

Supplementary Materials: Simulating Littoral Trade: Modeling the Trade of Wine in the Bronze to Iron Age Transition in Southern France. *Land* 2016, 5, 5.

Stefani Crabtree

1. Purpose

This model explores a simple economic model, examining the transition from one type of artifact to another. In this simulation one type of artifact holds a monopoly in an area until a new type of artifact appears; the transition between these two is examined through an economic model of strictly local processes. This is done through an archaeological case study of southern Gaul. While this model examines economics (the shift from a monopoly object to another object) it also intervenes in

long-standing debates about the prehistory of France. One of the main purposes of this model is to create the first agent-based model in French archaeology. As such, this model uses simplified landscapes and simplified agents to examine trade in prehistory. This model will eventually expand from basic principles to a richer representation of real-world scenarios.

2. Entities, State Variables, and Scales

State Variables: Two State Variables were parameterized in this simulation. The first is Grain Trade Rate, and the second is Preference.

Grain Trade Rate: Grain trade rate examines the quantity of grain in hectoliters traded for 10 amphorae of wine. This is set at the system level. While future models may enable barter, the model presented here sought to reduce variables, so a state-level rate was used. In this simulation the optimum trade rate was 40 hectoliters of grain for 10 amphorae of wine. This is explored in Section 2.1 of the manuscript.

Preference: preference refers to which type of wine a Gaulish agent will choose to purchase. Gaulish agents choose a random number between 1 and 100, and compare that number to their preference value (Table S1). If the Gaulish merchant chooses a number that favors Etruscan trade, they will preferentially trade with Etruscans. If the Gaulish agent chooses a number that favors Greek trade, they will trade with Greeks. This value was set at the simulation level, so simulations were run with one preference value per run. This was examined in Section 2.1 in the paper, and is described further below under Scheduling: Buying Wine.

Table S1. Preference Values swept across in this study.

Preference	Explanation
0	Weight is strongly in favor of Etruscan Wine
10	Weight is strongly in favor of Etruscan Wine
20	Weight is in favor of Etruscan Wine
30	Weight is slightly in favor of Etruscan Wine
40	Weight is slightly in favor of Etruscan Wine
50	There is no weighted preference between Greek or Etruscan wine.
60	Weight is slightly in favor of Greek wine.
70	Weight is slightly in favor of Greek wine.
80	Weight is in favor of Greek wine.
90	Weight is strongly in favor of Greek wine.
100	Weight is strongly in favor of Greek wine.

Agents/individuals. In this model agents represent the economic production unit of a household. There are two types of agents—Gaulish agents, and Merchant agents.

Gaulish agents: Gaulish agents are farmers. They extract grain from the land, and the amount they extract depends on the size of their household. The size of the household corresponds to the amount of grain they have in storage, which is seen in Table S2 below.

Merchant agents: Merchant agents make wine and must trade wine for grain, since grain is essential for survival. The size of merchant households also scales with the amount of grain they have stored, although they need more grain to increase their household size than Gauls do. This is due to the inability of merchants to grow grain; they must plan more to be able to raise daughter households. There are additionally two sub-types of Merchant Agents:

- a. Etruscan Agents: Etruscan agents arrive at timestep 34 (see below) and bring Etruscan wine.
- b. Greek Agents: Greek agents arrive at timestep 100 (see below) and bring Greek wine.

Table S2. How storage level affects the number of individuals in a household and their consumption rates. This enables agents to increase their family size, and thus the productivity of their land, as well as increasing the ability to trade. However, once an agent trades, its storage level will be cut in half (as half is donated to the daughter household) decreasing the household size in the process. Merchants have a higher storage level because they cannot grow their own food, and thus need to plan more to be able to raise daughter households.

Storage Level Merchants	Storage Level Gauls	Size of Plots Gauls	Size of Harvest Gauls	Consumption Rates Gauls and Merchants	Corresponding Number of Individuals per Household
<45 hl	≤10 hl	5 ha	40 hl	6 hl	1
≥46, <50 hl	>10, ≤30 hl	5 × 1.5 (7.5 ha)	60 hl	12 hl	2
≥50, <60 hl	≥31, ≤40 hl	5 × 2 (10 ha)	80 hl	16 hl	3
≥61, <70 hl	≥41, ≤50 hl	5 × 2.5 (12.5 ha)	100 hl	20 hl	4
≥71 hl	≥51 hl	5 × 3 (15 ha)	120 hl	24 hl	5

- *Spatial units* (e.g., *grid cells*). The simulation window is divided into three types of grid cells: water, littoral cells, and land cells. One time step represents one year and simulations were run for 500 years. One cell represents 5 hectares, and the model landscape comprises 80 cells by 80 cells, i.e., 32,000 hectares.
 - *Water:* These cells take 2400 cells (12,000 ha) to the southern end of the simulation window. Water cells currently are not used in the simulation, and are kept for aesthetic purposes and for future development. For example, the littoral zone of France was one of the biggest producers of *garum* (Roman fish sauce) in the antique world, so future models may take advantage of sea resource exploitation.
 - *Littoral cells:* These cells take 320 cells (1600 ha) that abut the water cells. Wine can only be grown along the littoral zone. Cells here correspond to viticultural areas. Cells are not affected by changes in productivity, since modern wine farms are long lasting.
 - *Land cells:* These cells take 3680 cells (18,400 ha) in the rest of the simulation window. These cells correspond to grain farms. Cells have a 5-year lifecycle before they are unproductive and must be laid fallow for up to 5 years to be cultivated again.

3. Process Overview and Scheduling

Gaulish agents farm grain, while merchant-agents trade wine for grain. Below, the scheduling for both of these agent types is described.

Gaulish Scheduling: 150 Gaulish agents are placed randomly on the land portion of the landscape and given 20 grain on outset. When each year begins Gauls follow the following processes in this order: reproduction, planting grain, harvesting grain, eating grain, storing any extra grain, buying wine (if merchants have arrived), moving to a new patch (if the patch is unproductive), consuming any wine they bought, and finally checking their storage to see if they die. Each of these is explained below.

Reproduction: Reproduction is via fission and follows that established in the “Wolf-Sheep Predation” model developed by Wilensky (2005). Each year agents assess their stored calories. If their calories are above a threshold that enables a division of calories between parent and daughter offspring equal to or greater than one year’s metabolic needs, they probabilistically reproduce. For this simulation, agents were given a 3% probability of reproduction at every timestep as long as their storage is above the reproduction threshold.

When an agent reproduces it divides its storage evenly between itself and its offspring. Offspring spawn to a patch near their parent’s patch, preferably one cell away, but if all those cells are occupied, to a random cell within their required cell-type (merchants in the littoral zone, farming Gauls on vacant green patches). Agents are not allowed to live on sea-patches.

Planting: Gauls can only plant on a productive patch and are charged 4 grain units (hectoliters) to plant. Gauls would have needed to store seed to plant their fields each year, and planting would be energetically costly. Thus the parameter “planting” encapsulates both the stored grain, and the cost to plant a large field.

Of note, when fields are planted, a “degradation clock” is set on the cell. Each cell can only be planted for five years before it needs to lay fallow for between 1 and 5 years.

Harvest: When Gaulish agents harvest grain they harvest the quantity according to the number of individuals in their household, which is determined by the amount of storage they have accrued (Table S2). Harvest, however, is costly, and the costs are fixed (they do not scale like harvest amount does). The amount can be encapsulated by the following formula:

$$H_t = H_a - H_c$$

where H_a equals the amount harvested, calculated from Table S1, H_c equals the costs of harvesting, H_t equals the total harvested.

Harvests are known to come in at once and need to be harvested rapidly before the grain falls off the stalk. Thus Gauls likely relied on others to help with harvest who needed provisioning to help with the harvest. Further, some grain that grew may be lost in harvest, due to improper techniques, harvesting too late, or storing improperly. Thus “harvest” encapsulates the costs associated with harvest and storage. In the sweep presented here H_c is 4 *hl*.

Eating grain: Eating grain is encapsulated in “consumption rates” in Table S1. The amount of grain eaten scales according to the number of individuals in a household. When individuals eat grain it is taken from the storage first; if storage is not sufficient, the calories are taken from the recent harvest (which is stored in the next step).

Storing grain: Here Gaulish agents store the grain that is leftover from the harvest, or H_t .

Buying wine: When Gaulish agents have a storage of twice the Grain Trade Rate (described above) they assess a probability, in this simulation set to 1%, of whether or not they will buy wine in the current year. If they will buy, who they buy from depends on what year it is in the simulation.

After Etruscan Arrival, before Greek Arrival: In this case, Gaulish agents ask an Etruscan agent if it has enough wine to sell. If it does, Gaulish agents trade the amount of grain set by Grain Trade Rate for 10 amphorae of wine. The Gaulish agent then calculates the distance between itself and the Etruscan agent. It multiplies that number by a carrying-cost multiplier (set to 0.25 for the simulation), and subtracts that quantity from storage. So,

$$D_{ge} \times 0.25 = GTC$$

where D_{ge} is the distance between the Gaulish and Etruscan agents, 0.25 is the carrying-cost multiplier, and GTC is the amount to be subtracted from Gaulish storage. This distance factors into how Gaulish agents choose to move.

After Greek Arrival: If Greek Merchants have already arrived, Gaulish agents assess their preference for which type of wine they like best. This is in Table S2. Gaulish agents choose a random number between 1 and 100, and compare that number to their preference value (Table S1). If the Gaulish merchant chooses a number that favors Etruscan trade, they will preferentially trade with Etruscans. If the Gaulish agent chooses a number that favors Greek trade, they will trade with

Greeks. Then the Gaulish agent follows the same protocol as above, calculating its distance and subtracting carrying costs from its storage.

Consuming wine: Wine is consumed at one amphora per type, per year, and is decreased from the Gaulish amphorae storage.

Moving to a new patch: In this model cells degrade after 5 years of farming use; cells become productive again after up to 5 years lying fallow, set randomly. If a Gaulish agent's farm cell has become unproductive, the agent must move to another cell. When Gauls move, they will look at its most recent trading costs and assess how costly they were. If the trading costs were greater than $\frac{1}{4}$ of the grain in storage, the agent will move to a productive cell closer to the merchant settlements. If the costs were less than $\frac{1}{4}$ of the agent's grain storage, the agent will simply look for another productive cell in a radius of 10 cells (if available, if not to another cell in their habitation type) to begin a new farm. The Gaulish agent is charged 1 *hl* to move to a new farm.

Death: If an agent has a total of 0 grain in its storage (or if it has 0 grain in both storage and its immediate harvest total) an agent dies. Further, if an agent has reached its life expectancy (set to 80 for this simulation) the agent has a 5% probability of dying each time it calls the "death" function.

Merchant scheduling: 50 Merchant agents of each type are placed on the littoral portion of the landscape and given 60 grain on outset. When each year begins Merchants follow the following processes in the order presented below.

Trade wine: The first thing merchant agents do is try to trade wine, since this enables them to get grain. If a Merchant agent has less than 20 *hl* of grain, it rolls the dice and has a 25% chance of attempting to buy grain. The Merchant agent asks a Gaulish agent with twice the Grain Trade Rate in storage to sell. The Merchant agent then calculates the distance between itself and the Gaulish agent. It multiplies that number by a carrying-cost multiplier (set to 0.25 for the simulation), and subtracts that quantity from storage. So,

$$D_{gm} \times 0.25 = GTC$$

where D_{gm} is the distance between the Gaulish and Merchant agents, 0.25 is the carrying-cost multiplier, and GTC is the amount to be subtracted from Merchant storage.

Reproduce: Merchants then reproduce. Reproduction is via fission and follows that established in the "Wolf-Sheep Predation" model developed by Wilensky (2005). Merchants assess their stored calories. If their calories are above a threshold that enables a division of calories between parent and daughter offspring equal to or greater than one year's metabolic needs, they probabilistically reproduce. For this simulation, agents were given a 3% probability of reproduction at every timestep as long as their storage is above the reproduction threshold.

When an agent reproduces it divides its storage evenly between itself and its offspring. Offspring spawn to a patch near their parent's patch, preferably one cell away, but if all those cells are occupied, to a random cell within their required cell-type (merchants in the littoral zone, farming Gauls on vacant green patches). Agents are not allowed to live on sea-patches.

Consume wine: Wine is consumed at one amphora per type, per year, and is decreased from the Merchant amphorae storage.

Eat grain: Eating grain is encapsulated in "consumption rates" in Table S2. The amount of grain eaten scales according to the number of individuals in a household. When individuals eat grain it is taken from the storage first; if storage is not sufficient, the calories are taken from the recent harvest (which is stored in the next step).

Plant/tend vineyard: Vineyards only are planted once, but are costly to maintain. Merchants are charged 4 grain units (hectoliters) to plant and maintain their vineyards. Merchants would have needed to prune branches, check for molds and diseases, and maintain the soil of their vineyards.

Harvest wine: Harvesting grapes and turning them into wine would be costly. The cost of harvest was set to 4 *hl* for this simulation, while the yield was set to 10 amphorae of wine for this simulation.

Grapes ripen at once and need to be harvested before they rot, are eaten by scavengers, or freeze on the vine. Thus Etruscans and Greeks likely relied on others who needed provisioning to help with harvest. Further, some grapes that grew may be lost in harvest, due to improper techniques,

harvesting too late, or storing improperly. Thus “harvest” encapsulates the costs associated with harvest and storage. In the sweep presented here H_c is 4 *hl*.

Death: Death follows the same as it does for Gauls. If an agent has a total of 0 grain in its storage (or if it has 0 grain in both storage and its immediate harvest total) an agent dies. Further, if an agent has reached its life expectancy (set to 80 for this simulation) the agent has a 5% probability of dying each time it calls the “death” function.

System Scheduling:

Each year, at the beginning of the year the simulation checks to see if there are no agents, or if there have been more than 500 years since the start of the simulation. If either of these are true, the simulation stops.

After Gauls, then Etruscans, then Greeks perform their scheduling as detailed above, the simulation checks its carrying capacity. Then the simulation regenerates dead patches, and finally degrades those patches that need degrading.

Carrying capacity: This catch is rarely used in the simulation. A carrying capacity of 1000 Gauls, 600 Etruscans and 600 Greeks was set for the simulation. If there are greater than that many agents for each type, all agents that are above the life expectancy (set to 80) die that year. Otherwise, as described above, those agents that reach the carrying capacity have a 5% chance of dying every year. This ensures that the simulation is not overpopulated with very old agents.

Regrow patches: Once a cell has been farmed for five years it needs to lay fallow before it can be refarmed. Each cell is given a random number between 0 and that set by the parameter “grass regrowth time” and has that many years to regrow. It is updated yearly until the patch is productive again.

Degrade patches: When a patch is occupied by a Gaulish agent and farmed it is given a 5-year clock. Each year this is updated, until it has been 5 years, when the cell starts its “regrow patches” clock.

4. Design Concepts

Questions: There are eleven design concepts. Most of these were discussed extensively by Railsback (2001) and Grimm and Railsback (2005; Chapter. 5), and are summarized here via the following questions:

Basic principles Existing models for the interaction between Gaulish inhabitants and colonial traders along the littoral (the region abutting the Mediterranean) of southern France are descriptive. According to Py (2012:135) the paradigms underlying research by proto-historians working in these contexts can be summarized as follows: indigenous Gauls living along the littoral zone were forced to abandon some of their traditional practices, such as semi-nomadic pastoralism, to generate the agricultural surplus required to develop their economies and engage in trade with outsiders (Py 2012). Yet these descriptive models have not been formally tested; thus, the research here formally examines how early colonialism can create distinctive economic partnerships and artifact patterns. This model examines these principles, formalizes them, and explores them. First I assess whether it would have been feasible for Etruscan and Greek merchants to live in Southern France if they did not farm—could Gauls have provisioned them? Second, I examine whether the replacement of Etruscan amphorae by Greek amphorae could be generated by strictly local processes. This is the first model made in Southern France, so it is highly simplified, with the goal of adding realism after this model is published.

Emergence. The emergent property in this model is the distribution of artifact types across the landscape. As this model has variable productivity related to the use of the landscape, costs associated with trading, and the reality that Gaulish agents do not need to trade for wine to survive, the decisions of Gaulish agents on where to farm, when to reproduce, and when to trade will effect Merchant survival. Gauls also decide to move based upon the costs of trading, so this will effect where they plant. Since Merchants can initiate trade, and Merchants need to trade to survive, their “goals” are potentially at odds with Gaulish agent goals. Even though Gauls prefer one type of wine over another, since Merchants can initiate trade as well, they *should* be able to survive.

However, this simulation shows that there are phase transitions related to preference after which it's hard for one or another type of Merchant agent to survive. This shows the emergence of the replacement of one artifact type over another.

Adaptation. Gaulish agents only trade when they have above a certain threshold of stored grain. This will dramatically affect the survivability of Merchant agents. Gaulish agents “want” to survive and reproduce. Wine helps decrease harvest costs, but buying wine decreases storage. Therefore a Gaulish agent must “choose” each timestep to reproduce and/or to trade. They adapt by moving their farms to reflect the costs that trading incurred.

Objectives. Objectives for agents are to maximize storage, maximize reproduction, and minimize harvesting costs. These are accomplished by farming, storing, reproducing, and buying wine (for Gauls), or harvesting, trading, and reproducing (for Merchants).

Prediction. Merchant agents predict future consequences of having too few grain and seek to trade with a Gaulish agent. If they have too few grain they die. Gaulish agents predict the costs related to trading based on previous costs, and attempt to minimize those in the future.

Sensing. Gauls can “sense” when their homecell is no longer productive, and choose to move to a productive cell. This is tied to how much it cost to trade for wine the last time they traded.

Interaction. The direct interaction modeled in this simulation is trade, and trade is only between Gaulish agents and Merchant agents. Indirect interaction is between Etruscan and Greek agents. Since both of them have to live along the littoral cells, they compete for arable land. If one population is higher than the other, it becomes increasingly hard for the other agents to live on the landscape.

Stochasticity. Preference is partly random; Gaulish agents choose a random number between 1 and 100 and compare that to the preference value, which drives whether they trade with one type of agent or another (Table S1). It is improbable, but possible, that even with a high preference value (90—in favor with Greeks) that every Gaulish agent could choose an integer of the remaining 10 and always trade with Etruscans. Further, reproduction is random, as agents only have a 3% chance of reproducing at every timestep. Finally, a random subset of cells at the onset of the simulation are set to be unproductive, and that determines where Gaulish agents can initially farm.

Collectives. Collectives are important in this simulation, as they dictate who trades with whom. Gauls are a collective, Etruscans are a collective, and Greeks are a collective.

Observation. Both individual level and population level statistics are collected from this simulation. Individual level statistics include the amount of Etruscan or Greek wine an agent has, and the amount of storage an agent has. Group level data include the population of each agent type through time.

5. Initialization

Simulation Instantiation: At simulation instantiation, the different types of patches (described above) are created. 1/3 of all land patches are unproductive on the first year of the simulation, and each of these patches are given a random regrowth clock (set to 60 timesteps initially) to allow them to become productive for farming. The region Gauls entered had been used by semi-nomadic forager-farmers for centuries, so it is reasonable to expect that not all of the land was available for farming upon their arrival, either due to being occupied by other groups, due to over exploitation, or due to thick vegetation that needed clearing. The simulation will look slightly different on initialization every time due to the random placement of unproductive patches, and the random placement of Gauls. When Etruscans, and later Greeks, arrive they are placed randomly along the littoral.

6. Input data

No input data was used for this version of the simulation.

7. Submodels

In this model, the user can choose to have one type of merchant agent (default set to Etruscans) or two types of merchant agents (Etruscans and Greeks). These were analyzed separately in Sections 2.1 and 2.2. These are two submodels—first examining the ability for merchant agents to survive when they do not farm, and second examining the competition between two types of Merchant agents.

While this was not examined here, infrastructure is in place to allow for two types of Gaulish agents—those that farm exclusively, and those that mine for metals that can then be traded. This resource diversification model is another submodel, which will allow the examination of different types of goods that were traded to visiting merchants.



© 2016 by the author; licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons by Attribution (CC-BY) license (<http://creativecommons.org/licenses/by/4.0/>).