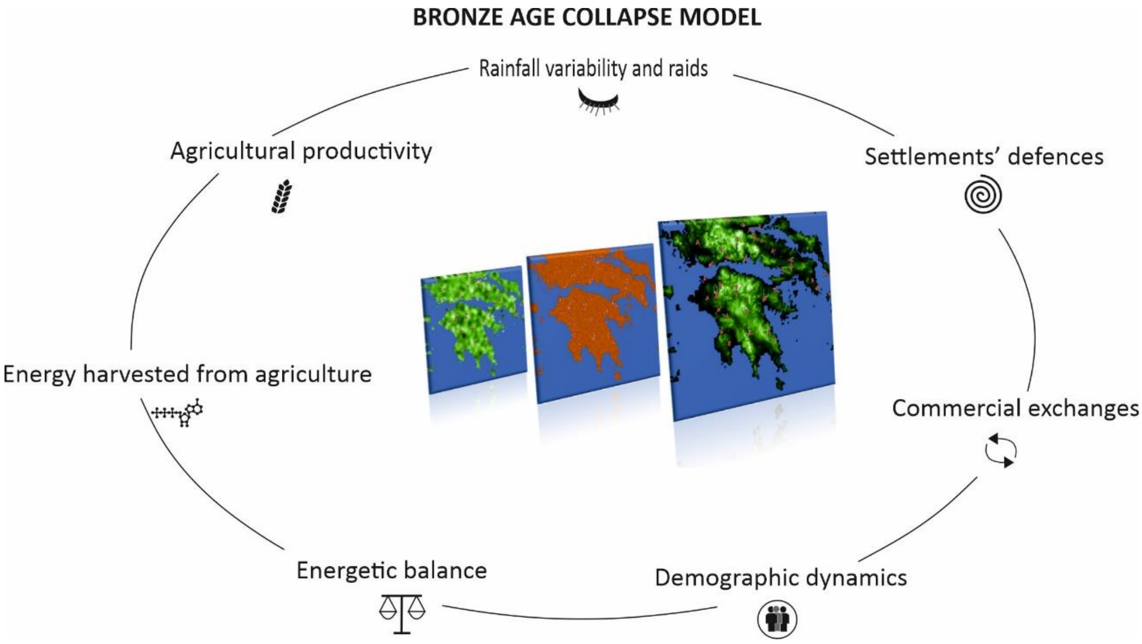
BACO: BRONZE AGE COLLAPSE MODEL.

ODD PROTOCOL



Purpose

Bronze Age Collapse model (BACO model) is an agent-based model designed to provide a tool to identify and analyze the main factors which made resilient or vulnerable the Late Bronze Age and Early Iron Age socio-ecological system in the face of the environmental aridity recorded in the Aegean. The model explores the relationship between dependent and independent variables. Independent variables are: the inter-annual rainfall variability for the Late Bronze Age and Early Iron Age, raids, the population dietary patterns, the soil erosive processes, farming assets and storage capacity. Dependent variables are: the human pressure for land, the settlement patterns, the number of commercial exchanges, the demographic behavior, and the number of migrations.

Agent classes, variables and temporal and spatial scales

The environment is a 2D space characterized by a matrix of 125 * 102 cells, i.e. patches. The environment corresponds to the southern and central Greek mainland (Figure 1). Each cell represents an area of certain number of kilometers squares, depending on the patch size previously fixed by the user. There are two kind of patches: sea-patches, and land-patches, which can be cultivated by households. Each land-patch is characterized by certain variables that influence its potential yield productivity: the carrying capacity, the soil fertility, the slope, the annual rainfall received, and the population size living on that patch.

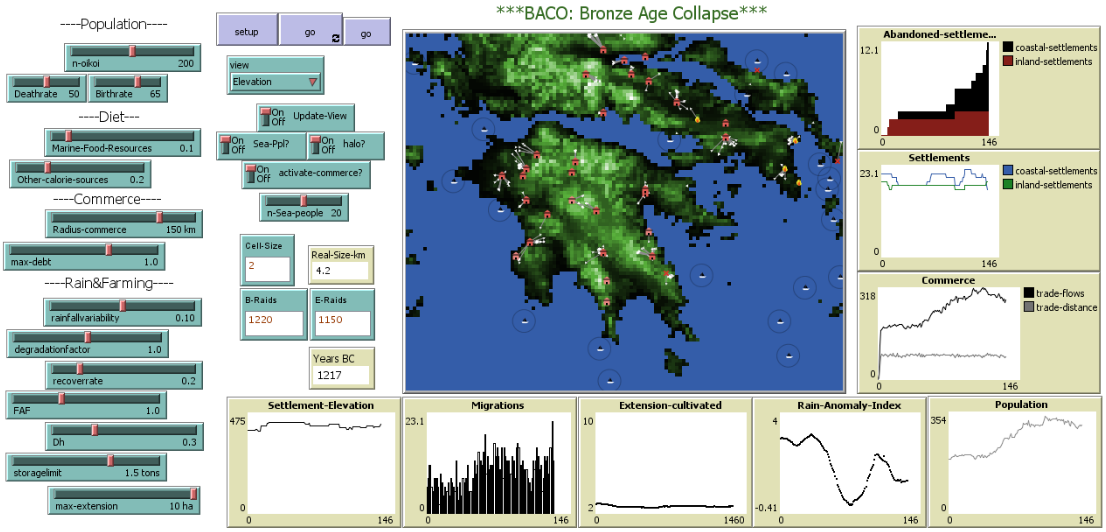


Figure 1. BACO model interface with controls or sliders, spatial view, and graphs tracking model data.

There are three kind of independent agents in the current model: households (*oikoi*), settlements, and Sea Peoples. Households represent families and are characterized by its dietary patterns (the percentage of meat, fish, and agricultural resources included in the diet), its energy requirements, their annual harvest and stocks, their energetic shortage or surplus, their loans and debts, their farming assets, the extension of land cultivated, and their death and birth rates. Each settlement is a community of at least three households, and is characterized by its defensiveness from Sea Peoples' raids, which depends on three defensive resources: the number of households living in the settlement, their energetic surplus, and the terrain slope where the settlement is located. Finally, Sea Peoples represent the invasions occurred between the 1200 BC and the 1150 BC through the Mediterranean coasts. Each time step represents one year, and the model makes simulations through 430 years, since 1350 BC until 930 BC, taking into account the annual rainfall reconstructed from different archaeological and geological records.

Table 1. Main variables used in the model. It is also specified if the initial value of that variables is fixed by the user as a preliminary configuration of the experiment. Y = yes, N = Not.

Parameter	**Equation**	**Fixed by the user?**
Population size (P) at certain location	-	N
Recovery rate (Rr) of the soil	-	Y
Degradation rate (Dr) of the soil	-	Y
Annual depletion rate (Dh) of the soil by households	-	Y
Maximum yield productivity (Sc) of certain patch	-	N
Rainfall signal based on the Rainfall Anomaly Index. A higher τ improves yield productivity	$\tau = 1.5 * \left(1 - \exp\left(\left(\log_{10}(\frac{1}{3})/4\right) * (\mathrm{RAI} + 4)\right)\right)$ (Janssem, 2010)	N

Soil fertility (Sf), which depends on carrying capacity, depletion and recovery rate, and the terrain slope.	$Sf_j = Sf_{j\ (t-1)} + Rr * Sf_{j\ (t-1)} * \left(\frac{Sf_{j\ (t-1)}}{Sc_j}\right)^{Dr} * \left(1 - \frac{Sf_{j\ (t-1)}}{Sc_j}\right) - Dh * P_j$ (Janssem, 2010)	N
Terrain slope factor, which affects yield productivity.	$slope\_factor = (1 - 0.06)^{slope}$ (Chliaoutakis & Chalkiadakis, 2016)	N
Terrain slope, expressed in degrees	$slope = sin^{-1} \frac{m}{\sqrt{1 + m^2}}$ (Gravel-Miguel & Wren, 2018)	N
Residence-continuity: number of years that households are at certain cell	-	N
Farming Assets Factor (FAF): a higher FAF makes households improve faster their farming efficiency	-	Y
Farming assets: farming experience of households.	$farming\_assets = \sum_{i=1}^{n} \frac{residence\_continuity_j}{residence\_continuity_j + (FAF_{max} - FAF)}$	N
Extension of land cultivated by households	-	N
Extension-cultivated: increment of the land extension cultivated by households	$extension\_cultivated = extension\_cultivated_i + \left(1 - \sum_{i=1}^{n} \frac{extension\_cultivated_j}{\mathrm{extension\_cultivated_{max}}}\right)$	N
Oikoi_harvest: energy harvested from agriculture each year	$oikoi\_harvest = expected\_harvest * farming\_skills * extension\_cultivated * 3390$ (Chliaoutakis & Chalkiadakis, 2016; Janssem, 2010)	N
Sea-distance: distance between the household and the sea	-	N
Initial percentage of sea resources (r_{-sea}) included in the diet by households	-	N
Final percentage of sea resources included in the diet (R_{-sea}) by households	$R_{-sea} = r_{-sea} - (\beta * sea\_distance)$	Y
Other-calorie-sources (R_{-other}): percentage of terrestrial animal products included in the diet by households	-	Y
Percentage of agriculture resources included in the diet by households ($R_{-agriculture}$)	$\mathrm{R}_{-agriculture} = 1 - (R_{-sea} + R_{-meat})$	Y
Energy requirements of households	$Energy\_requirements = 7300000 * R_{-agriculture}$	N
Carrying capacity: the maximum number of households that may live on certain area	$K = \frac{Sc_i}{Energy\_requirements_{-av}}$	N
Initial birth rate	-	Y
Initial death rate	-	Y

Energy stored by households	-	Y
Energetic balance of households	$Energetic\_balance = (oiko\_harvest + okoi\_stock) - energy\_requirements$	N
Probabilities of households' reproduction	$\text{Pr-R} = \left(\frac{b}{max-b} * Rr\right) * \left(1 - \frac{P}{K}\right)$ (Tsoularis & Wallace, 2002; Wren, Xue, Costopoulos, & Burke, 2014)	N
Probabilities of dying	$Pr\text{-}D = 1 + \left(\frac{oikoi\_shortage}{energy\_requirements}\right) * Death\_rate$	N
Households' energetic surplus	-	N
Defensiveness of the settlement expressed as a percentage	$defence\_capability = \left(\frac{1}{3} * \left(\frac{\sum_{i=1}^{n} P_{t}}{max - P}\right)\right) + \left(\frac{1}{3} * \left(\frac{\sum_{i=1}^{n} oikoi - surplus_{h}}{max - oikoi - surplus_{h}}\right)\right) + \left(\frac{1}{3} * \frac{15}{slope}\right)$	N

Process overview and scheduling

Each time step represents one year, in which an energetic balance is calculated by subtracting the households energic requirements from the energy provided by farming (harvest). The energy harvested depends on the rainfall signal, the population size, the soil fertility, the terrain slope, the carrying capacity, and the household's farming assets. Once farming resources are obtained, it is calculated an energetic balance. If the energetic balance is positive, the household will have an energetic surplus that will be stocked. Once the maximum storage capacity is reached, if the household still has a surplus, this surplus will be shared with the neighbors that have an energetic shortage. The remaining surplus will be used for commerce, whenever commercial routes are safe (without Sea Peoples). If the energetic balance is negative, the household will have certain shortage and will look for a loan from another neighbor with an energetic surplus, resulting in a debt. Furthermore, if the harvest does not cover the energetic requirements or certain settlement is no longer safety, the household will emigrate to another safety location with a better farming productivity expectation (Figure 2). When a household emigrate to a better location, the household will look for a close settlement which provides protection. However, if there are no settlements close and there are more than two households without a settlement in the surroundings, they will create a new city/ settlement. Finally birth and death rates are adjusted for each household depending on its energetic balance.

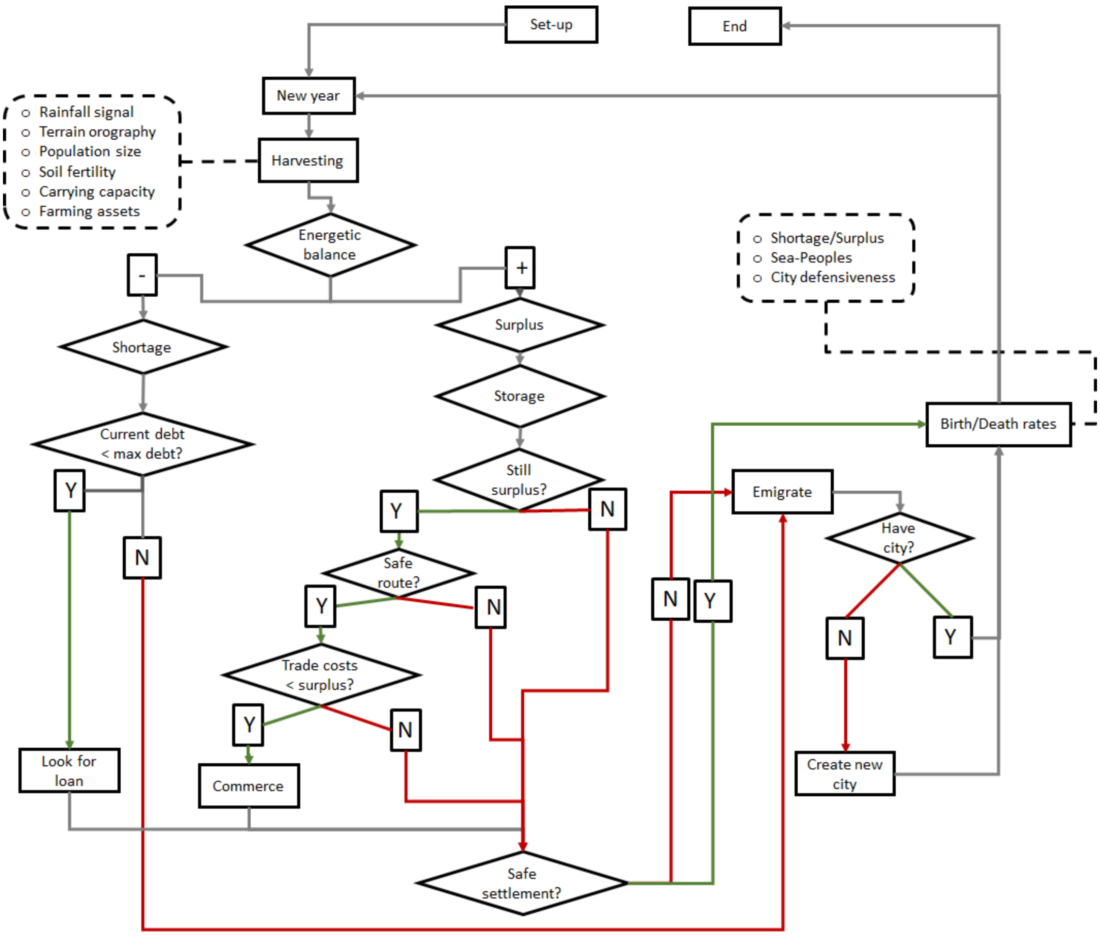


Figure 2. Flow chart of the model for one household during one year. Dashed lines indicate the main variables influencing the energy harvested from agriculture and the agent's birth and death rates.

Design concepts

Adaptation: households adapt to their environment by farming, emigrating, storing resources, and trading with their energetic surplus. With a longer duration of the households in certain settlement, the knowledge and the relative yield productivity increase. When the harvest obtained is not enough to meet their energetic requirements, household will try to increase the extension of land cultivated. On the other hand, when a commercial route is not safe, household will look for another safe route.

Fitness: households need to meet their energy requirements. Otherwise, they will have a debt or a shortage. If they have an energetic shortage or the settlement is no longer safe (due to Sea Peoples' raids), they will emigrate to another safe location and dying probabilities will increase proportionally to their energetic shortage. On the other hand, settlements have certain defense capability against Sea Peoples' raids, which depends on the terrain slope, the relative number of households living in that settlement, and the amount of surplus available to defend the settlement.

Objectives: in the current model, it is assumed that the only goal of Sea Peoples is attacking and looting cities. The main objective of households is surviving, reproducing and making commercial trades.

Prediction: when households have to emigrate to another location, they first estimate the expected yield productivity of that location.

Interaction: households interact with their environment, with other households, with settlements, and with the Sea People. Households may trade, request or make loans to other households. Furthermore, households also share their experience and interact indirectly with their neighbors by depleting the soil fertility. Besides, households provide defensive resources to their settlements and may create new settlements, or make them to disappear when emigrate. Finally, Sea Peoples determine if the settlement is safe or not. When cities are destroyed, households lose their energetic stocks and surplus, and must emigrate to another safe location.

Emergence: the model shows the emergence and disappearance of households and settlements, the required extension of land cultivated per household to survive, and the number and distance of the commercial trade flows. These outcomes reveal the expected variations in settlement patterns, migrations and demographics, commercial dynamics, and the pressure for land according to Sea Peoples' raids and to the environmental droughts during the Greek Dark Ages.

Sensing: households know if they are inside an urban perimeter/ area or not. Furthermore, they also know when Sea Peoples are close. When households decide to emigrate, they firstly examine the expected yield productivity of the surrounding area. Households know the energetic shortage or surplus of other households living inside certain radius (established by the user with the *Radius-commerce* slider). Finally, households know if the commerce routes between settlements are safe or not.

Stochasticity: a central component of this model is the stochastically varying conditions of agriculture production, rainfall variability, dietary patterns of households, the commerce radius, the maximum debt a household may have, the household's storage limit, and the maximum extension of land that households may cultivate.

Observations: population size, settlement patterns, migrations and trade flows may be observed during the simulations and these data can be gathered via the behavior space tool in NetLogo.

Initialization

The world is a gird matrix obtained from an ASCII archive (BASEMAP.asc), which includes terrain elevation data from southern Greece. The model also needs data from annual rainfall evolution between 1350 and 930 B.C. from a document named "RAI.txt". Before setup, both documents ("RAI.txt" and "BASEMAP.asc") must be located in the same folder as the model itself. The cell size changes according to the map resolutions previously fixed by the user in the *Cell-Size* box. Following Gravel-Miguel and Wren (2018), the elevation of each cell is interpolated by using the bicubic_2 method.

At setup, forty settlements are initially allocated on the landscape. Half of these cities are randomly located in a coastal zone (≤ 20 km away from the sea), and the other 50% is randomly located in an inland zone (> 20 km away from the sea). Households are randomly located around settlements with no stocks, no debts, an initial land extension to cultivate of 2 ha, and an initial harvest twice the amount of their energy requirements.

Input

The main input of the model is the Rainfall Anomaly Index (RAI) calculated from two speleothems recovered at the Peloponnese Peninsula and one recovered at Albania: Mavri Trypa Cave (Weiberg & Finné, 2018), Kapsia Cave (Finné, 2014), and Shkodra Cave (Zanchetta et al., 2012). These geological records have been dated and widely used to reconstruct the palaeoclimatological conditions during the Late Bronze Age. According to Bar-Matthews and Ayalon (2007), the stable oxygen isotope ($\delta^{18}O$) recovered from speleothems may be directly used to estimate the annual rainfall, so in the current study, $\delta^{18}O$ has been to calculate the Rainfall Anomaly Index (RAI) for the period between 1350 B.C. and 920 B.C. The RAI is a widely used parameter to detect, standardized and classify dry and rainy years in a scale between 4 and -4 (Table 1). When there is a positive anomaly, RAI calculation is performed according to equation (1), while a negative anomaly requires the application of equation (2):

$$(1)\ \mathrm{RAI} = 3 * \left(\frac{PP_{\mathrm{y}} - PP_{\mathrm{av}}}{\mathrm{PP}_{\mathrm{max}} - PP_{\mathrm{av}}}\right)$$

$$(2)\ \mathrm{RAI} = -3 * \left(\frac{PP_{\mathrm{y}} - PP_{\mathrm{av}}}{\mathrm{PP}_{\mathrm{min}} - PP_{\mathrm{av}}}\right)$$

Where *PP* is the annual precipitation in mm of the year *y*, PP_{av} is the mean annual rainfall of the historical series, PP_{max} is the mean of the ten largest annual precipitations from the historical series, and PP_{min} is the mean of the ten lowest annual precipitations from the historical series.

Table 2. Classification of Rainfall Anomaly Index (RAI) outputs according to (Lins et al., 2018)

RAI rank	Classification
≥4	Extremely humid
2 to 4	Very humid
0 to 2	Humid
0 to -2	Dry
-2 to -4	Very dry
≤-4	Extremely dry

- **Agricultural productivity**

Equations used to model agricultural resource dynamics are adapted from Janssen (2010) and Chliaoutakis and Chalkiadakis (2016). Agricultural productivity varies through time and space, but the potential yield productivity of each patch is a function of the cell's slope, its fertility, and the rainfall signal. Thus, the expected amount of harvest obtained each time by households is:

$$(1)\ expected\_harvest\ =\ rainfall\ *\ Sf_j * slope\_factor$$

where *rainfall* is the rainfall signal, Sf_i is the soil fertility of patch *j*, and *slope-factor* is a terrain slope factor. It is assumed that agricultural activities are not possible in cells with a slope larger than 40° (Chliaoutakis & Chalkiadakis, 2016). Thus, the influence of the terrain slope (*slope-factor*) on the yield productivity is derived from an exponential decay function:

$$(2)\ slope\_factor = (1 - 0.06)^{slope}$$

where *slope* is the slope terrain expressed in degrees. That slope is calculated according to the following equation:

$$(3)\ slope = sin^{-1} \frac{m}{\sqrt{1+m^2}}$$

where m is the elevation change between two adjacent patches divided by the distance between them, all expressed in metres (Gravel-Miguel & Wren, 2018).

As stated previously, the rainfall signal (*rainfall*) is based on the RAI. Thus, following the Mitsherlich-Baule production function (Frank, Beattie, & Embleton, 1990; Janssem, 2010), the influence of the RAI on yield productivity is:

$$(4)\ rainfall = 1.5 * \left(1 - \exp\left((\log_{10}(\tfrac{1}{3})/4) * (\mathrm{RAI} + 4)\right)\right)$$

According to equation (4), yield productivity decreases exponentially as the Rainfall Anomaly Index is lower and the environment is drier (Figure 4) [Figure 4 here]

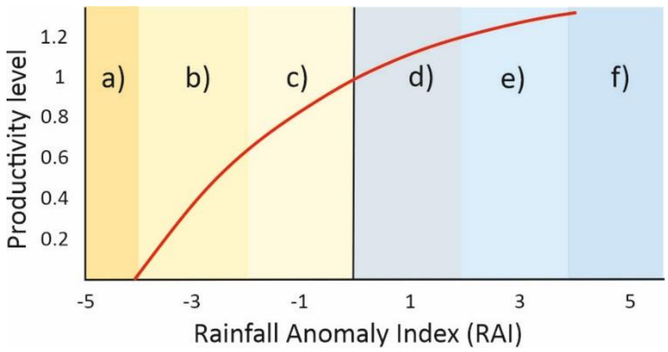


Figure 3. Influence of Rainfall Anomaly Index (RAI) on yield productivity according to equation 4. It is shown the classification of RAI outputs according to Lins et al., (2018): a) extremely dry, b) very dry, c) dry, d) humid, e) very humid, and f) extremely humid.

To examine the effects of rainfall variability without modifying the average annual precipitations reconstructed from the geological records, *rainfall* is multiplied in each cell by $1 + RV$, where RV (rainfall variability) is randomly estimated from a normal distribution with a mean of 0 and a standard deviation set by the user as a preliminary configuration of the experiment. As noted above, the yield productivity of patch j is a function of the terrain slope (*slope-factor*) and the rainfall signal (rainfall) but also depends on the soil fertility (*Sf*), which varies according to the amount of labour applied on a certain cell by agents, the soil capacity, the population size living on that patch, and the household's faming assets:

$$(5)\ Sf_{\mathrm{j}} = Sf_{\mathrm{j\,(t\text{-}1)}} + Rr * Sf_{\mathrm{j\,(t\text{-}1)}} * \left(\frac{Sf_{\mathrm{j\,(t\text{-}1)}}}{Sc_{\mathrm{j}}}\right)^{Dr} * \left(1 - \frac{Sf_{\mathrm{j\,(t\text{-}1)}}}{Sc_{\mathrm{j}}}\right) - Dh * P_j$$

where Sf_j is expressed in kg/ha/year, Rr is the recovery rate of the soil, Dr is the degradation rate of the soil, Sc_j is the soil's maximum productivity at cell j, Dh is the annual depletion rate of resource per household, and P_j is the population size at location j. Therefore, the initial capacity (Sc_j) of certain patch and the recover-rate (Rr) increment the actual soil fertility (Figure 5), whereas population size (P_j) and the annual depletion rate (Dh) reduce it (Figure 5). According to Jardé (1979), during the Bronze Age in Greece, the maximum wheat productivity varied between 800 and 1200 kg/ha/year, while the maximum barley production varied between 1600 and 2000 kg/ha/year. Thus, soil capacity (Sc_j) is randomly estimated from a normal distribution with a mean of 1600 kg/ha/year and a standard deviation of 300 kg/ha/year. Although this is a simplistic formulation of yield productivity, it has been widely used to model agriculture dynamics (Chliaoutakis & Chalkiadakis, 2016; Heckbert, 2013; Janssem, 2010) and allows the exploration of different soil erosion processes (Dr, Rr and Dh) in the model as long as they are user-fixed variables via the interface.

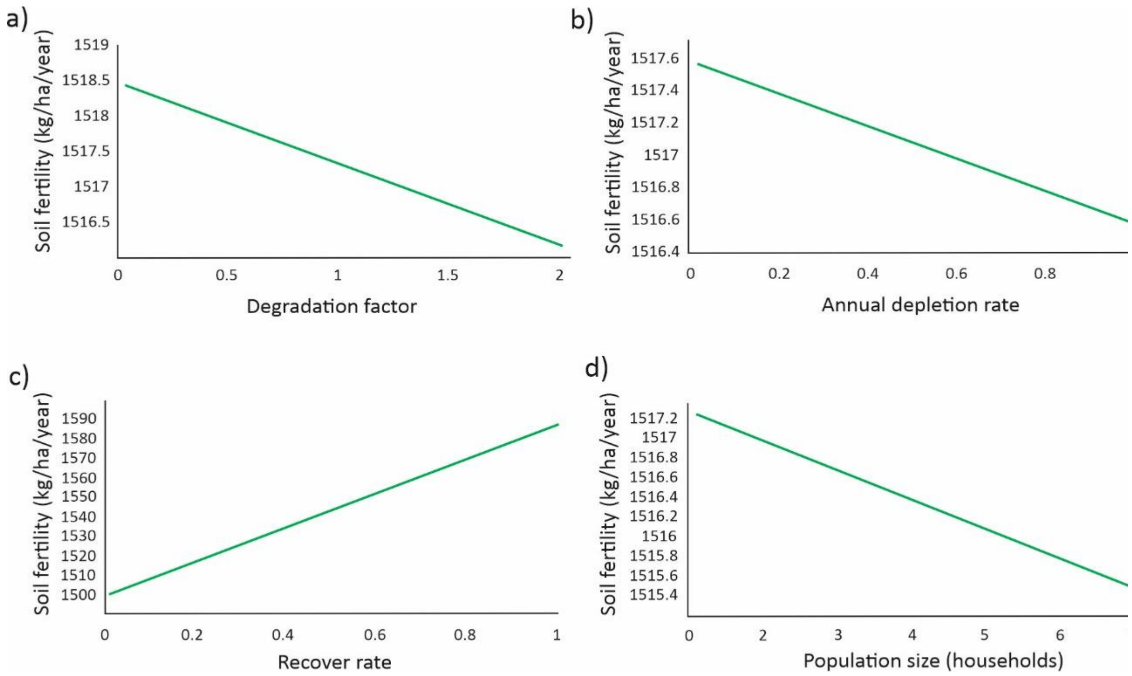


Figure 4. Influence of (a) degradation factor, (b) annual depletion rate, (c) recover rate and (d) population size on the soil fertility. These are the main components of the equation 5 to estimate the agricultural productivity.

- **Energy harvested from agriculture**

The net amount of energy harvested each year from agriculture (*oikoi-harvest*) also depends on the area of land cultivated and the farming assets, which is a function of a household's knowledge or experience. It is assumed that with longer experience in a certain cell, there is higher efficiency in its exploitation:

$$(6)\ farming\_assets = \sum_{i=1}^{n} \frac{residence\_continuity_j}{residence\_continuity_j + (FAF_{max} - FAF)}$$

where *residence-continuity* is the number of years of all current households in cell *j*; *FAF* is the *farming-assets-factor*, a parameter previously fixed by the user; and FAF_{max} is the maximum value of the *farming-assets-factor*. According to equation (6), as the *residence-continuity* increases, yield productivity increases, whereas *FAF* indicates the magnitude of this increment (Figure 6). Therefore, the farming assets can be interpreted as the influence of the cumulative knowledge of the local environment on yield productivity.

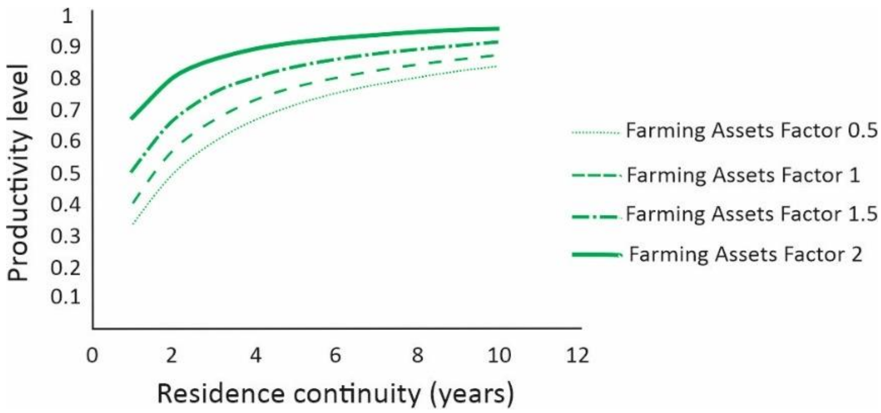


Figure 5. Influence of *residence-continuity* on the productivity level according to different *Farming-Assets-Factor* (*FAF)* from equation 6.

Regarding the area of land cultivated, each household starts farming a land area of 2 hectares; however, it may decide to increase this cultivated area if the harvest is not enough to meet its energetic requirements. Therefore, it is assumed that the cultivated area may be expanded by the households whenever there is free cultivable land:

$$(7)\ extension\_cultivated = extension\_cultivated_i + \left(1 - \sum_{i=1}^{n} \frac{extension\_cultivated_j}{\mathrm{extension\_cultivated_{max}}}\right)$$

where *extension-cultivated* is expressed in hectares, $extension\_cultivated_i$ is the actual area cultivated by the household *i*, $extension\_cultivated_j$ is the actual area cultivated by all households at cell *j*, and $extension\_cultivated_{max}$ is the maximum area in hectares that may be cultivated by households in each patch. As a result, the final energy harvested each year is:

$$(8)\ oikoi\_harvest = expected\_harvest * farming\_skills * extension\_cultivated * 3390$$

where *oikoi-harvest* is expressed in kcal/household/year and 3390 is the average kilocalories obtained from 1 kg of wheat (USDA, 2006).

- **Energetic balance**

Regarding the households' energy requirements and dietary patterns, it is assumed that each person has an average daily energy expenditure of 2000 kcal/day (FAO, 1985; Jochim, 1976). Furthermore, each household is composed of ten individuals, so the energy requirement per household is 7,300,000 kcal/year. These energy requirements are not only met from agriculture resources, but also from marine resources and other caloric sources (e.g. meat products). However, one of the main aims of the current model is to analyse the human pressure for cultivable land taking into account the droughts, so it is assumed that the percentage of marine food resources (R_{-sea}) and other calorie sources (R_{-other}) is always met by households. The percentage of other caloric sources (R_{-other}) is adjusted by the user as a preliminary configuration of the experiment via the interface. The initial percentage of marine food resources is also directly adjusted by the user, but the final percentage of marine resources included in the diet of each household will decrease slightly as the distance between the settlement and the coast increases:

$$(9)\ R_{-sea} = r_{-\text{sea}} - (\beta * sea\_distance)$$

where R_{-sea} is the final percentage of marine food resources included in the diet, r_{-sea} is the initial percentage of marine resources according to the percentage specified by the user, and *sea-distance* is the distance between the settlement and the coast, with weighting parameter β determining the strength of this effect. Therefore, the percentage of agricultural resources included in the diet is:

$$(10)\ \text{R}_{\text{-agriculture}} = 1 - (R_{\text{-sea}} + R_{\text{-other}})$$

Accordingly, the energetic requirement of each household, expressed in kcal/year, is:

$$(11)\ Energy\_requirements = 7{,}300{,}000 * R_{-agriculture}$$

Therefore, it is important to note that for the sake of simplicity and generality, the current model assumes that the energetic requirements from R_{-sea} and R_{-other} are always met by households, so the shortage, surplus or stores will be made up of only agricultural resources.

- **Demographic dynamics**

Regarding the demographic dynamics, population growth models are usually employed by using variations of the classic Verhulst logistic growth equation (Tsoularis & Wallace, 2002):

$$(12)\ \mathrm{d}P/\mathrm{d}t \ = \ R \ * \ \left(1 - \frac{P}{K}\right)$$

where P is the population size, t is the time, R is the intrinsic growth rate per capita, and the multiplicative factor $(1 - P/K)$ is the constraining factor based on the carrying capacity (K) of the environment. In the current model, the carrying capacity (K) is set by calculating the maximum population that may be sustained in a settlement, which depends on the soil capacity (Sc_j) and the average energy requirements ($Energy\_requirements_{-av}$) of the households living at that cell:

$$(13)\ K = \frac{Sc_{\mathrm{j}}}{Energy\_requirements{-}av}$$

Furthermore, the reproduction probability (*Pr-R*) of a household *i* depends on its energetic balance (b), which is calculated according to the following equation:

$$(14)\ Energetic\_balance = (oiko\_harvest + okoi\_stock) - \ energy\_requirements$$

where *energetic-balance* is expressed in kcal/year, oikoi-harvest is the energy obtained from the harvest, *oikoi-stock* is the energy stored, and *energy-requirements* is the household's energy requirements. Following Wren et al. (2014), *Pr-R* is adjusted according to the difference between the energetic balance of a certain agent and that of the most successful agent (*max-e*) in the settlement, which is multiplied by a base reproduction rate previously fixed by the user (R). Accordingly, the reproduction probability is:

$$(15)\ \text{Pr-R} \ = \ \left(\frac{b}{max - e} * R\right) * \left(1 - \frac{P}{K}\right)$$

The probability of dying (*Pr-D*) also depends on the energetic balance and on the safety of the settlement. There is a user-fixed base death rate (*Death-rate*) affecting all households, but this probability is adjusted in proportion to the energetic shortage (*oikoi-shortage*):

$$(16)\ Pr\text{-}D = 1 + \left(\frac{oikoi\_shortage}{energy\_requirements}\right) * Death\_rate$$

- **Settlement's defences and migrations**

It is assumed that if raiders are close to certain households and that households have no settlement protection, their *Pr-D* will be twice as large. All settlements are characterised by their defences against raiders. One third of the settlement defence capability depends on the settlement's population density (*P)*. Another third depends on the terrain slope (*slope*). The remaining third depends on the relative surplus of the households living in that settlement. The larger the defence capability of the settlement is, the lower the probability of being destroyed:

$$(17)\ defence\_capability = \left(\frac{1}{3} * \left(\frac{\sum_{i=1}^{n} P_{\mathrm{t}}}{max - P}\right)\right) + \left(\frac{1}{3} * \left(\frac{\sum_{i=1}^{n} oikoi - surplus_{\mathrm{h}}}{max - oikoi - surplus_{\mathrm{h}}}\right)\right) + \left(\frac{1}{3} * \frac{15}{slope}\right)$$

where *defence_capability* is expressed as a percentage, *P* is the number of households at the settlement, *max-P* is the number of households in the largest settlement in a radius of 50 km^2, *oikoi-surplus* is the energetic surplus of all households at the settlement, and *max-oikoi-surplus* is the largest energetic surplus of all settlements in a radius of 50 km^2.

As stated previously, households only emigrate when the energy obtained from the harvest is not enough to meet their energetic requirements or when the settlement is no longer safe because of raids. Before emigrating, households examine the expected yield productivity of the cells located in a radius of 50 km^2 using equation (3), but including one more household ($P_j + 1$) and taking into account the terrain slope factor (*slope-factor*). Thus, households take into account the influence of the slope factor and their own impact on the yield productivity before moving to that location. Accordingly, they only move to another cell if the current patch is no longer safe or if they have an energetic shortage and the expected yield productivity of another patch is better than that from their own location.

- **Commercial exchange**

Households store their energetic surplus up to a certain storage limit. Once the storage limit is reached, the remaining energy is given to the neighbours with an energetic shortage; that is, within each settlement, households share their energetic surplus with neighbours that have an energetic shortage up to the point that those households meet their energy requirements. Then, the remaining surplus is used for commercial exchanges. When households have enough surplus to trade, they first look for another household from their own settlement with an energetic surplus that may be used commercially. In this way, they look for a customer inside a certain radius fixed by the user. If the route between the household and the customer is safe, the household will calculate the trade costs. Otherwise, the household will look for another customer in a shorter radius than that fixed by the user. If the household finds a customer and the route is safe, he will calculate the exchange costs, which depend on the distance household-customer and the terrain slope. For the sake of simplicity, the current study only simulates terrestrial trade routes. If the trade route is safe and the trading costs are lower than the energetic surplus, there will be a commercial exchange. For each commercial exchange, we track the distance between the household and the customer. According to Brannan's (1992) data, the energetic cost of walking one kilometre can be calculated from the terrain slope:

$$(18)\ Cost\_slope = \exp(4.64177 + 0.0219174 * \ slope) \qquad \text{r. } 0.75$$

where *cost-slope* is expressed in kcal/km and *slope* is the terrain slope expressed in degrees. The slope may be positive ($C\text{-}S_p$) or negative ($C\text{-}S_n$), which must be specified before applying equation (18). This positive or negative gradient is established according to the elevation difference between adjacent patches. If the gradient is negative, *slope* in equation (18) will be multiplied by -1. Accordingly, the energetic cost of one commercial exchange is calculated from the sum of the costs of moving through the patches between the household and the customer, adjusted to the real kilometres of each patch (*real-size-km*), and taking into account the energetic costs of coming back.

$$(19)\ Trading\ costs = \left(\sum_{i}^{n} \text{C-S}_p * real\_size\_km\right) + \left(\sum_{i}^{n} \text{C-S}_n * real\_size\_km\right)$$

where C-S is the energetic cost of walking one kilometre according to equation (10) and *real-size-km* is the real size of each patch expressed in kilometres.

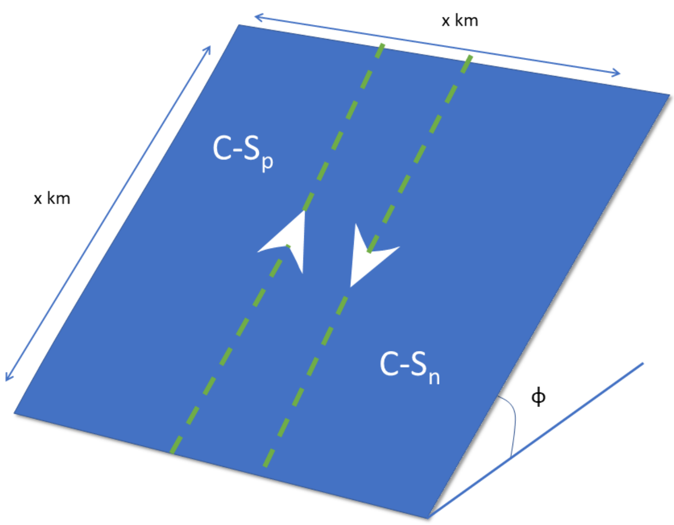


Figure 6. Both sides of each cell have the same kilometers. Each patch has a slope, which will be positive or negative according to the elevation difference between adjacent patches. When an agent makes a commercial route, it is assumed that will go through the same patches twice, so the energy costs of going through a patch (*C-S*) will assume a positive and a negative slope.

Calibration of the model, testing outputs and statistical analyses

Agent based models generate large volumes of dynamic and high-dimensional data, which makes them difficult to analyze. In the current study, we have followed the methodological approach proposed by Patel et al. (2018), which uses exploratory, statistical and data mining techniques for analyzing the relationships between inputs and outputs parameters. Sensitivity analysis consisted on the application of the OFAT technique ("One Factor at Time"). Thus, multiple runs were performed for different parameter values at discrete intervals. To compare the variation in population size, settlement patterns, migrations, commercial exchanges and land area cultivated, we first constructed different exploratory plots by using the "ggplot2" and "Rcmdr" R packages (Fox, Bouchet-Valat, Andronic, Ash, & Boye, 2020; Wickham, 2011). To assess the significance of the identified associations between parameters and outputs, Spearman's rank correlation coefficient was used and pots were constructed with the "corrplot" R package (Wei and Simko, 2017). Furthermore, to assess the contribution of each input variable for a given output, a Random Forest test with "randomForest" R package was used (Breiman, 2001).

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