitation, VYP = variance in yearly precipitation, EMR = end-of-year minimum residual resources (0.1 = 10%)

Table 4 Parameterisations for Experiment 3 (a to c). K-S (Kutch-Saurashtra, local), NWI (NW India, regional), wI (whole India, continental), AYP = average yearly precipitation, VYP = variance in yearly precipitation, EMR = end-of-year minimum residual resources

Figures

Fig. 1 Simulation area and ground model. The simplified ground model includes three land units. Green (gray): interdune, Yellow (white): dune, Blue (black): water point

Fig. 2 Precipitations patterns in the study region. (a) The local (Kutch-Saurashtra, K-S), regional (NW India, NWI) and continental (whole India, wI) scales (map was modified from the original version published at www.tropmet.res.in with permission from the Indian Institute for Tropical Meteorology). (b) Historical climatic data. In grey, records of AYP < 300 mm (c) Boxplots of variance in yearly precipitation (VYP) for meteorological data at different geographic scales

Fig. 3 Population dynamics relative to 'end-of-year minimum residual resources' (EMR) parameter. (a) Local (K-S). (b) Regional (NWI). (c) Continental (wI)

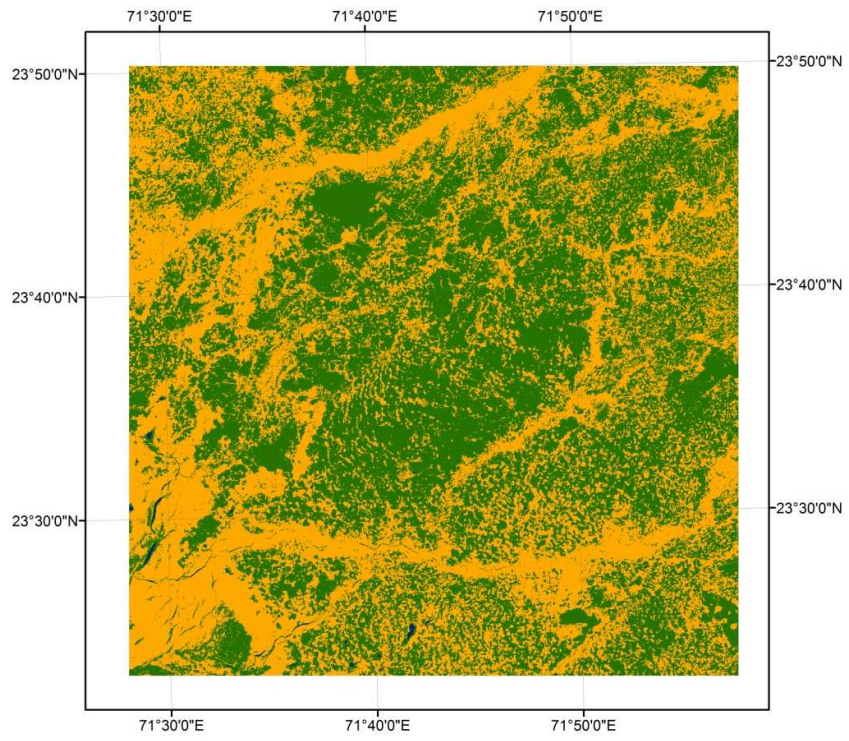
Fig. 4 Population dynamics relative to variability in continental climate trends over the long period, i.e. average yearly precipitation (AYP). The x-axis is shown as a discontinuous ordered sequence of AYP values (as in Table 2)

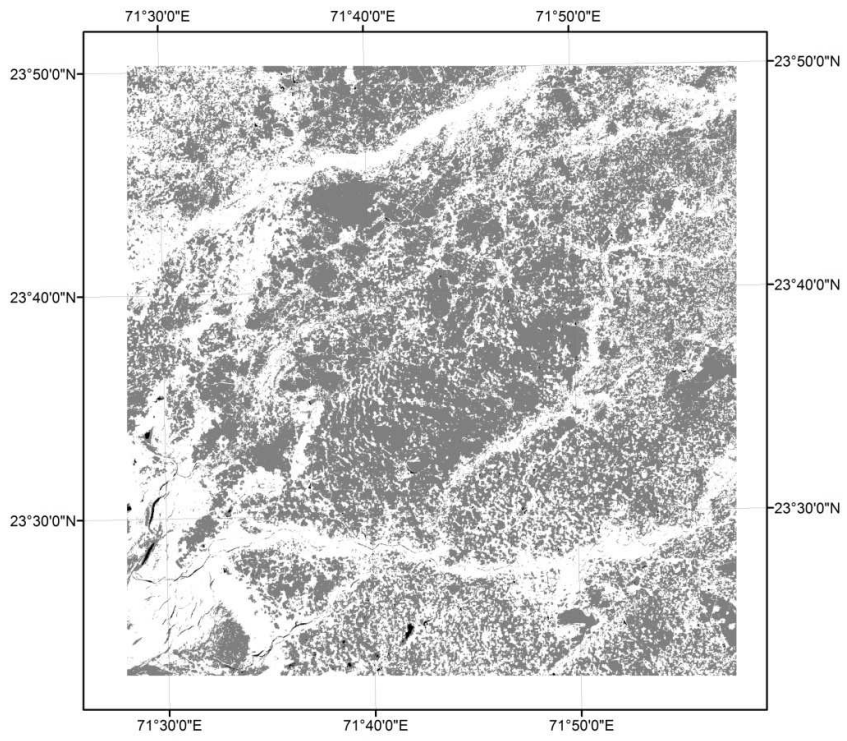
Fig. 5 Population dynamics relative to variability in continental climate trends over the mid period (Holocene), i.e. average yearly precipitation (AYP). (a) Local (K-S). (b) Regional (NWI). (c) Continental (wI). ka BP: thousands of years before present

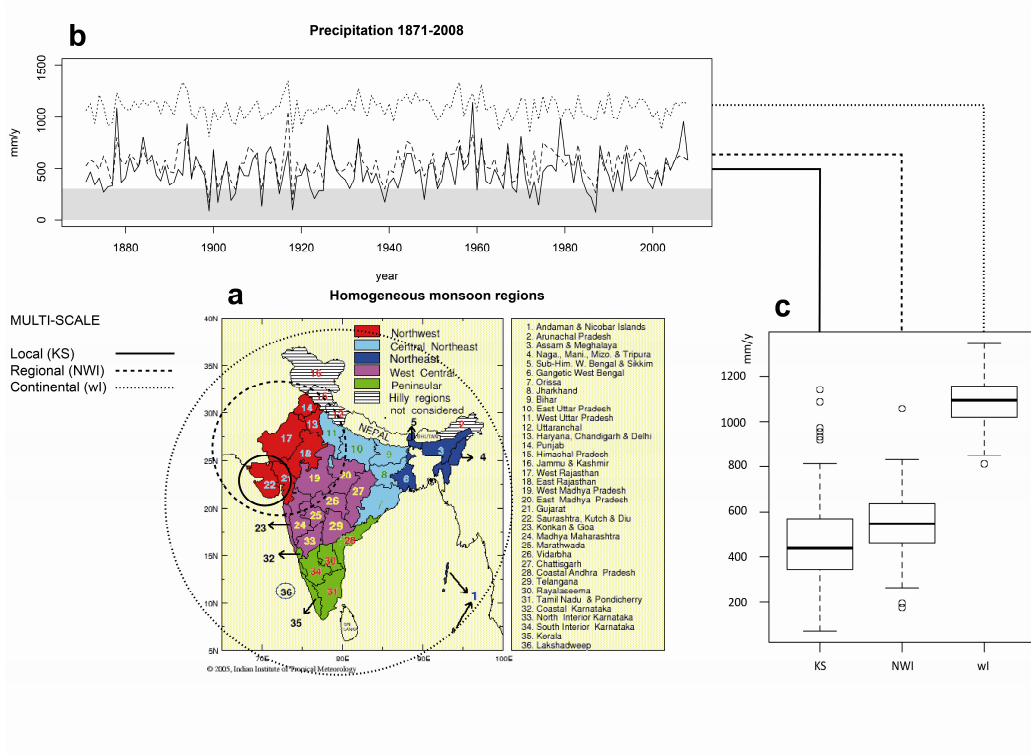
Fig. 6 Population dynamics relative to variability over the short period, i.e. variance in yearly precipitation (VYP). (a) Local (K-S). (b) Regional (NWI). (c) Continental (wI). All simulations started with 100 agents. Each boxplot represents the human population at year 50 for each parameter configuration after ten executions. Vertical dotted lines indicate VYP 4 ka for the respective geographical scale. Population increase at VYP 300 is an artefact due to the inherent asymmetry of the gamma distribution at low precipitation regimes (i.e. precipitation cannot be less than 0)

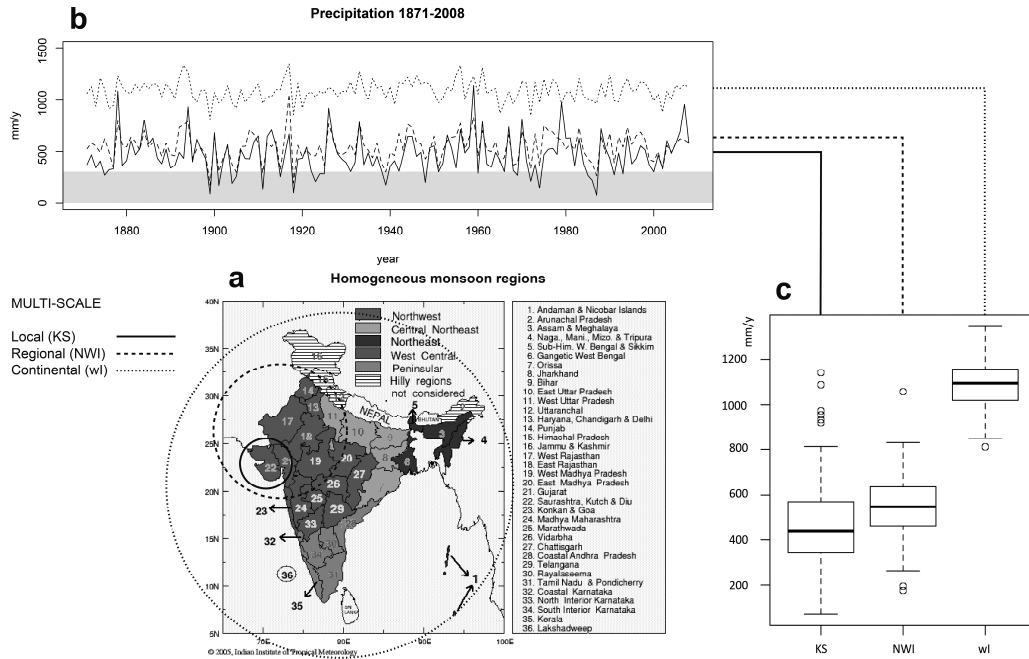
Supplementary Information

SI 1 ODD

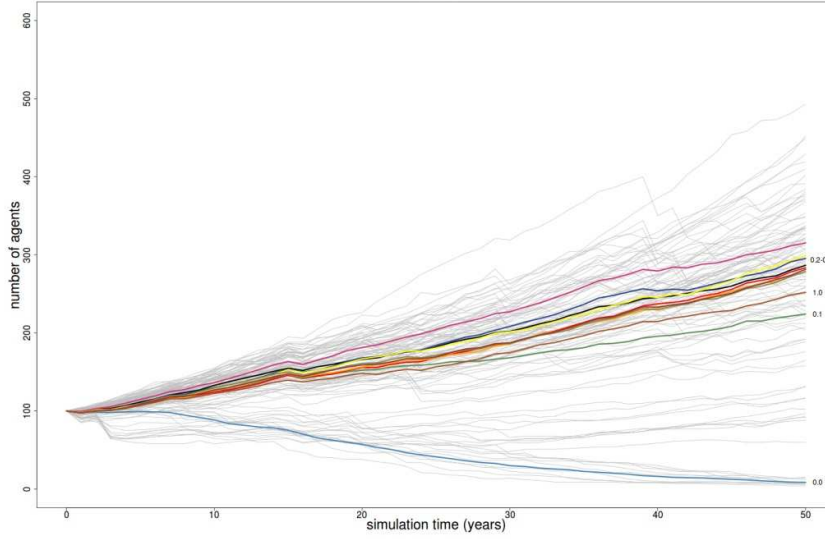




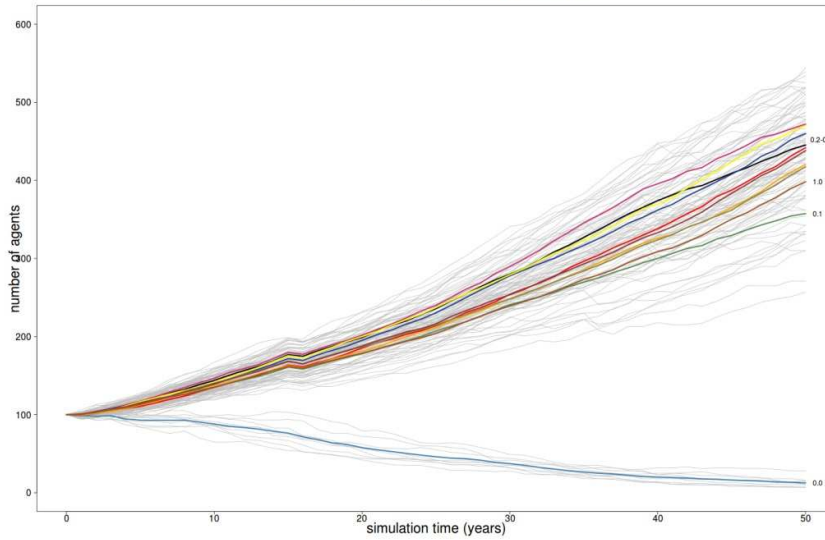




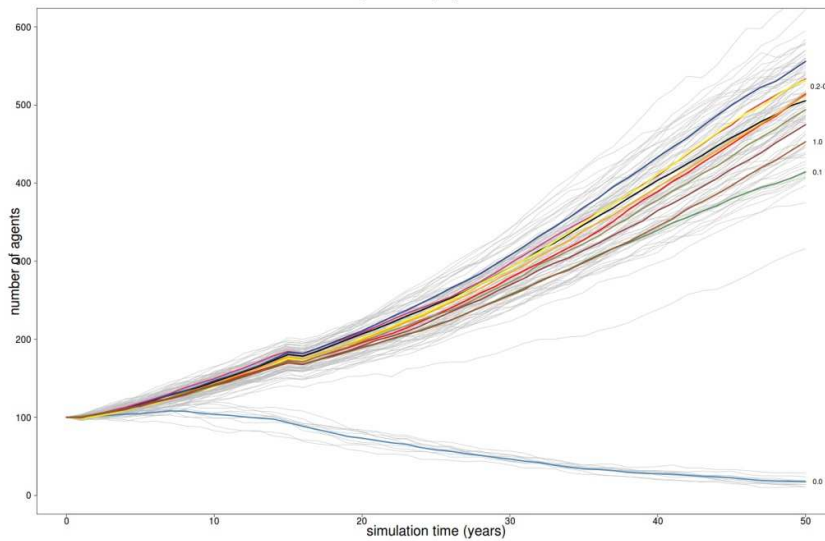
EMR impact on population for KS



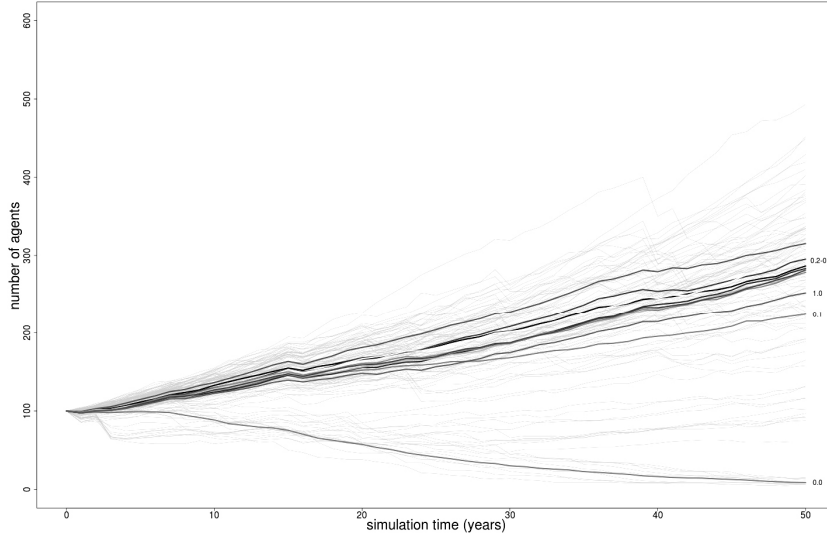
EMR impact on population for NWI



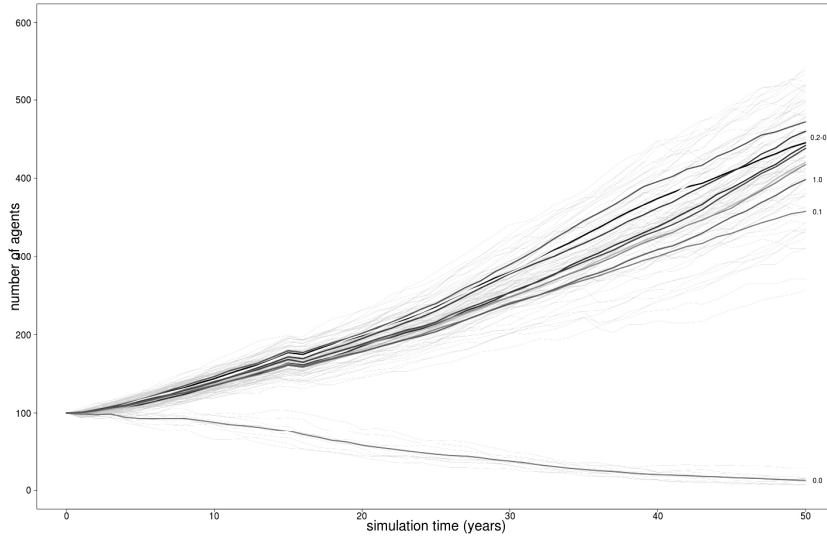
EMR impact on population for wI



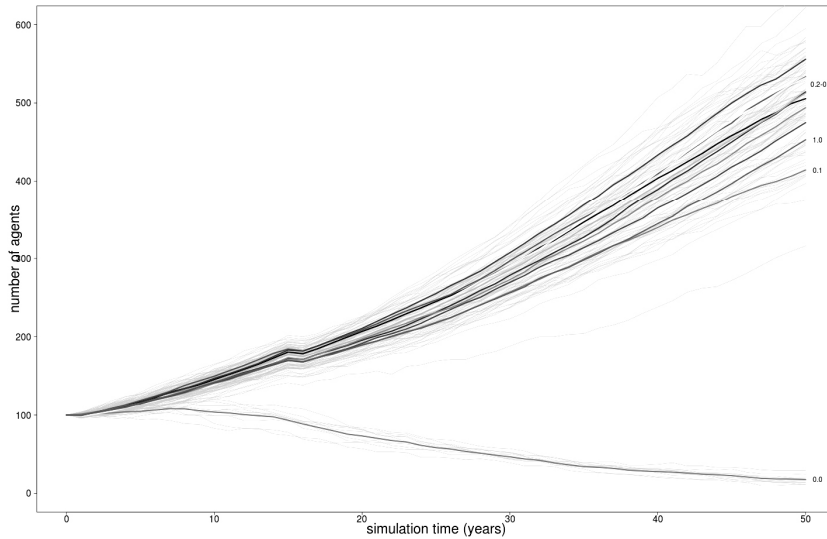
EMR impact on population for KS

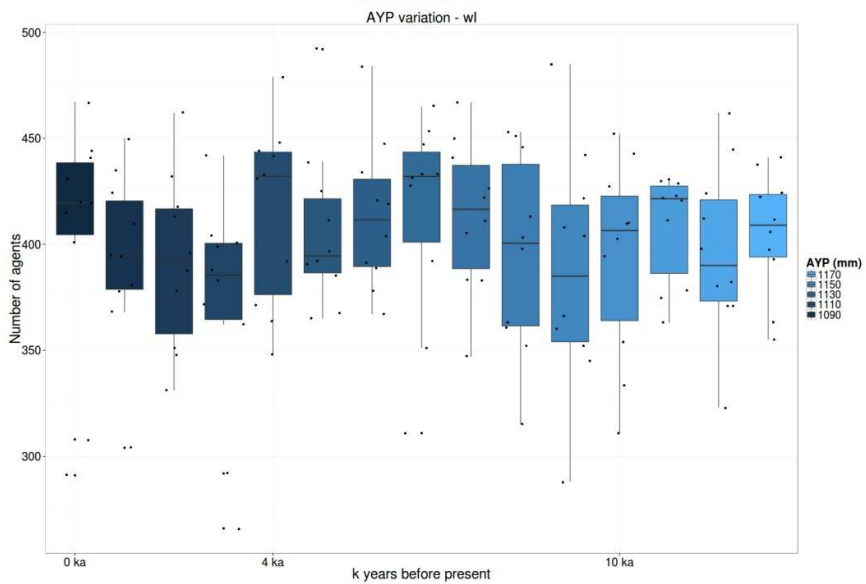
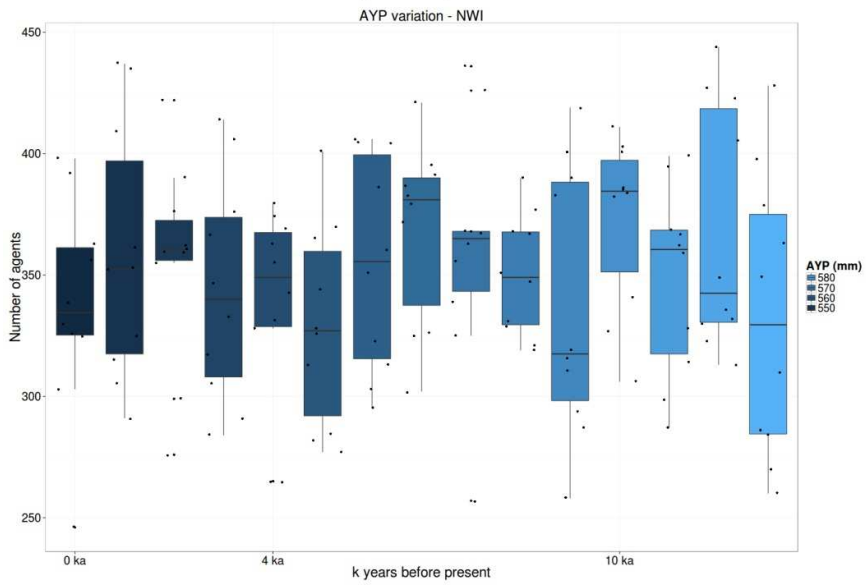
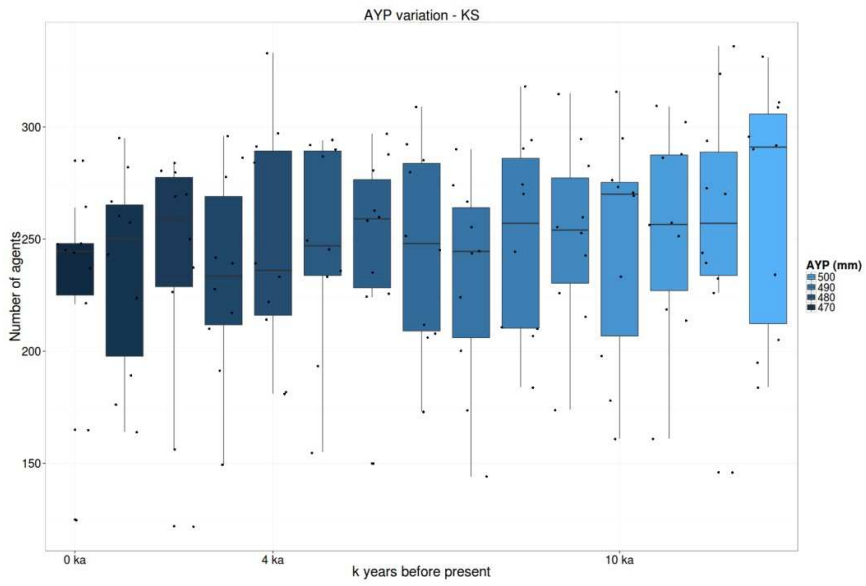


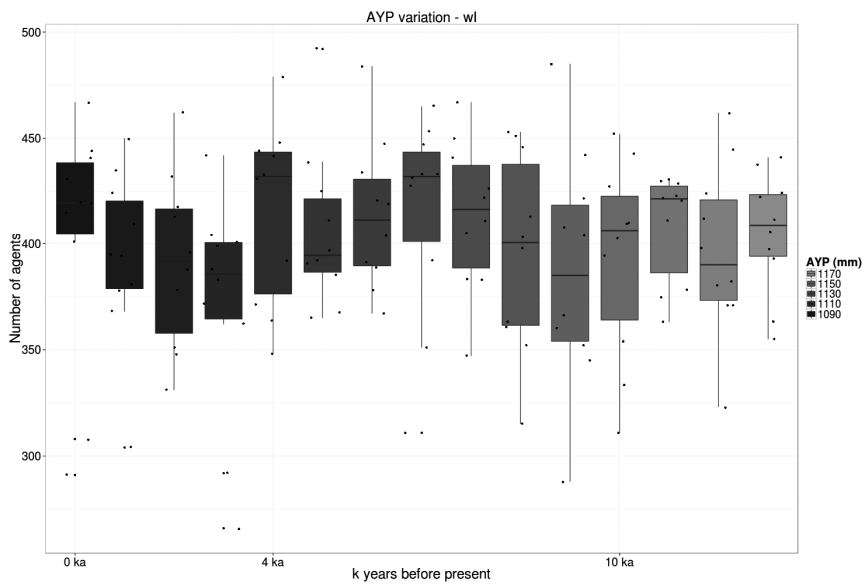
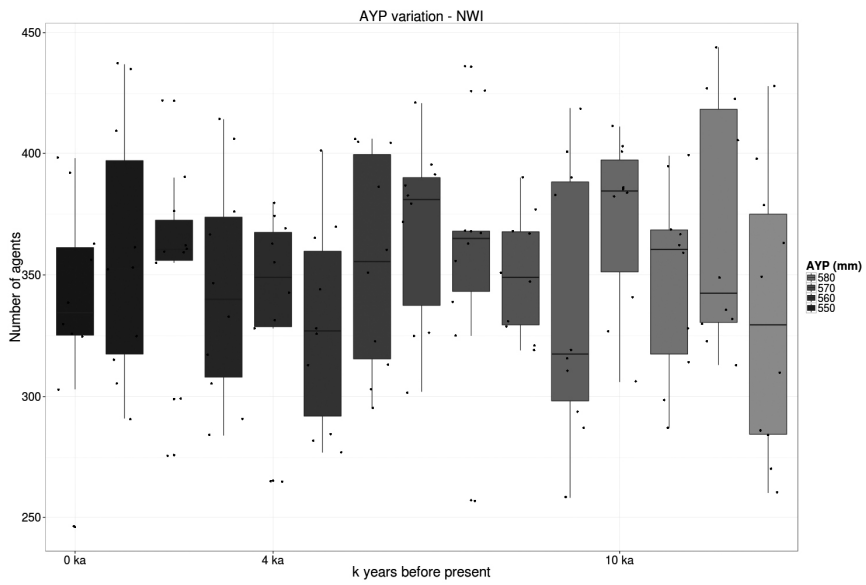
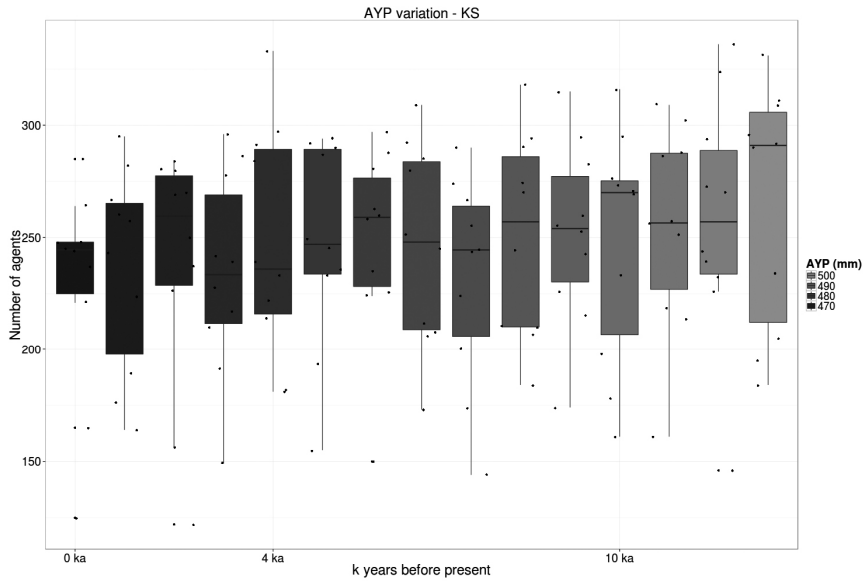
EMR impact on population for NWI

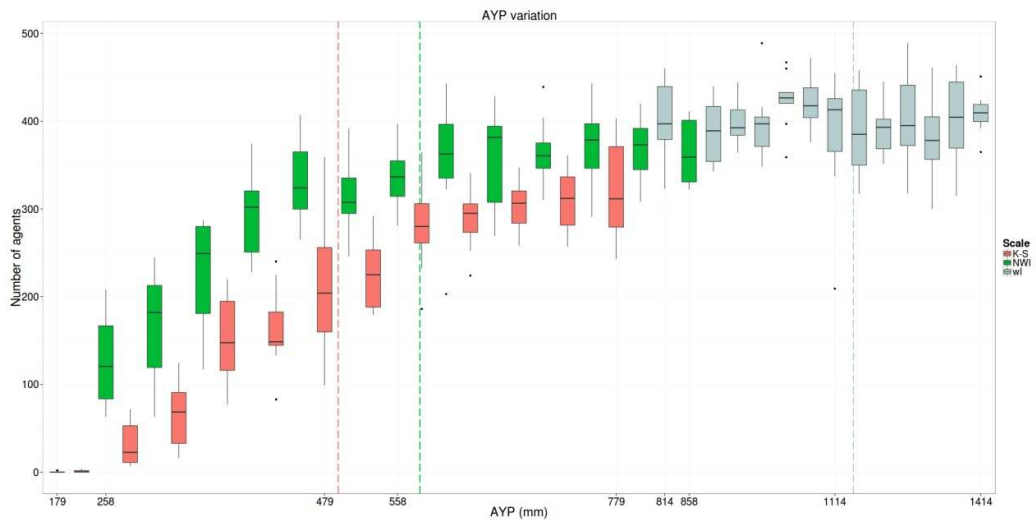


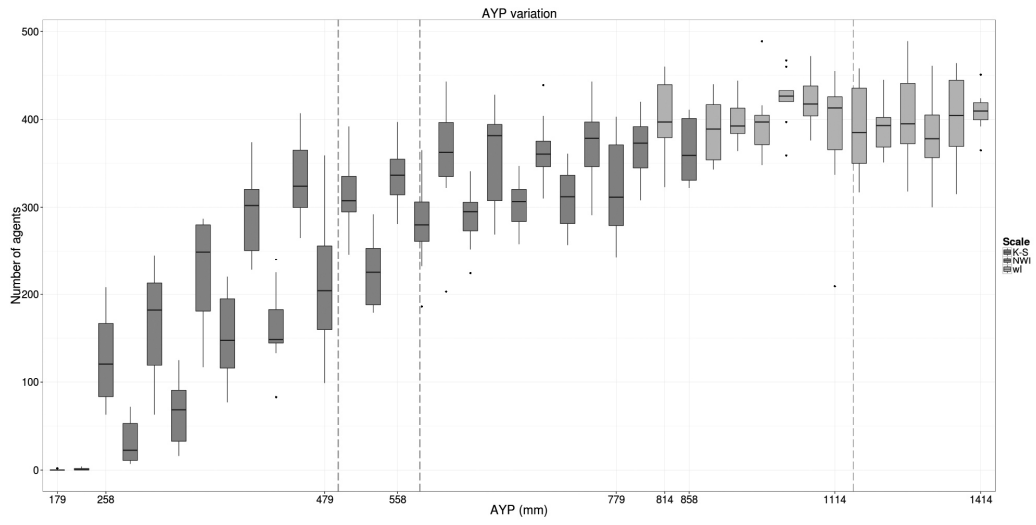
EMR impact on population for wI

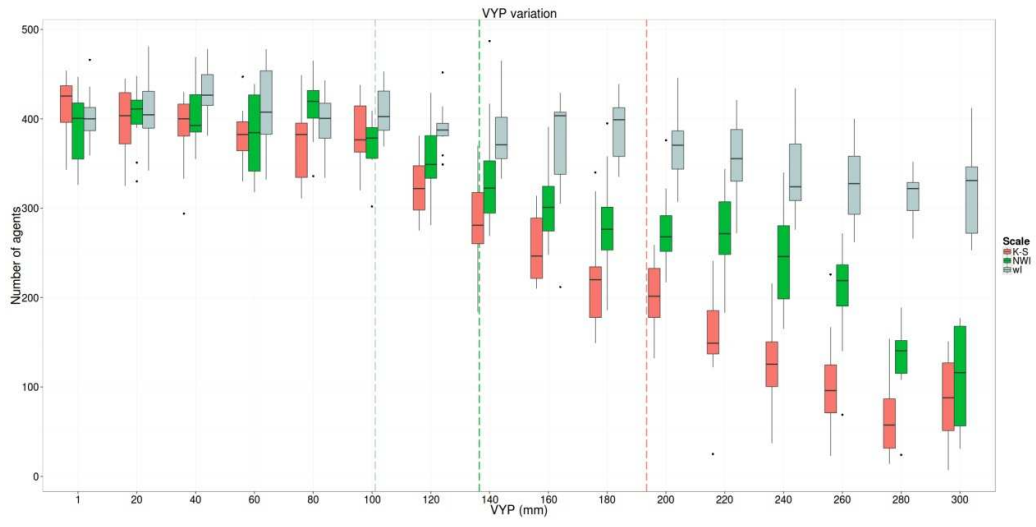












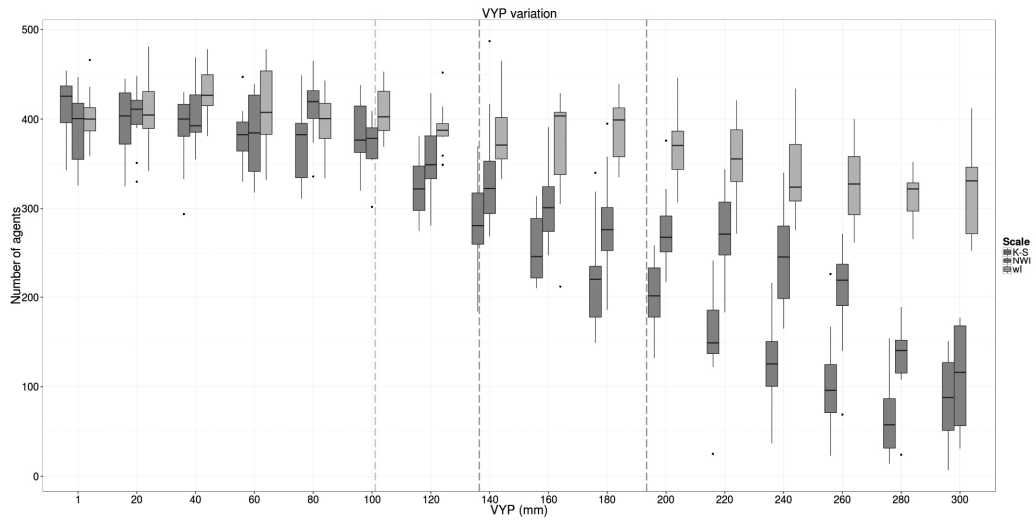


Table 1. Calibration of historical meteorological data (0 ka) for the Holocene period based on palaeoclimatic model by Liu et al (2003). KS (Kutch-Saurashtra, local), NWI (NW India, regional), wl (whole India, continental), AYP = average yearly precipitation, VYP = variance in yearly precipitation.

Time	Precipitation increment rate (%)	AYP KS (mm)	AYP NWI (mm)	AYP wl (mm)
0 ka	0	468.20	545.73	1088.67
4 ka	2.33	479.11	558.45	1114.04
10 ka	5.83	495.50	577.55	1152.14
12 ka	7	500.98	583.93	1164.88
VYP		193.47	136.52	101.11

Table 2. Parametrizations for Experiment 1 (a to c). KS (Kutch-Saurashtra, local), NWI (NW India, regional), wl (whole India, continental), AYP = average yearly precipitation, VYP = variance in yearly precipitation, EMR = end-of-year minimum residual resources.

Experiment	Scale	AYP (mm)	VYP	EMR
1a	KS	495.50	193.47	0-1 (0.1 increments)
1b	NWI	577.55	136.52	0-1 (0.1 increments)
1c	wl	1152.14	101.11	0-1 (0.1 increments)

Table 3. Parameterizations for Experiment 2 (aa to cb). KS (Kutch-Saurashtra, local), NWI (NW India, regional), wl (whole India, continental), AYP = average yearly precipitation, VYP = variance in yearly precipitation, EMR = end-of-year minimum residual resources (0.1 = 10%).

Experiment	Scale	AYP min (mm)	AYP 4 ka (mm)	AYP max (mm)	interval (mm)	interval (ka)	VYP (mm)
2aa	KS	179.11	479.11	779.11	50.00	c. 20	193.47
2ab	KS	468.20	479.11	500.98	2.73 (2.5)	c. 1	193.47
2ba	NWI	258.45	558.45	858.45	50.00	c. 20	136.52
2bb	NWI	545.73	558.45	583.93	3.18 (3)	c. 1	136.52
2ca	wl	814.04	1114.04	1414.04	50.00	c. 20	101.18
2cb	wl	1088.67	1114.04	1164.88	6.35 (6)	c. 1	101.18

Table 4. Parameterizations for Experiment 3 (a to c). KS (Kutch-Saurashtra, local), NWI (NW India, regional), wl (whole India, continental), AYP = average yearly precipitation, VYP = variance in yearly precipitation, EMR = end-of-year minimum residual resources.

Experiment	Scale	AYP (mm)	VYP min (mm)	VYP max (mm)	interval (mm)	VYP
3a	KS	479.11	1	300	20	193.47
3b	NWI	558.45	1	300	20	136.52
3c	wl	1114.04	1	300	20	101.11



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Balbo, AL; Rubio-Campillo, X; Rondelli, B; Ramirez, M; Lancelotti, C; Torrano, A; Salpeteur, M; Lipovetzky, N; Reyes-Garcia, V; Montanola, C; Madella, M

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