Land use and land cover change in Roman North Africa

Model overview, design concepts, and details

Nicolas Gauthier

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1 Purpose

The purpose of this model is to capture the bidirectional feedbacks between ecohydrology, agropastoral production, and land use North Africa during the Roman Imperial period. From a population of agropastoral household agents with simple heuristics for allocating labor to different land use activities in response to variable crop yields, the aim is to simulate the emergent spatial patterns of land use and land cover change. The model is intended for use with either fixed climatic and economic boundary conditions representing North Africa at approximately CE 200 (to assess equilibrium land-use patterns), or with two-way coupling with a climate model (to assess social-ecological dynamics).

2 Entities, state variables, and scales

One time step in the model corresponds to one year in the real world, and simulations are intended to run on time scales ranging from 50 - 500 years.

2.1 Agents

The core agent type is a small-scale agropastoral household. A household's `occupants` is an integer number representing the number of individuals contained in that household, and is used to calculate food requirements and labor availability (i.e. the maximum number of fields an agent can farm). The number of `occupants` in a household can change over time due to stochastic birth and death processes. Agents own a set of patches, `farm-fields`, from which they harvest food, and agents actively choose to keep, add, or drop individual farm patches each time step using information from previous time steps and a user-defined objective. Food in the form of grain is harvested from these patches and is used to grow a household agent's `grain-supply`, measured in kg. An agent's `grain-supply` decreases each time step due to natural decay, consumption by the household's `occupants`, and to supply seed to plant the `farm-fields` in the next time step. If the volume of food in `grain-supply` is insufficient to meet a household's subsistence requirements, no births can occur during that particular time step. Agents also have an imperfect memory of the average crop yields from its `farm-fields` in previous time steps, and use this information along with its current grain supply to make land use decisions.

2.2 Spatial units

The landscape is divided into discrete patch grid cells. One patch represents an area of 0.8 ha (or approximately 90m on a side) by default, but the user can vary this effective patch size via the `patches-per-hectare` parameter. The landscape is 200 x 200 patches by default, but will adjust to match the extent of any input environmental raster maps. Three primary state variables characterize a patch's environmental quality: `vegetation`, `slope value`, and `fertility`. `Vegetation` is a continuous, dimensionless land cover classification number between 0 and 50, with 0 corresponding to bare ground and 50 to Mediterranean climax woodland. `Slope value` is a discrete, dimensionless number between 0 and 1 representing the suitability of a given slope for farming (with 1 corresponding to most suitable). These values can be supplied by the user, or reclassified from continuous slope data from a DEM using 1 = 0° - 10°, 0.75 = 11° - 20°, 0.25 = 21° - 60°, and 0 = 61° - 90°. `Fertility` is a measure of nutrient availability to support vegetation or crops, and is a continuous percentage value.

2.3 Environment

The variable `annual-precip` represents the total accumulation of rainfall over the model domain, in meters, occurring in a year. Rainfall cannot vary spatially in a given model domain. By default, rain does not vary from year to year, and always equals the `mean-precip` parameter set by the user. If the `stochastic-rain?` setting is turned on, a new value for `annual-precip` is drawn randomly each year from a Gaussian distribution with average `mean-precip` and standard deviation `mean-precip * precip-CV`. Optionally, the user can introduce "memory" into the precipitation time series using the `persistence` parameter, a value between 0 and 1 that determines the impact of the previous year's accumulation total on the current year (a value of 1 shifts the mean of the Gaussian distribution away from `mean-precip` and closer to the previous year's `annual-precip`).

2.4 Collectives

Household agents are grouped together into `villages`. A village represents the spatial location of the households, and inhabits a set of `settled-patches` that have been stripped of vegetation. The number of `settled-patches` owned by a village changes according to a sublinear power law relationship between village population and settled area.

3 Process overview and scheduling

1. Land selection: Agents asynchronously add or drop patches from `farm-fields` according to pre-defined objective functions and information about previous years' crop yields.

2. Rain: Annual precipitation accumulation is calculated based either on user-specified value or a stochastic, autoregressive process.

3. Food decay: Food stored in each agent's `grain-supply` is reduced at a constant rate.

4. Farm: Agents asynchronously collect food from `farm-fields`, add it to `grain-supply`, and extract food to feed `occupants`. The `fertility` of `farm-fields` is decreased.

5. Gather wood: Agents asynchronously extract woody biomass from unoccupied vegetated patches for firewood.

6. Birth and death: If turned on households add or remove `occupants` at a constant probability. If an agent's `fed-prop` is less than a user-defined threshold, no births occur.

7. Regenerate landscape: `Fertility` and `vegetation` of all patches is partially restored.

4 Design concepts

4.1 Basic principles

Agent behaviors are rooted in the principle of regulatory feedbacks from control theory. A dynamical system (the land surface) converts inputs (rainfall) into outputs (food). Agents monitor only the outputs from the dynamical system, and use this (potentially noisy) information to make time/labor allocation decisions that feed back into system.

4.2 Emergence

The change in patterns of land use and land cover over space and time emerges from the subsistence activities of individual household agents, interactions between those agents via the land surface, and interactions between the agents and rainfall variability.

4.3 Objectives

Agents seek to maintain at least as many `farm-fields` as is their `field-req`, an integer number of patches it needs to satisfy subsistence requirements. Agents follow one of three land-selection criteria, random, maximizing, or satisficing, in order to meet `field-req`. In each case, agents calculate how many patches they need to have in `farm-fields`. In the random strategy, agents simply calculate how many fields they need in ecah time step and aquire them anew, dropping previous patches. Satisficing households keep the same `farm-fields` each time step, adding or dropping fields as needed to match `field-req`. Maximizing households similarly keep fields from one time step to the next, but only drop fields that fall in the lowest performing proportion of their fields, with this proporiton defined by the tunable `tenure-drop` parameter.

4.4 Learning

Agents can remember crop yield information from multiple previous years, so can potentially generate a more precise estimate of yield variability beyond information from the previous year alone.

4.5 Prediction

Agents attempt to predict how many farm patches they will need in the current time step, given information about the crop yields of patches from previous time steps and its available labor, and food requirements.

4.6 Sensing

Agents can sense all patch-level variables in their environment, such as fertility and vegetation type, as well as the yields of crops from farmed patches. Patch-level variables are able to be sensed by the agent whenever this information is required, but yield information is only sensed from the environment once per time step before being stored in agent memory.

4.7 Interaction

All interactions between agents are indirect, occurring via occupying and using land patches. A patch used for farming by one agent cannot be used by another agent for any purpose. An agent can acquire a patch that was previously owned by another agent, and will need to deal with any impacts to that patch's `fertility` and `vegetation` made by the previous owner. Similarly, multiple agents can harvest wood from the same un-owned patch, and wood-gathering by one agent can decrease the supply of wood available to other agents at that patch.

4.8 Stochasticity

The rates at which patch `fertility` degrades due to farming and regenerates vary randomly between patches and years. The percentage decrease in the `fertility` of a farmed patch in a given year is drawn from a normal distribution with mean 3 and standard deviation 2, and the percentage increase of all patches with fertility less than 100% follows a normal distribution with mean 2 and standard deviation 0.5. If the `stochastic-rain?` parameter is set to `TRUE`, annual rainfall accumulations are drawn from a normal distribution with optional autoregression at lag 1. The mean, coefficient of variation, and AR(1) parameters of this distribution are set by the user. Agents' memory of crop yields from their farmed patches is subject to noise, drawn from a normal distribution with standard deviation equal to 0.0333 * the actual yield average.

4.9 Collectives

Individual household agents are organized into `village` collectives, but these groupings serve no functional role beyond defining the initial spatial distribution of agents and converting patches into settled areas.

4.10 Observation

Variables observed at the end of model simulations are equilibrium average soil `fertility` of farmed patches, the realized distribution of `annual-precip`, and the distributions of households' `grain-supply`.

5 Initialization

Initial locations of villages are randomly generated. Initial populations of agents in each village, and the size of the agents, can be set by the user. Initial values for fertility and vegetation are set to their maximum values (100 and 50, respectively), unless external raster data are available for these variables. Household variables related to food, such as `grain-supply` and memory, are initialized so that agents are certain to survive the first year. As such, a few time steps into each simulation should be discarded while the model is allowed to reach a dynamic equilibrium food production.

6 Input data

The model does not use input data to represent time-varying processes by default.

7 Submodels

7.1 Land selection

Given a number of patches to be added to `farm-fields` by an agent, agents assess the farming value F_{val} of different potential field patches based on a function of the patch state variables slope S, fertility F, vegetation V, and the distance D of that patch from the asking agent:

$$F_{val} = S\left(\frac{F}{100} - \frac{\frac{D}{D_max} + \frac{V_{deval}}{100} + \xi}{3}\right), \tag{1}$$

where V_{deval} is the vegetation devaluation, a piecewise linear function of V defined as

$$V_{deval} = \begin{cases} \frac{5}{6}V & V \leq 30 \\ 3.25V - 72.5 & 30V \end{cases}, \tag{2}$$

and ξ is patch fragmentation value defined as the inverse of the number of adjacent patches (Queen's case) owned by the asking agent.

7.2 Rainfall generator

Annual precipitation P at time step t is drawn from an approximately Gaussian distribution with user defined mean precipitation $\hat{P}$, coefficient of variation P_{cv}, and AR(1) coefficient ϕ:

$$P_t = \left(\phi\left(P_{t-1} - \hat{P}\right) + \hat{P}\right)(1 + \epsilon P_{cv}), \tag{3}$$

where $\epsilon \sim \mathcal{N}(0,\, 1)$ is a white noise process.

7.3 Crop yields

Crop yield Y are calculated based on a maximum yield value and various yield reduction factors based on climatic and topographic variables. The maximum possible yield Y_{max} for wheat is set to 3,500 kg/ha. First a yield reduction factor is calculated as proportion of potential yields Y_{pot} using the average of two regressions against annual precipitation P in meters and soil fertility F percentage:

$$Y_{pot} = \frac{(0.51 \ln(P) + 1.03) \times \left(0.19 \ln\left(\frac{F}{100}\right) + 1\right)}{2}. \tag{4}$$

Actual yields Y is then computed by multiplying Y_{pot}, maximum yield Y_{max}, and the slope value S, adjusting for the area of a single patch in hectares A_{ha}:

$$Y = \frac{Y_{pot} \times Y_{max} \times S}{A_{ha}}. \tag{5}$$

7.4 Vegetation succession

The rate of regrowth of vegetation $\dot{V}$ after clearing for farming or wood gathering is a nonlinear function of soil fertility F:

$$\dot{V} = -0.000118528F^2 + 0.0215056F + 0.0237987. \tag{6}$$