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

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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 (Widlok 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/m^2, efficiency to 23%, energy to 18400 KJ/m^2 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 (SI1).

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 (Widlok 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).

Acknowledgments

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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

Figure 1

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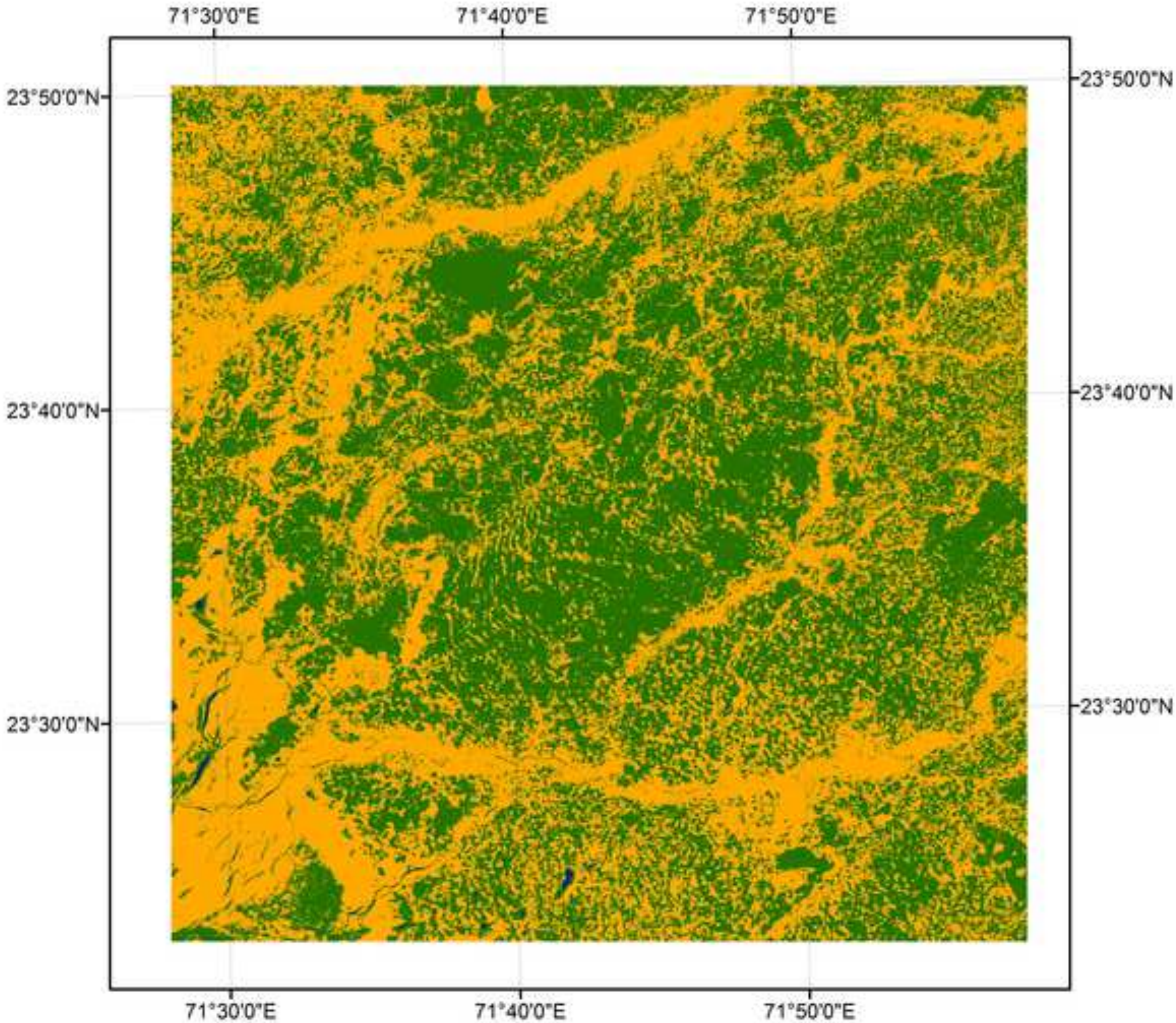

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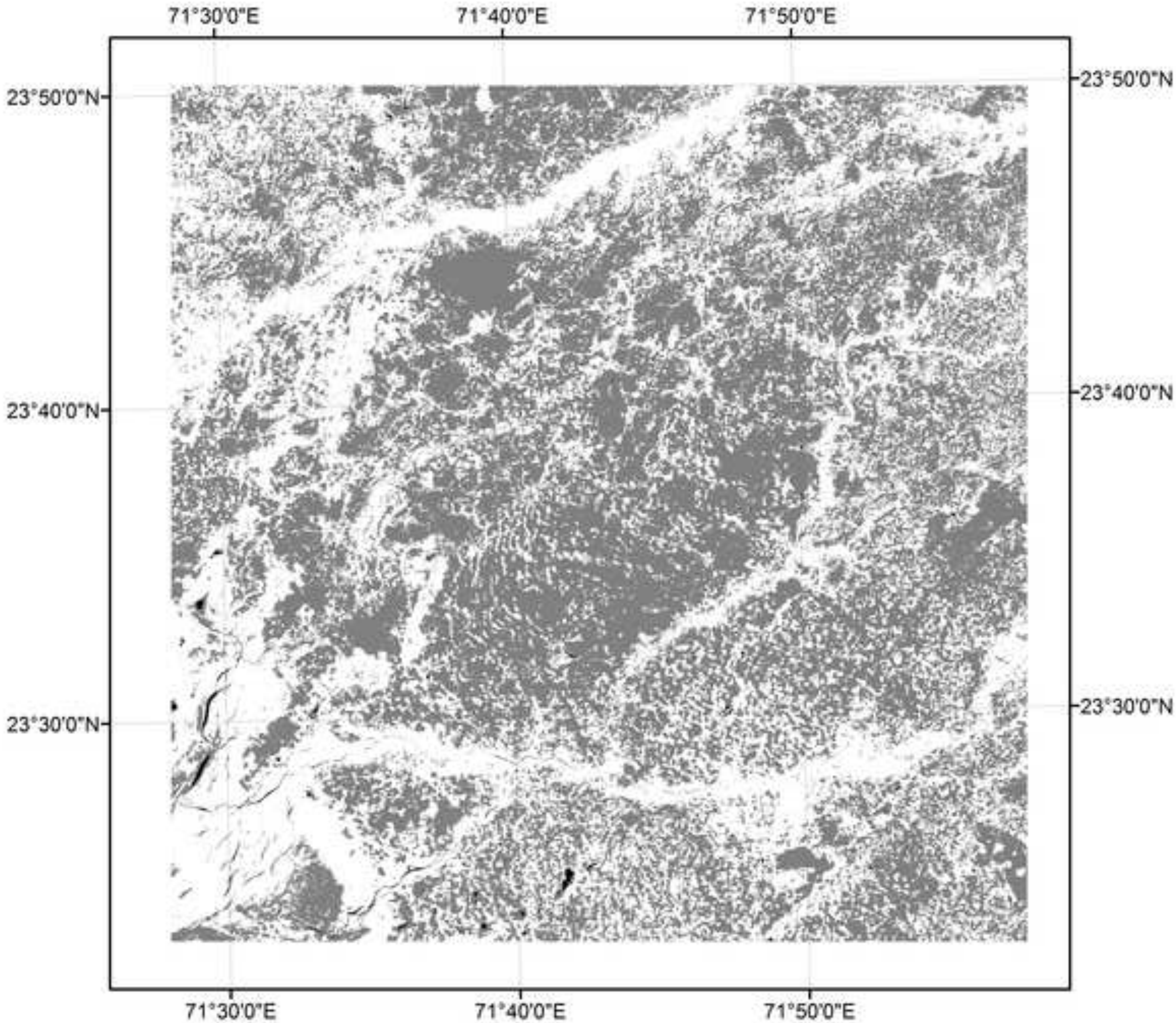

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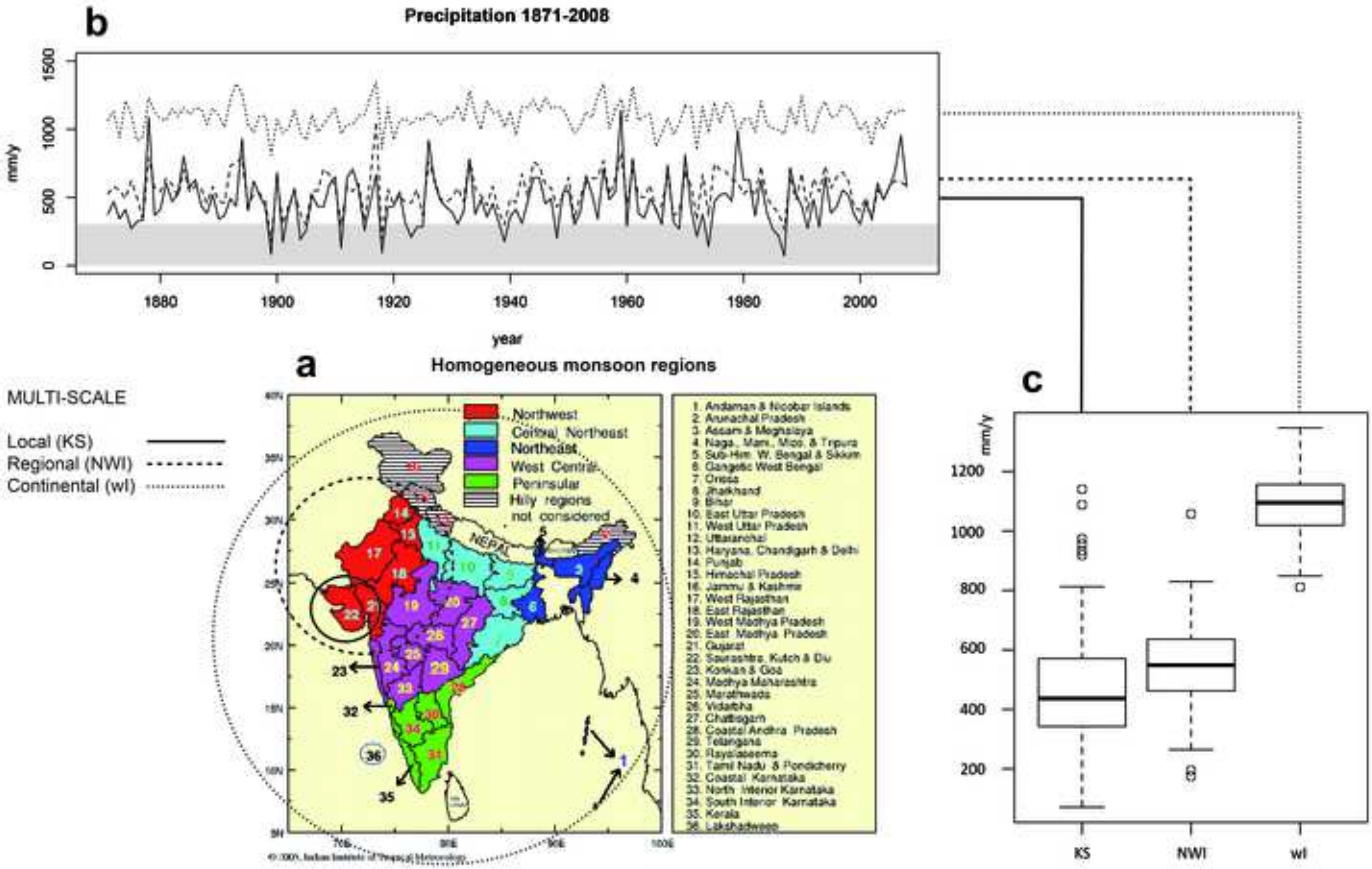

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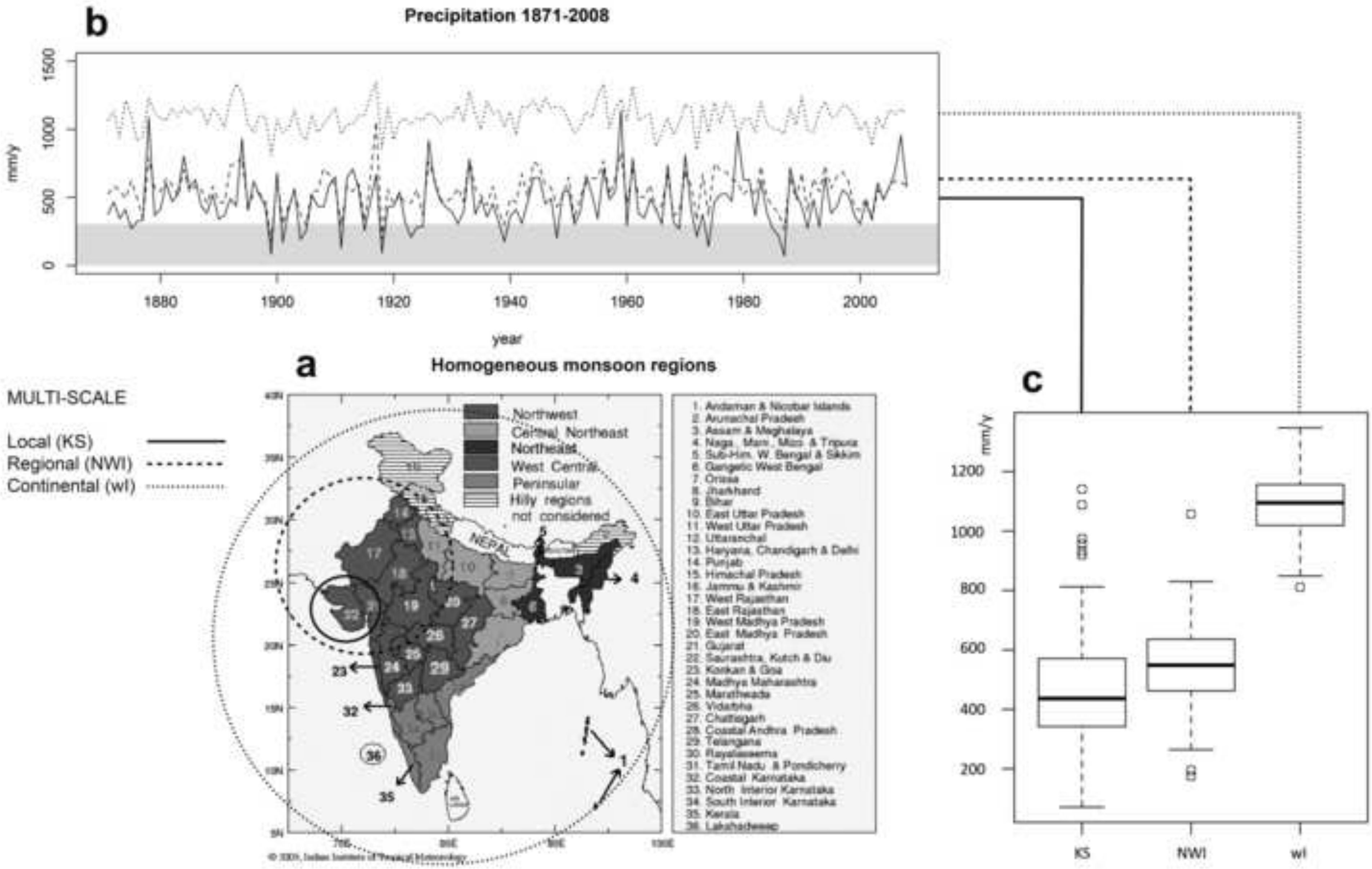

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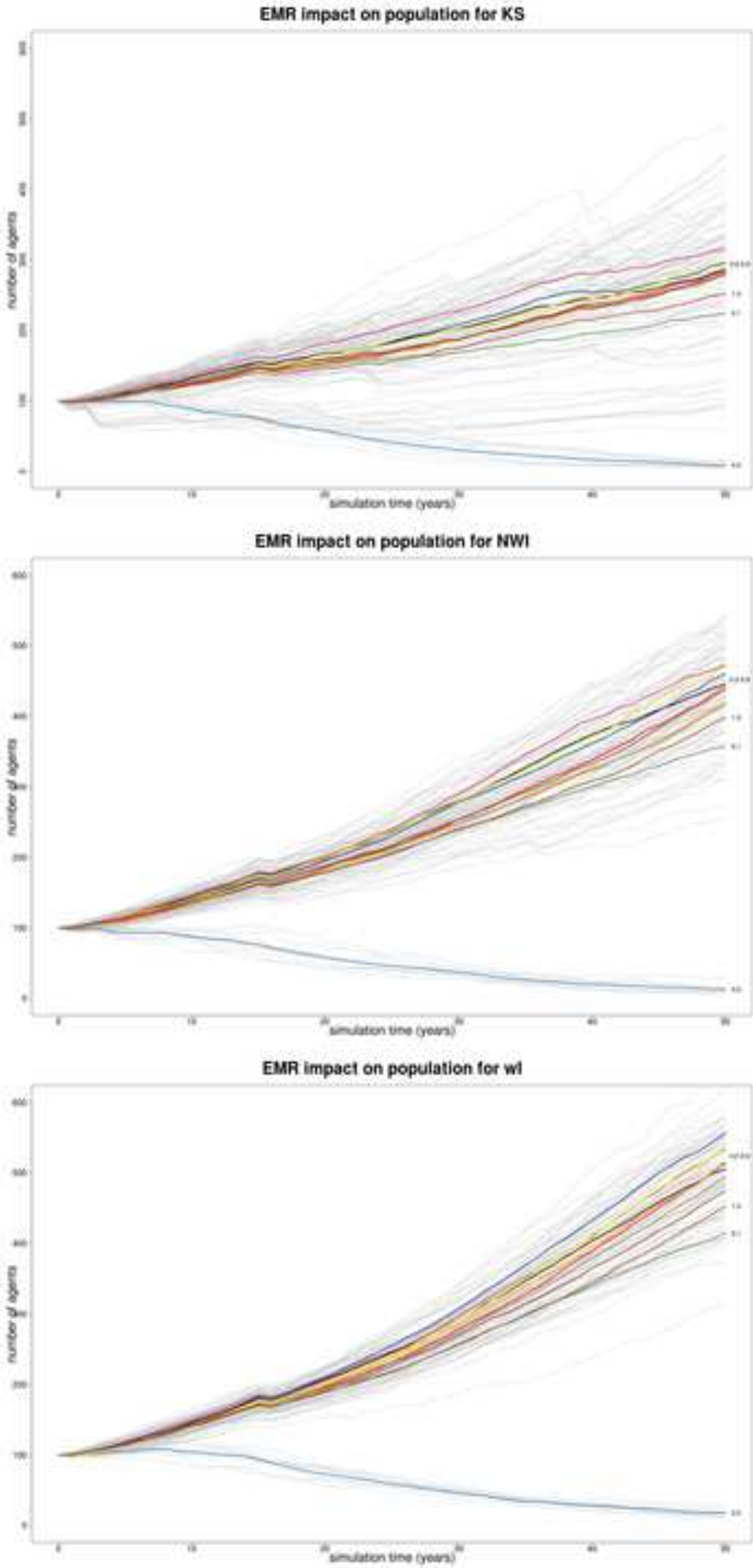

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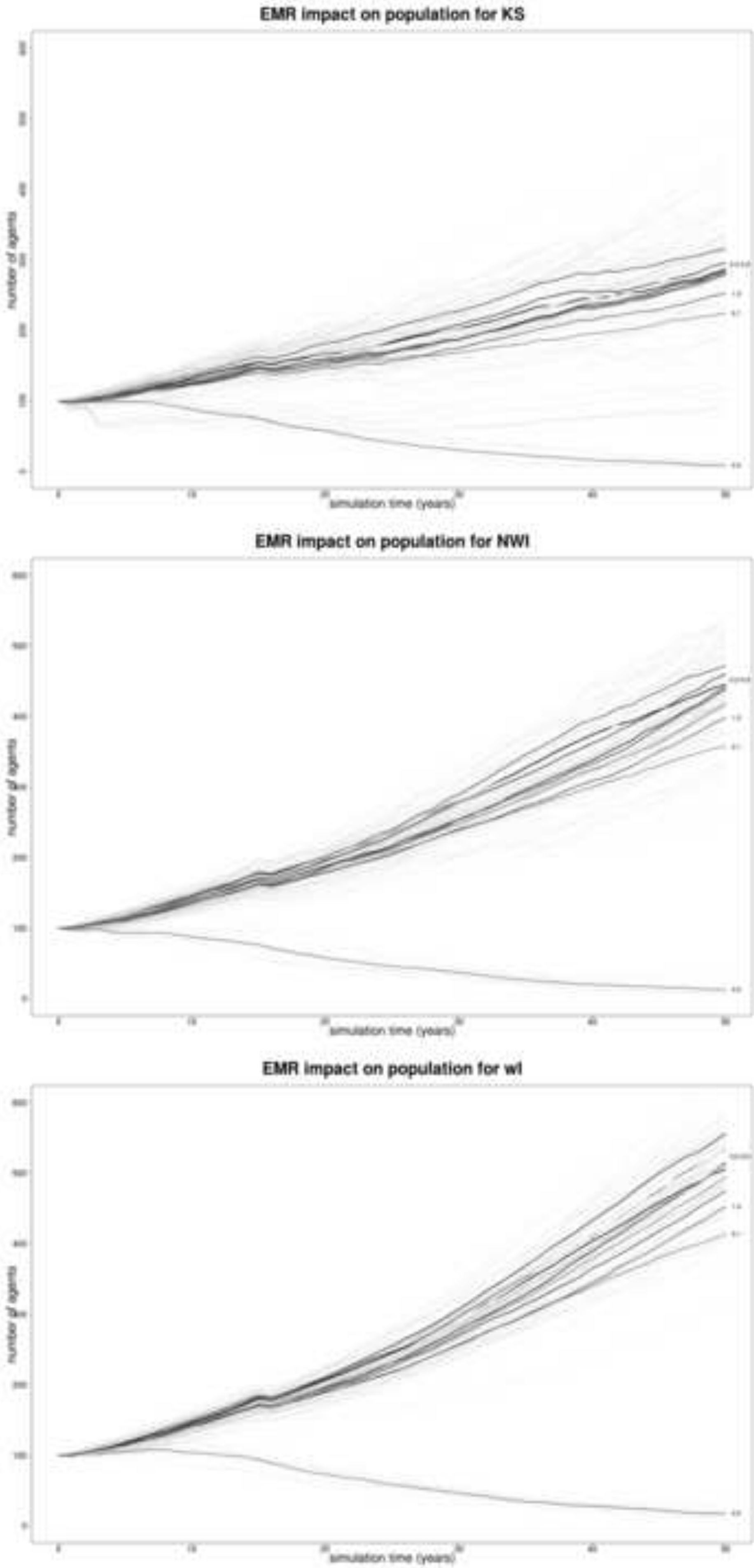

Figure 4

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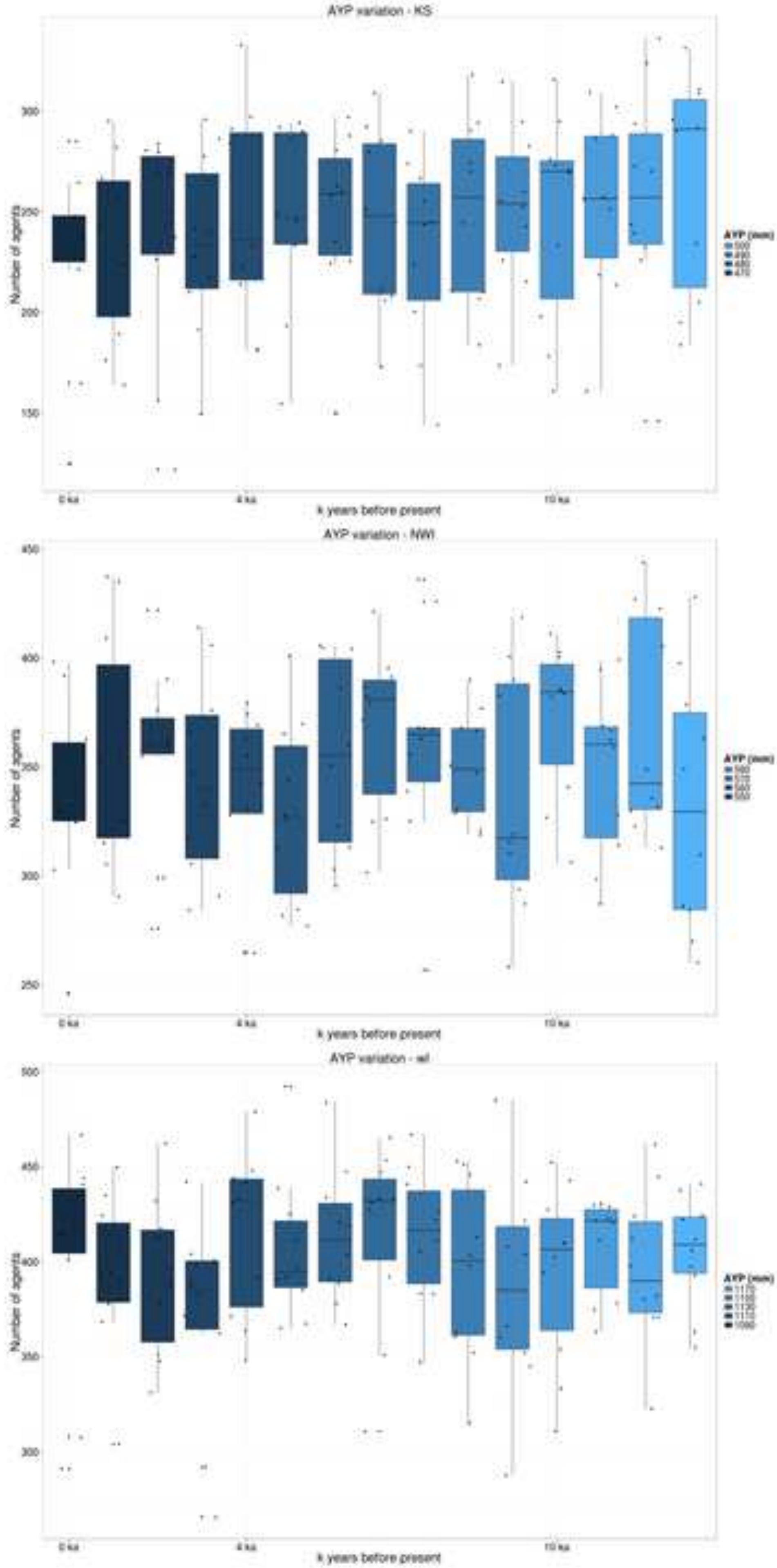

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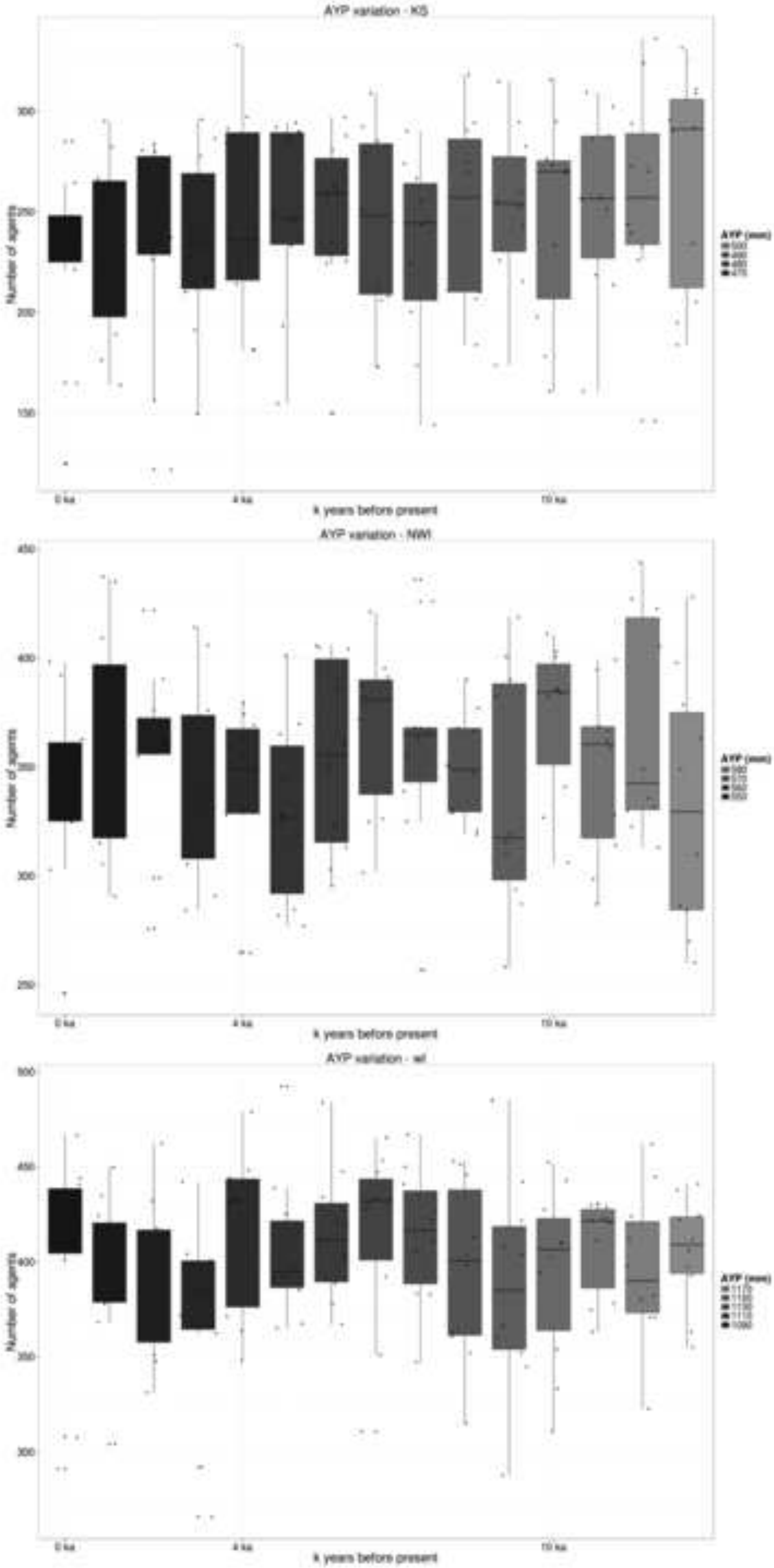

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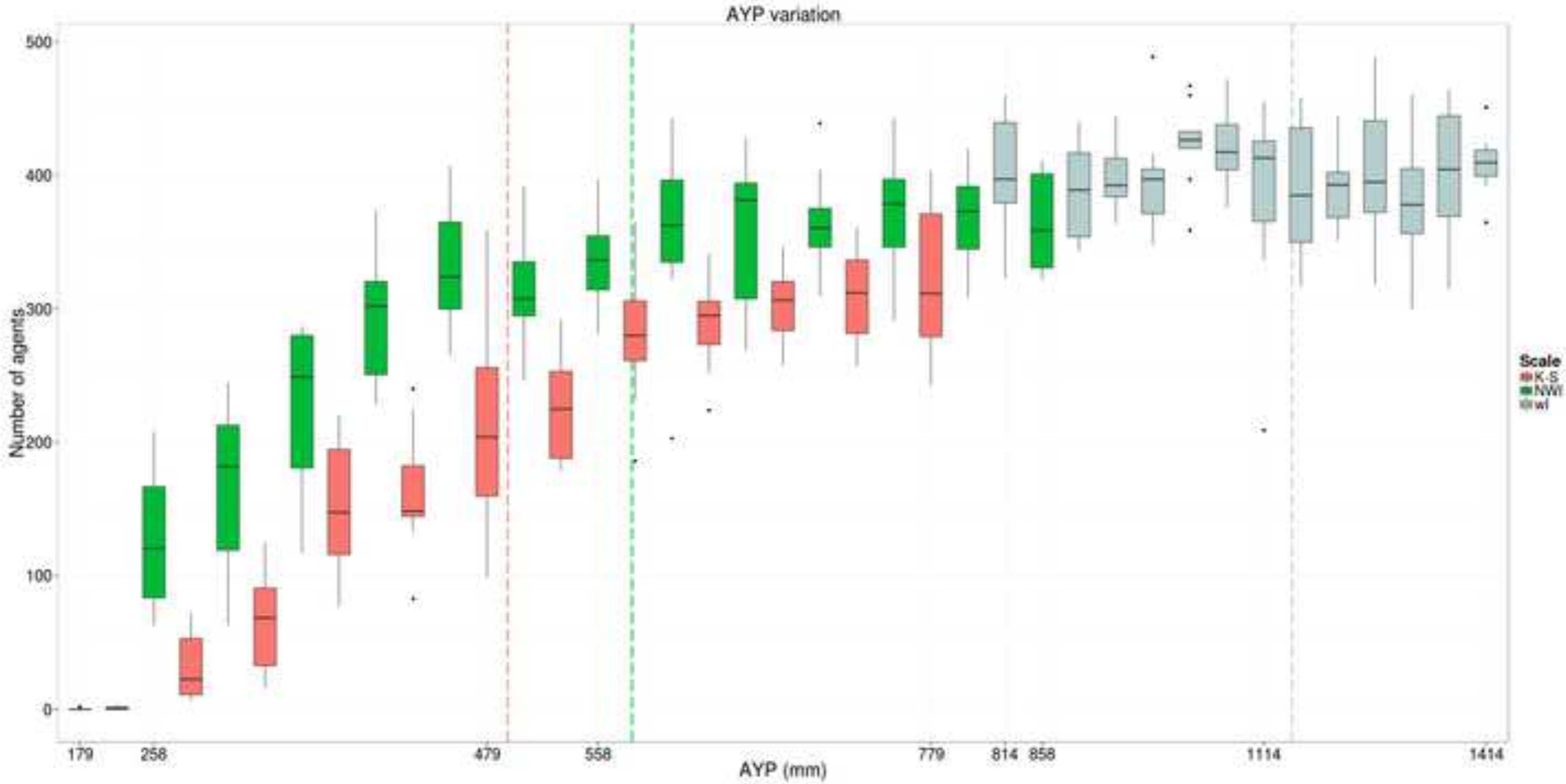

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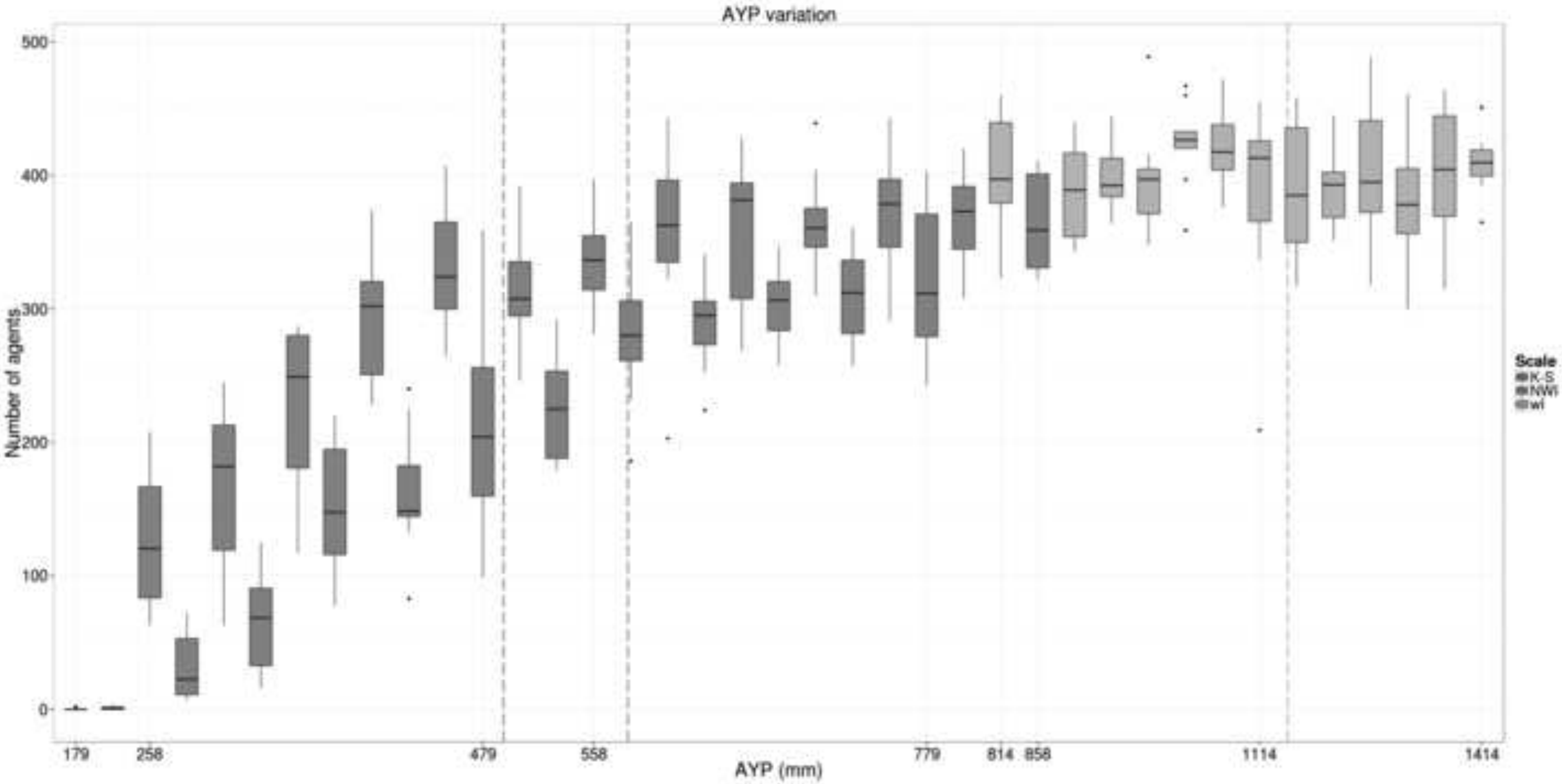

Figure 6

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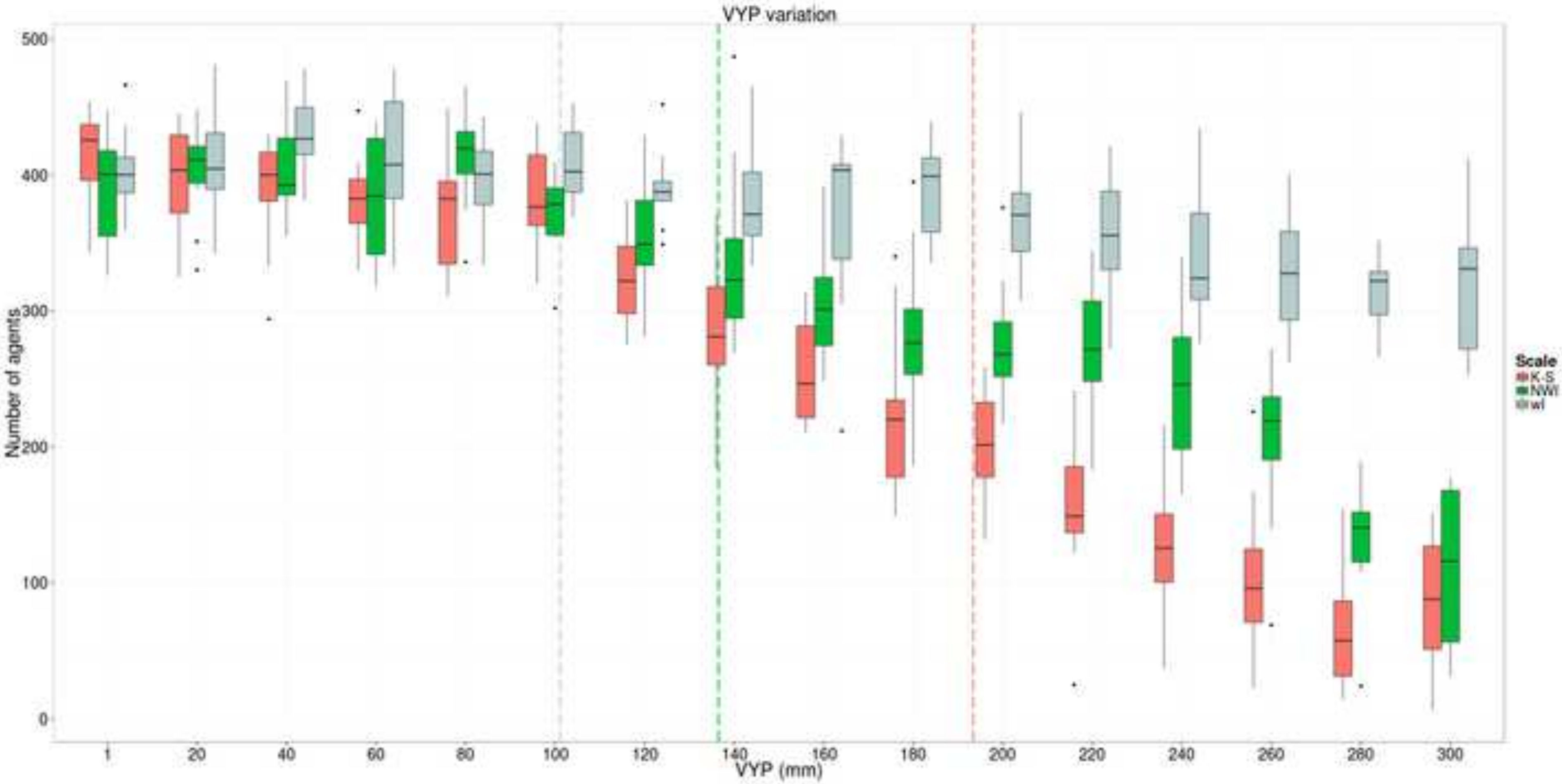

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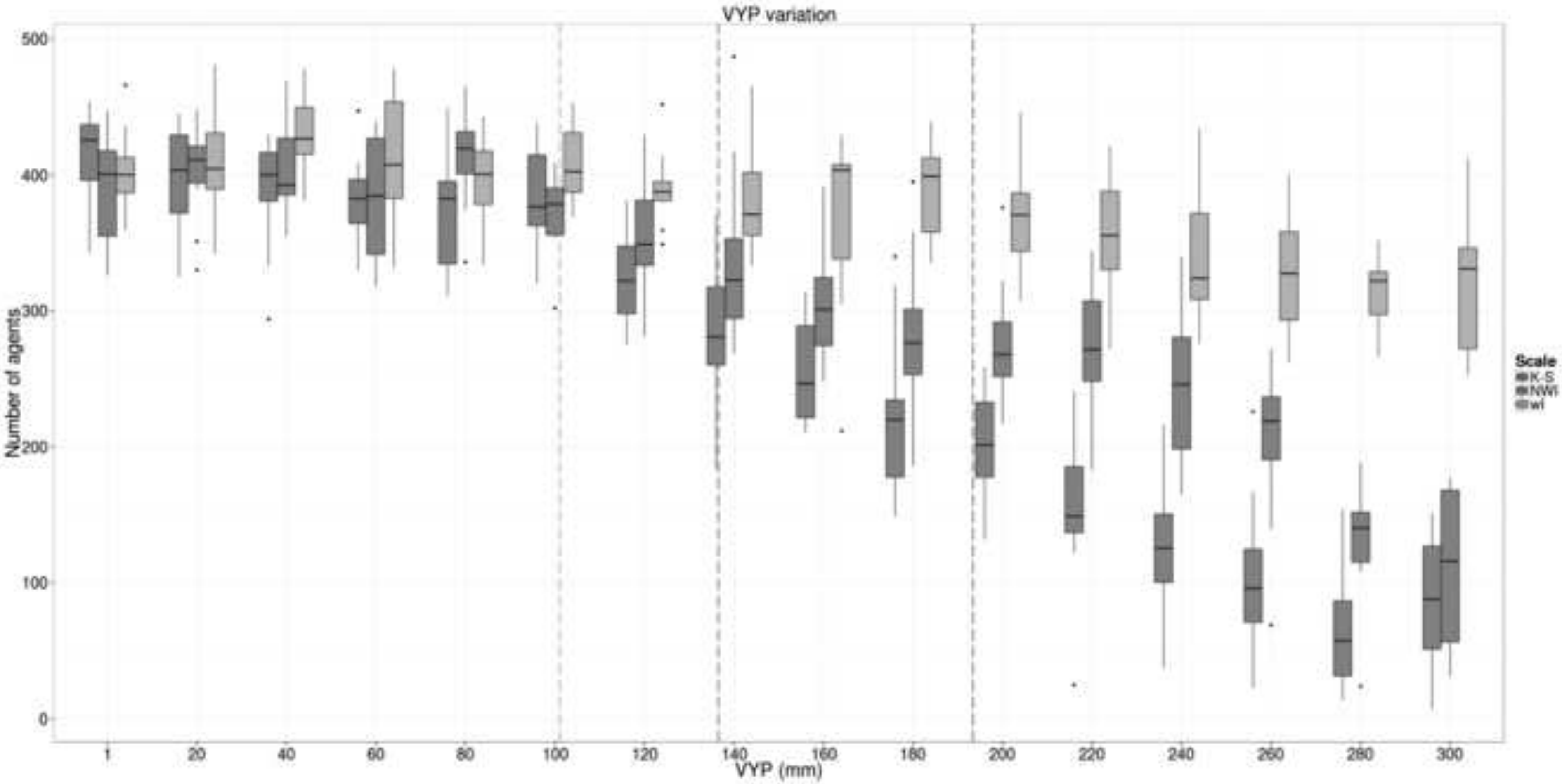

Table 1

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

Time	Precipitation increment rate (%)	AYP KS (mm)	AYP NWI (mm)	AYP wI (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-Saurastra, 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.

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	wI	1152.14	101.11	0-1 (0.1 increments)

Table 3. Parameterizations for Experiment 2 (aa to cb). KS (Kutch-Saurastra, 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%).

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	wI	814.04	1114.04	1414.04	50.00	c. 20	101.18
2cb	wI	1088.67	1114.04	1164.88	6.35 (6)	c. 1	101.18

Table 4. Parameterizations for Experiment 3 (a to c). KS (Kutch-Saurastra, 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.

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	wI	1114.04	1	300	20	101.11

SI1: ODD

Table of Contents

1 Introduction

The agent-based simulation we propose explores the potential for the persistence of hunter-gatherer (HG) communities relative to climate-driven environmental change during the Holocene in N Gujarat, a semi-arid region in NW India.

The model description follows the ODD (Overview, Design concepts, Details) protocol for describing individual- and agent-based models (Grimm et al. 2006, 2010).

2 Purpose

In our starting hypothesis HG groups are adapted to marked seasonality (represented by the monsoon) in the arid margins of northern Gujarat. We intend to explore HG resilience (Holling 1973, Carpenter et al. 2001) considering climate variability.

3 Entities, state variables, scales

The model explores the socio-ecological behaviour of HG populations. Agents interact within a given territory.

3.1 Scales

3.1.a Agent Scale

The basic agent is defined as a couple (one woman and one man). This is considered to be the entity engaging in all decision-making processes and actions modeled in the simulation.

3.1.b Time Scale

Time Scale for the simulation is one day. This time step is coherent with the granularity of agents' planning.

3.1.c Space Scale

The *spatial* resolution of the proposed simulation model is constrained by the resolution of available relevant geographic data and the nature of the agent mobility and resource gathering activities being modeled.

Hence, it was decided to use 31.5m x 31.5m cells, corresponding to ca. 1000 square meters. This is the level of resolution of the most detailed geographical information available for the area. This surface fits the type of settlements recognized from archaeological surveys.

3.2 Environment

The simulation environment is large enough to develop all potential processes defined by the model. It extends over an area of 50 Km x 50 Km (2500 Km2). Space is represented as a regularly spaced grid of cells (a raster map). Each cell is a square of 31.5 m per side, and the total size of this environment translates into a space of 1600 x 1600 cells (50,400 m x 50,400 m).

The ground model includes elevation and land features. Elevation is determined by a Digital Elevation Model (DEM), a raster map containing the elevation value for each cell calculated from contemporary satellite imagery. Land characteristics are reduced to three elemental features:

- Water: represents rivers and lakes.
- Dune: represents elevated aeolian deposits. Home location of the agent will always be in a dune cell.
- Interdune: represents the depression between dune, where most resources grow. The different land features do not seasonally change in extension but their productivity (in terms of moist content and therefore resources supported) does.

The cornerstone of our environmental modeling is the climatic 'engine'. The climate module determines the quantity of rain that precipitates evenly on the landscape on every time step. Precipitation is used in conjunction with the terrain model to calculate the amount of biomass for each cell and season. The climate model is based on historical data, as well as Holocene monsoon models.

3.2.a *Climate*

The focus on resource utilization strategies within a particular environment requires to make explicit the potential variations in the landscape. In particular for our case study, the presence of the monsoon generates a strong seasonality (asymmetrical precipitation patterns).
Monsoon seasonality determines the presence of three critical “moments” in simulation time, each spanning 4 months. Therefore, the seasonal subdivision in three periods will be repeated in a cyclical way as follows:

- JJAS (rain season: high precipitation, high temperature, low evapotranspiration)
- ONDJ (post-Monsoon: low precipitation, cool temperature, medium evapotranspiration)
- FMAM (dry season: low precipitation, high temperature, high evapotranspiration)

It is important to note that any given “year” in the model starts with the beginning of the rain season (June). In fact, virtually all rain in the region is carried by the monsoon that falls between June and September (JJAS). Therefore, it is during the JJAS season that the totality of the generated yearly precipitation value is calculated (following a Gamma distribution). No additional precipitation is considered for the remaining eight months of the year (ONDJ and FMAM).

3.2.b Resources

Each cell has a finite number of resources. Resource availability for each cell is calculated from the following variables:

- Yearly precipitation (rainfall, using a Gamma distribution)
- Type of cell (Water, Interdune, Dune)
- Mean yearly Biomass per cell and type.
- Cell history (e.g. whether part of the resources in the cell were consumed before).

Resources include the total biomass that can be found in a cell (fauna and flora). They are exploited by HG agents engaging into foraging activities. Foraging includes activities such as hunting animals and gathering plants, fruits, seeds, etc. Indeed, from a literature review it is clear that secondary biomass production (animals) is directly related to primary biomass quantity. Moreover, as there is no interest in our simulation to explore gender-based labour division we decided to consider hunting and gathering as a single activity (foraging) without distinguishing between plant or animal utilization. In the light of this, it was decided to consider a value for cell (dune vs interdune) based on published information of primary biomass production in desert (dune) and savannah (interdune) biomes (after Kelly 1983 – Table 3).

Table. Parameters for resource parametrisation according to Kelly (1983; Table 3, p. 284)

Cell type	Yearly primary biomass production	Efficiency	Energy	KCal
Dune (desert)	700g/m²	13.00%	1820KJ/m²	435KCa
Interdune (savanna)	4000g/m²	23%	18400KJ/m²	4395KCal

Cell area = 1000m²
1 g Primary Biomass = 20KJ
1 kcal = 4.184 KJ

Distance to water
This average value of resources is modified based on the distance of a cell from the closest water body. This weight decreases linearly to the distance, and models the heterogeneity of biomass generated by a higher presence of flora and fauna near the zones where needed water can be collected.

Efficiency
The total primary biomass value does not constitute the entire primary biomass available for consumption to animals and humans. This value represents the entire biomass production including both edible (fruits, tubers some roots etc.) and non-edible (wood, stems, branches etc.) parts of the plants. The ratio of profitable biomass versus whole biomass will be the efficiency value specified in the above table that allow to calculate the energy effectively available for humans.

3.3 Agents

The following attributes have been chosen to account in our model

- **Age** – A numeric variable that keeps track of how many time steps a given agent has been active in the simulation.
- **Children** - number of children per agent. Birth and mortality rates are bound to resource availability.
- **Home location** - the cell where the agent resides and the spatial centre of the activities it carries out. Any number of agents can share a given cell.
- **Home range** - Maximum distance an agent may travel in one day. This attribute restricts foraging and social activities from taking place in cells too far from the agent Home location. The area enclosed in the circle of radius “Home range” is divided in six equal sectors. Such division models the idea of direction of exploration for the agent actions, while simplifying the decision-making process (an agent will choose to forage in one of the six sectors, independently of single cells).
- **Social range** - Maximum distance within which an agent with individuals coming of age will seek suitable matches to generate a new agent.

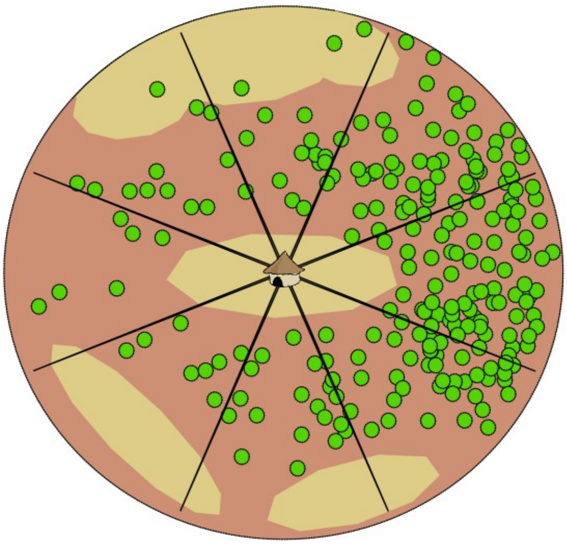


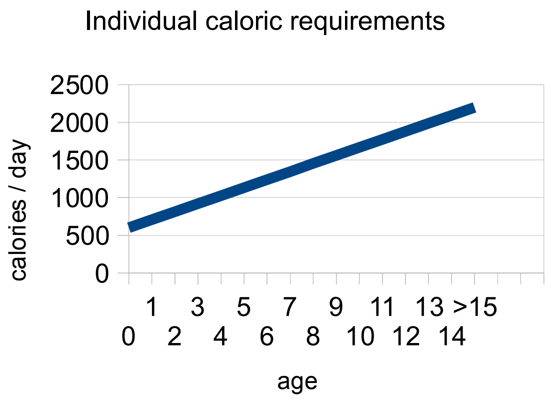
Figure. Home range division for foraging and moving home actions

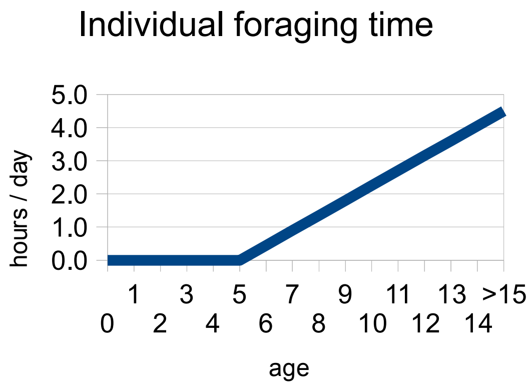
- **Food needs -** Value that sets the minimum calories a given individual needs in each time step in order to survive. The total amount of food needs for an agent is computed as the sum of the food needs of the individuals that form a given agent. The probability of death increases for all the individuals that form a given agent when this basic quantity of resources is not foraged within a day (due to starvation). Needs are defined by the following table:

- **Available forage time** - Daily time that an agent can spend on foraging. The total amount of foraging time for any given agent is computed as the sum of the foraging time of the individuals that compose it. Foraging time increases from infancy to adult life, modelling learning processes as defined in the following table. Foraging learning process is modeled using vertical transmission. Individual children within a given agent gradually learn to forage in an efficient way from their care-givers, and for this reason the available foraging time contributed by children increases until adulthood.

4 Process overview and scheduling

Tables. Individual caloric requirements (left), Individual foraging time (right)





Execution follows two time-scales. On the one hand, three processes ('yearly precipitation', 'biomass yearly production' and 'population size adjustment') are executed once every year. On the other hand, agents decision-making processes are updated on a daily base. The simulation follows this schedule, beginning the first day of the JJAS season:

For each year:

1. Precipitation calculation
2. Biomass yearly production
3. For each day of the year:
   a. Daily biomass availability
   b. Agent planning:
      i. Knowledge update
      ii. Choice of actions
   c. Execution of agents actions
4. Population size adjustment

Details for each simulation phase are given hereafter.

4.1 Precipitation calculation

The total amount of rain is calculated as a random number following the Gamma distribution defined in section 7 (Input Data)

4.2 Biomass Yearly Production

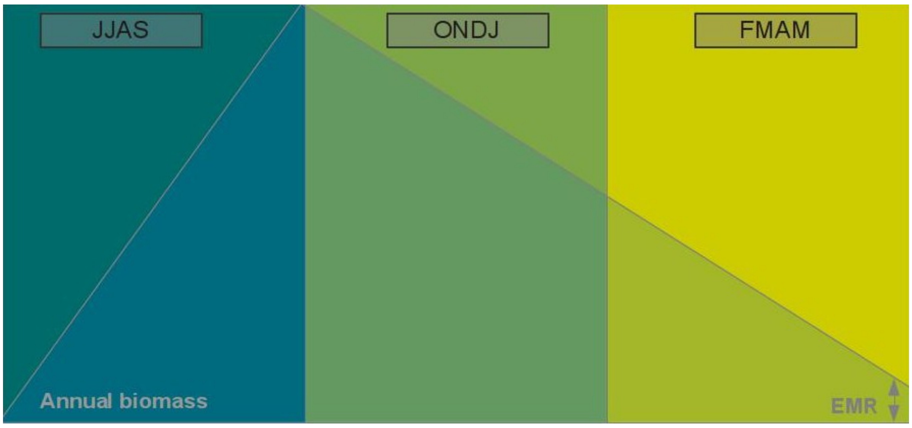
The biomass that a cell will produce in an entire year is calculated from rainfall and mean year production for its particular type, provided by historical records.

We consider a linear relation between rain and biomass production. The deviation of rain in a given year from the period mean allows interpolating the amount of biomass deviation from the yearly mean biomass. That is, if the mean of rain is 100 liters and the climate model produces 80 liters the deviation to apply is 20%, and for that year the biomass will be a 80% of the mean yearly production for the period.

4.3 Daily processes

4.3.a Biomass availability

Yearly biomass production does not appear immediately in the cell in the first day of JJAS season. Resources increase gradually, following a cumulative pattern that accounts for the progressive accumulation of water through JJAS, until the beginning of ONDJ. From then on, resources decrease linearly to the end of the year, when they reach a percentage of the highest peak defined by the 'end-of-year minimum residual resources' parameter (EMR). Variations in EMR does not affect overall yearly biomass production so that the higher the EMR, the lower the maximum peak of resources at the JJAS-ONDJ boundary.



Biomass overall production for a given year

Figure. Modelled biomass availability through the year

4.3.b Agent planning

Each day the agent will update its knowledge about environment and choose an action to execute (the decision-making process is defined in the Submodels section 8). The list of available actions is:

- **Forage -** The agent takes multiple walks of a bounded length computed from available foraging time. Walks are limited to the agent's Home range. From the visited cells, resource reward is retrieved based on biomass of the cells. The agent will halt the walk when reward achieves food needs.
- **Move home** - The agent moves from its current home location to a new one within Home range. The new home settlement is chosen randomly between the dune cells situated in the richest sectors (containing the highest amount of resources) within Home range. Afterwards, a Forage Action is executed using half the available daily Foraging time of the agent in order to include the time spent on movement.

4.4 Adjustment of agent population size

This processes are executed for each agent:

1. **Age**. Agent aging (increment human objects age).
2. **Death.** Every individual inside an agent will have a probability of dying. At the end of the year every individual within an agent must pass two tests to survive:
    - **Natural death.** Every individual has a 1.5% annual death probability, except during the first four years of life, when this probability is 10%.
    - **Starvation.** Depends on the capability of an agent to fulfil its caloric requirements. Every day the agent computes the percentage of needed resources that it was unable to collect. This 'starvation value' is accumulated through the year. The cumulative starvation value is translated into the overall percentage of full days of the year in which the agent was unable to gather sufficient resources. This percentage is translated at the end of the year as the probability for each individual composing the agent to die of starvation.
3. **Removal**. If all the individuals that form an agent are dead, the agent will be removed from simulation.
4. **Reproduction**. At the end of the year every agent where both adults are still alive will have a 50% chance of having a new child.
5. **Emancipation**. An agent with individuals coming of age will seek suitable matches among agents within its social range. When two individuals coming of age from different agents join a new agent is created.

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.

In our simulations, for children, the natural death probability is 10% during the first four years of life. In other words children have a probability of 65.61% to reach 4 years of age. That is, 34.39% of offspring die before age 4.

For individuals older than 4 years (65.61% of total offspring), the natural death probability is 1.5% per year, which means a probability of approx 83.5% for all individuals who have reached age 4, to reach the reproductive age (15 years), and of 31% to reach the age of 50 years. That means that 54.78% of all offspring (c. one half) reach reproductive age, and 20.34% of all offspring (c. one fifth) reach age 50.

In addition, a simplified version of the model was run on R to assess reproduction in our simulations, i.e. with no fertility age limits but taking into account the effects of mortality rates. The following results were obtained:

Experiment 1: average for 1000 simulations with starvation rate 0.5%.

- Mortality mean age for women: 64 yrs (this number does not matter)
- Total number of children being born per agent during the lifetime of the agent: 12
- Number of children alive per agent during the lifetime of the agent: 5
- Child mortality (<15 years): 38%
- Infant mortality (<12 months): 18%

Experiment 2: average for 1000 simulations with starvation rate 1%.

- Mortality mean age for women: 56 yrs (this number does not matter)
- Total number of children being born per agent during the lifetime of the agent: 10
- Number of children alive per agent during the lifetime of the agent: 3.8
- Child mortality (<15 years): 43%
- Infant mortality (<12 months): 21%

Starvation rates emerging from our simulations vary between 0 and 10%, depending on climatic settings. As a result, reproduction rate in our simulations is coherent with that observed in reality.

For comparison with available data from preindustrial societies, the following values can be extrapolated based on the average of several HG groups published by Hewlett (1991):

- Fertility rate (average number of live births per woman over the age of 45): 5.5
- Child (<15 years) mortality: 43.4%
- Infant mortality (<12 months): 20.3%

5 Design concepts

5.1 Basic principles

The behavior defined in this model is derived from the Optimal Foraging Theory (OFT), developed within behavioral ecology. The main principle of OFT is the maximization of long-term energy gain. In other words, it is usually assumed that animals attempt to maximize the benefit to cost ratio. Evidence exists e.g. among great tits, birds that show relatively successful strategies in terms of OFT. Although it is doubtful whether humans attain the optimal rate of energy gain, they do succeed in improving their foraging efficiencies, or 'memorising'.

5.2 Emergence

The model explores the emergence of viable HG populations under different climatic conditions.

5.3 Adaptation

At the present moment the model is not interested on the emergence of individual adaptive traits, and for this reason adaptive options for the agents are limited to the decision making process. The different agents try to respond to the dynamics of environment choosing Home locations and Foraging actions depending on their particular situation.

5.4 Objectives

Following the basic principles stated before, the objective for any agent is the survival of its individuals. This assumption is clearly from optimizing the system, as the different populations won't be guided by the mission of 'colonizing' the entire landscape. Anyway, this outcome will be seen following evolutionary mechanisms and positive selection. Well adapted agents will have more possibilities to survive, thus creating more children and agents with similar cultural traits.

5.5 Prediction

An agent does not keep track of previous rainfall values, so it is not able to predict the future state of the environment.

5.6 Sensing

An issue seldom addressed in the literature of ABM applications into Social Sciences is the fact that agents do not have perfect information on their environment. Home range limits the zone that agent know around its home location.

5.7 Interaction

The interaction between agents is currently limited to the fission process that is executed when two agents with adult children are inside social range.

5.8 Stochasticity

Stochasticity is used in three different concepts:

- Environment. Precipitation is calculated as a stochastic process following a Gamma distribution.
- Outcomes. Some actions have different outcomes depending on stochastic processes, like forage. It encapsulates the complex process of resources collection (i.e. risk, variability, etc.), and it is important due to the fact that Actions will be chosen depending on their outcomes and risk of failure.
- Life events. Death and reproduction are stochastic processes following realistic distributions.

5.9 Collectives

The agent, atom of the decision-making process, is itself a collective of different related individuals.

5.10 Observation

Population dynamics are the most important concepts to derive from the model.

6 Initialization

Initial state of the model is divided by entities:

6.1 Climate

Rainfall yearly precipitation is a stochastic value calculated from input data, as seen in section 7. Calculated values depend on the initialization seed used in the random number generation, that is stored as a parameter of the model's configuration. Next parameters can be modified during initialization time:

- EMR: End-of-year minimum residual resources
- AYP: Average Yearly Precipitation
- VYP: Variance in yearly precipitation

6.2 Environment

Ground Model and land features are raster maps created from real data (see also section 7). The model is able to load any raster map with correct values. This process is done during init time from the file specified in the configuration.

6.3 Resources

The conversion functions that create available biomass from landscape and rainfall for each cell use parameters specified in the configuration. They are based on published research; nevertheless they can be modified in order to explore different worlds.

6.4 Agents

Several parameters can be changed from the configuration. These values are loaded during init time, and remain stable during the entire execution. This is the list of parameters used for this model:

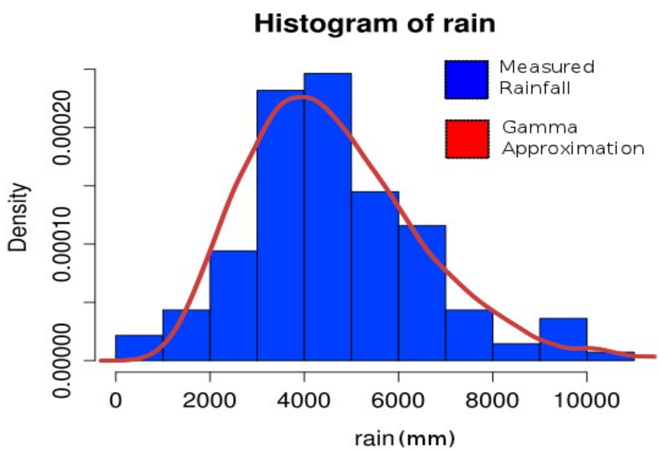
- Life-event related:
  - Adulthood age: 15
  - Number of agents: 100
  - Social Range: 300 cells

- Resource related:
    - Home Range: 300 cells
    - Number of sectors: 8
    - Forage time cost: 30 minutes
    - Walking Speed: 3 km/hour

7 Input data

7.1 Rainfall

Rainfall (yearly precipitation) is the 'environmental engine' of the model. Data for precipitation rate are extracted from historical data (1871 - 2008). The climate engine is defined as a probability distribution, from which the total precipitation during a year is derived. The Gamma distribution was the best fit for the available rainfall dataset.



Gamma distribution and historical data
Figure. Precipitation Gamma distribution

7.2 Ground Model

This model is derived from LANDSAT and ASTER satellite imagery (combining pre- and post-monsoon imagery) and includes DEM and land features. Satellite data are transformed using unsupervised classification and clustered in the 3 classes (water, interdune and dune). The model is exported as a Raster map.

7.3 Behavior

Archaeological data are incomplete and limited in terms of derivable behavioural patterns. HG behaviour for the model was derived from published studies of historical and present-day populations in similar ecological settings. There are groups of HG that live near N Gujarat (the Van Vargis, see Nagar 2008). However, these communities have a high degree of interaction with and dependency from settled agricultural communities for their subsistence strategies. This occurrence constitutes a strong bias towards the use of these groups to model our HG agents. Instead, we used as surrogates of our HG population, African groups of the San communities.

Among living and historical HG communities, the San (especially the G/wi and G//ana groups of Botswana) represent the best-fitting parallel in terms of ecosystem (Tanaka and Sugawara 1996). These groups are found on a flat plateau in the central part of the Kalahari desert. The landscape morphology is characterised by fossil rivers and traces of sand dunes. Rainfall is concentrated in the summer months with c. 400 mm annual average precipitation. The vegetation of the area is dominated by plants of the Gramineae family (grasses) and a mixture of shrubs of the same genus/families that are found in North Gujarat.

Description	Item	Info
G/wi and G//ana groups *Botswana (central Kalahari Desert, Africa)*	Lifestyle	Hunter-gatherers

	Band	[25..85] members. *Formation and fission dependent on drought, disease, overpopulation and resource overloading*.
Some households have quasi extensions of one or even two elderly parents of one or both spouses. Although separate shelters are occupied by the two senior generations, food, firewood, and other commodities are shared to some extent and the whole unit migrates together between campsites, into winter isolation, and between bands.	Family	Husband + 1 or more wifes + under puberty children (older sons stay in the bachelor's hut).
	Network	Kinship and affinity.
	Settlement	[1..20] families, mean=10
Guided by the interband intelligence network, the founder leads a party of men on an extended hunting trip into country offering the most likely prospect of sufficient resources. Later they take their families with them and spend a month or more away from the parent band, returning before the annual breakup in winter. The following summer, once the wet season is established, the pioneers make their first visit and continue to spend longer and longer periods in the new territory. The composition of the group changes to some extent as some withdraw and elect to remain with the parent band or to move to other established bands, and their places are taken by others. As the absences of the pioneers in their territory grow longer and more frequent, the separate identity of their group emerges until, eventually, it is recognized as an autonomous band	Movement	Dependent of the band. A movement group is formed based on kinship and friendship. Done at the end of summer.
	Hunting	* 2 strategies: day sortie, biltong. * Pair of hunters. * Stick to an area fixed the previous night with other pairs. * Everybody helps (information) the hunters track the games. * <5 pairs go hunting the same day. * Hunt range around the camp = [700..800]km^2. * Could spend night far from home (>20km away otherwise will return).
	Gathering	80% of total reward. [1h walking (if good tsama season)...6h walking] [3.5kg..5kg] per day and individual.
	Working day	* 4h39' / working day. * 9h away from camp = 4.5 h working + 4.5 leisure * [10:30 .. 16:00] = rest

8 Submodels

8.1 Agent execution cycle

The majority of Agent-Based Models mix knowledge acquisition, decision-making and execution in the same phase of an agent's execution. This choice is useful if we deal with agents with simple decision-making processes where the choice of behaviors is predefined. However, this classical approach to ABM has a major drawback, and is the fact that the agent will have scripted strategies, and for this reason it won't be able to choose strategies different from the ones defined there.

The model proposed here splits the different phases. During each time step every agent updates its knowledge about the environment (possibly including other agents). This action is combined with a set of possible actions, in order to choose which plan of actions will be executed. Several factors can be used to enrich the process:

- Agent's goals and agent's preferences referred to the choice of particular actions
- The information that the agent perceives from the environment and the reliability of such information.
- The information collected from other Agents, as well as its reliability.
- The feedback the agent receives from engaging into a given activity.

In this particular model the goal of every agent is to maintain alive its individuals, and the potential actions are the ones defined in the document. This approach will allow to integrate Artificial Intelligence techniques into the current decision-making process, depending on particular research around this first model.

The execution of the agents during each time step is divided in three different phases:

1. **Knowledge update**

The agent collects information from the environment, and creates an individual representation of the world using its preferences and objectives. Agents will calculate the amount of biomass available in each directional sector, as well as potential settlement zones.

2. **Action choice**

The agent decides which actions to execute once knowledge has been collected, based on the following algorithm:

- Agents checks whether there is any sector inside its home range where resources can be obtained. This is calculated based on available foraging time and resources on cells.
- If needed resources can be obtained the agent will choose to Forage in one of the Sectors where this is possible.
- If this is not possible, the agent will choose to Move Home. A collection of possible new homes is created based on the quantity of resources inside the Home range from this new location. The final location is chosen amongst the ones that fulfill resource requirements.

3. **Action**

Once every agent has defined a plan, all of them are executed sequentially following a randomized order.

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