CAA
2018

Frédérique Bertoncello et al.
https://dx.doi.org/10.15496/publikation-94863

Using ABM to Explore the Role of Socio-Environmental Interactions on Ancient Settlement Dynamics

Frédérique Bertoncello
Université Côte d'Azur, CNRS, CEPAM - UMR 7264 CNRS, frederique.bertoncello@cepam.cnrs.fr

Marie-Jeanne Ouriachi
Université Côte d'Azur, CEPAM - UMR 7264 CNRS, marie-jeanne.ouriachi@univ-cotedazur.fr

Célia da Costa Pereira
Université Côte d'Azur, I3S - UMR 7271 CNRS, Nice
celia.da-costa-pereira@univ-cotedazur.fr

Andrea Tettamanzi
Université Côte d'Azur, I3S - UMR 7271 CNRS, Nice
andrea.tettamanzi@univ-cotedazur.fr

Louise Purdue
Université Côte d'Azur, CNRS, CEPAM - UMR 7264 CNRS, louise.purdue@cepam.cnrs.fr

Rami Ajroud
Université Côte d'Azur, I3S - UMR 7271 CNRS, Nice
ajroud.rami@hotmail.fr

Jérémy Lefebvre
Université Côte d'Azur, I3S - UMR 7271 CNRS, Nice
lefebvre.jeremyp@gmail.com

Abstract

This paper presents a work in progress within the project « Modeling the role of socio-environmental interactions on Ancient Settlement Dynamics - ModelAnSet » developed by archaeologists, historians, palaeoenvironmentalists and computer scientists at University Côte d'Azur (Nice). Agent-based modelling is used to explore the respective role of environmental and social factors in the evolution of the settlement pattern and dynamics during the Roman period in South-Eastern France. The model aims at simulating the impact of the climatic and macro-economic conditions on the behaviour of Gallo-Roman landowners. According to the profit they derive from their farms and/or villas, which depends both on natural and socio-economic factors, the landowners can decide to maintain without change, improve, enlarge or abandon their agricultural holdings or to create a new one. Through the repeated landowners' decision-making, the ABM thus simulates a changing macro-level settlement pattern, in terms of number, type and location of the settlements. The paper focuses on the conceptual model in order to present the model entities and the dynamics underlying their interactions, and explain our choices and hypotheses.

Keywords: Agent-based modelling, Settlement dynamics, socio-natural systems, Roman Archaeology, Galia

Introduction

Since the early 90's, a group of French archaeologists has been developing a wide research program devoted to the analysis of long-term dynamics of the settlement system, in collaboration with geographers. Through successive projects1, they elaborated a series of indicators to describe and compare settlement's intensity, hierarchical structure and spatial distribution in various areas of Southern and Central France between the Iron Age and the Early Middle Age (Durand-Dastès et al. 1998; van der Leeuw, Favory & Fiches 2003).

Based on more than 2000 settlements identified in field surveys, these indicators were built on the same methodological basis in order to make the results comparable between different regions. They enabled to highlight regularities in the settlement's dynamics observed both in Southern and Central Gaul, as well as local specificities (Bertoncello et al. 2012; Ouriachi & Bertoncello 2015). For the beginning of the Roman period, two main patterns have been identified (Figure 1):

- from the 2nd c. BC to the 1st c. AD, a strong increase in the number of rural settlements caused a more concentrated spatial distribution of the settlements;
- During the 1st c. AD, the development of a new type of rural settlement - the Roman villa – led to a more hierarchized settlement structure;
- At the end of the 1st c. and during the 2nd c. AD, the number of settlements strongly declined in most areas, resulting in a more dispersed spatial distribution, while the hierarchical diversity of the settlements decreased.

In order to go beyond these observations regarding the state of the settlement system at different periods, it is necessary to investigate the processes that underlie its transformations through time. This interest in dynamics motivated the use of modelling to simulate the processes of creation, abandonment or maintenance of the rural settlements, in so far as these processes determine the quantitative, qualitative and spatial evolution of the settlement system. The Agent-Based Model we are presenting in this paper is in line with this perspective2: its purpose is to explore the respective role of environmental and human factors in the evolution of the settlement system during the Roman period. Agent-based modelling is particularly well suited to this goal as it allows to explore how interactions between the systems components at the micro-level generate new properties and structures of the system at the macro-level.

Our model is under development on the NetLogo platform (Wilensky 1999) and we will focus here on the conceptual model3. As usual in social sciences, the model components and their characteristics are based both on our knowledge (i.e. from archaeological and textual data) and on hypotheses that must be made explicit and that can be tested within this simulation framework. It is important to emphasize that our aim was, at this first stage of the modelling process, to set up the general framework of the model by defining its components and the main rules of their interactions underlying the system dynamics. Accordingly, this paper will present the entities of the model, the model dynamics and the expected outputs, before mentioning some future developments.

1 Mainly the two Archaeomedes projects (Archaeomedes I (1992-1994) « Understanding the Natural and Anthropogenic causes of soil degradation in the Mediterranean Basin », Program Environment of the European Commission DGXII; Archaeomedes II (1996-1999) « Policy relevant models of the natural and anthropogenic dynamics of degradation and desertification and their spatio-temporal manifestations », Program Environment of the European Commission DGXII, coordinated by Sander van der Leeuw, University of Cambridge), followed by the two Archaedyn projects (Archaedyn 1 (2005-2008) « Spatial dynamics of territories from Neolithic to Middle Ages », ACI « Spaces and Territories », French Ministry for Research and New Technologies, contract ET28; Archaedyn 2 (2009-2012), French National Agency of Research, contract ANR-08-BLAN-0157-01, coordinated by François Favory and Laure Nuninger, UMR 6249- USR 3124, Besancon, France).

2 This model is developed within the ModelAnSet project (« Modeling the role of socio-environmental interactions on Ancient Settlement Dynamics ») supported by UCAJEDI Complex Systems Academy of Excellence of University Côte d'Azur, Nice.

3 In order to ease the collaboration with the computer scientists in charge with the implementation of the ABM, we used the ODD (Overview, Design concepts, Details) protocol developed by Grimm et al. (2006; 2010) to describe the conceptual model.

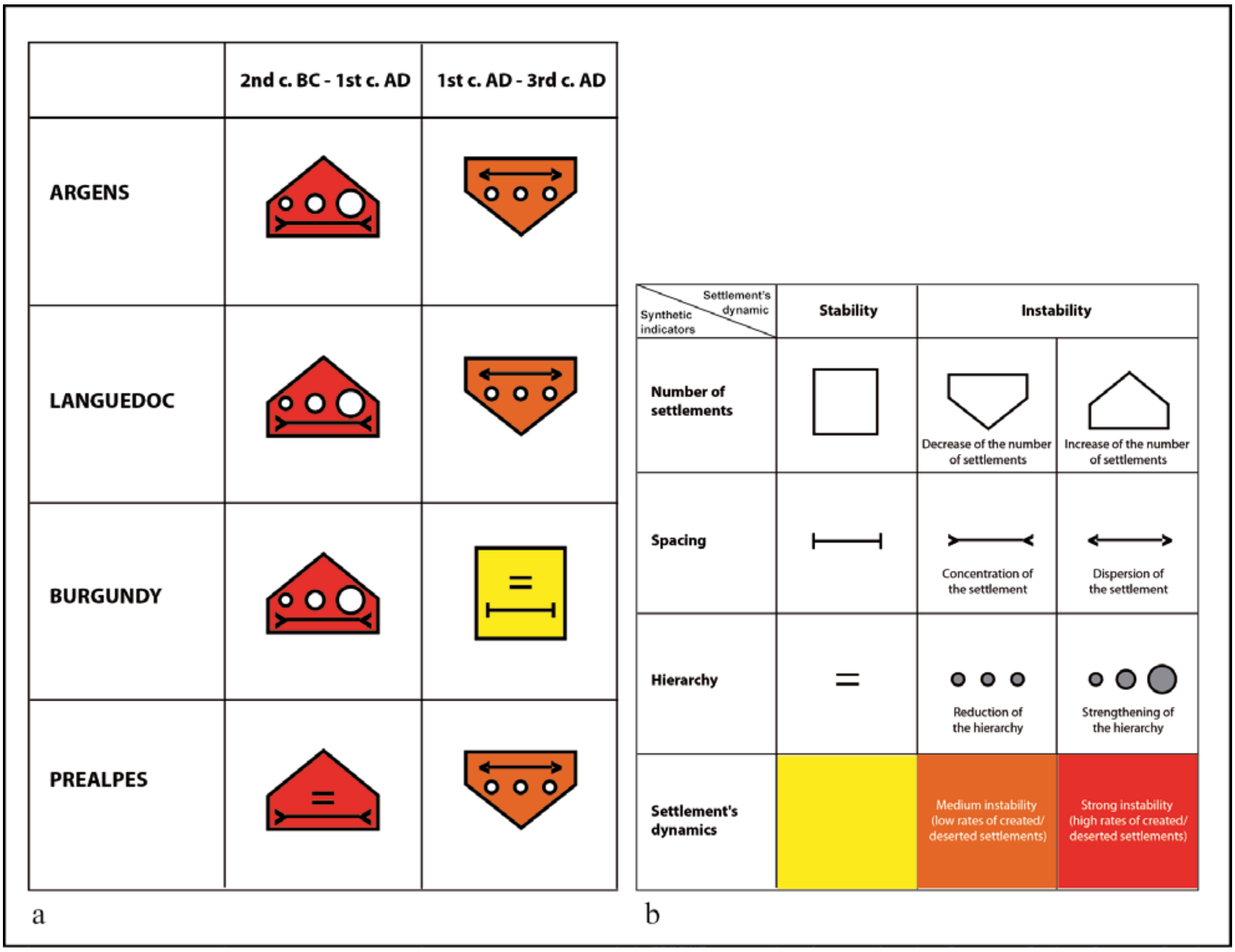

Figure 1. a: Synthetic representation of the settlement's dynamics in 4 French micro-regions between the 2nd c. BC and the 3rd c. AD according to the quantitative, spatial and hierarchical indicators developed within the Archaedyn project ; b: Legend of the symbols (from Ouriachi & Bertoncello 2015).

The Model Components: Agents and Spatial Entities

The dynamic of the system results from the creation, abandonment, or maintenance of the rural settlements. As the decision to create, abandon or maintain a rural estate mainly depends on its owner, we chose to simulate the behaviour of Gallo-Roman landowners regarding their agricultural holdings.

Although there was a great diversity of Gallo-Roman landowners, and as modelling imposes to simplify reality, we only consider three types of agents with different socio-economic status: the farmers, the big landowners, and within this group, the aristocrats, meaning magistrates who played a political role in the city. We decided that farmers could only possess one farm while big landowners and aristocrats could own several farms and villas, as evidenced by Latin texts. For the latter, theoretically, the number of properties held was set to a maximum of three for big landowners (including one villa) and six maximum for aristocrats (including at least three villas). In the model, this rule has to prevent one owner from possessing most of the lands in the territory of the city.

The size intervals assigned to each type of agricultural holding (farm/villa) were selected - as far as possible - based on historical and archaeological data. Indeed, this is a tricky historical problem: even when reliable data seem available (such as those given by the marble tablets of the cadastre of the Roman colony of Orange), it appears that the sizes mentioned (max. of 97 ha) are not those of the agricultural holdings, but those of public land allocated to farmers under land leases; moreover, among the successful tenderers, there are general farmers who want to

	Initial economic power	Maximum number and type of holdings	Spatial behaviour for the location of their holding(s)
Farmers	500 - 1000 (tokens)	1 (farm)	Restrained to their own holding
Big landowners	1000 - 5000 (tokens)	3 (including at least 1 villa)	Within a radius of 20 km from any of their holdings
Aristocrats	> 5000 (tokens)	6 (including at least 3 villas)	No spatial constraint (can create holdings anywhere); Attraction by the city capital: must have at least 1 of their holdings in a radius of 10 km from the capital

Table I: Attributes and behaviour rules of the agents.

take advantage of the "vectigal" (tax) collection but do not exploit the land (Favory 2012: 138-139). The assessment of the size of the Roman rural domain is mainly based on two types of data. The first ones are the size of the buildings and the storage or production capacity deduced from the agricultural installations. However, according to the authors, the same data produce very different results: for example, the domain of the villa of Settefinestre (Tuscany, Italy) varies from 25 to 125 ha, including 7.5 to 50 ha of vines (Compatangelo 1995: 46). In other cases, the surrounding landscape (concept of "natural region" based on topographical boundaries) is taken into account to define the area of land associated with a villa. Mauné (2010) thus estimates the surface of the villa of Quintus Iulius Pri(...) at Aspiran (Hérault, France) at 350 or 450 ha (Mauné et al. 2010: 113). Congès & Lecacheur (1994) evaluate the domain of the Pardigon villa (Var, France) at 80-100 ha with the first method (cellar storage capacity), and at 300 ha with the second one or 90 ha if considering only the plain (Congès & Lecacheur 1994: 286). We cannot mention all the numerous studies of this kind but these elements allowed us to set the size thresholds for the villas between 50 and 500 ha, knowing that some domains can reach far bigger sizes: for example, in another context, the estates of the villas in Roman Brittany varied between 60 and 1300 ha (Compatangelo 1995: 64-65)[4]. Concerning the farms, the surfaces are clearly lower: thus, Buffat (2010) mentions 15 ha of vines for the two farms of Gasquinoy (near Béziers, France), and more generally, archaeological surveys give areas from 10 to 20 ha (Buffat 2010: 183). Ouzoulias (2006) estimates that a tenant had to cultivate 17 to 22 ha of land in a subsistence farming context, to guarantee the persistence of his exploitation (Ouzoulias 2006: 199-200). Thus, for the farms, the size interval for the agricultural surface was set between 10 and 50 ha.

In addition to the dimensions of the domains, it is necessary to determine the behaviour of the landowners regarding each of their agricultural holding(s). We selected five actions: they can maintain their holding without change, enlarge or improve it, abandon it or create a new one. Their decision depends on their socio-economic status and the profit they derive from each holding or expect to derive if they create a new one. The socio-economic status of the landowners defines their initial economic power, the number and type of rural settlement they can own as well as their behaviour (tab. 1). We have some elements concerning the wealth of the aristocrats: we know that the census required from them is 400 000 sesterces under the Republic, and 1 million for the senators under the Principate, the census of the knights remaining unchanged. The magistrates had to pay the "summa honoraria/legitima" upon entering their public office. This sum varied according to the size of the city (for example 2000 sesterces in the colony of Urso for the "duumviri" and the "aediles", but 38000 sesterces in Carthage); nevertheless, it is obvious that magistrates were wealthy men. Regarding the farmers' income, ancient sources are even more scarce and it probably varied a lot from an area to another and according to the origin of the farmer (in our case: Gaul or Roman). We can get some clues from the case of the veterans of the Roman legions: from the information provided by Roman historians

4 We must also bear in mind that the "fundus" is an accounting unit that must be distinguished from the production unit. A fundus may comprise several production units (Compatangelo 1995: 52).

and biographers (especially Suetonius and Tacitus), F. Gayet calculated that the capital available for a veteran after his demobilization might amount to a minimum of 16 500 sesterces during the Augustan period, and between 10 500 and 12 000 sesterces minimum from Caligula to the Antonine period (Gayet, oral information).

It is very difficult to define values of general scope from figures so variable and specific to particular cases. Thus the ranges of values we chose for the initial economic power of each type of landowners are largely arbitrary and relative, in a ratio of 1 to 10 or more between the less wealthy farmer and any aristocrat (tab. 1). Allowing to change and « play » with these parameters is one of the interest of modelling to test and refine our hypotheses.

Things are getting even trickier when it comes to defining the landowners' behaviour. Regarding their economic behaviour, we consider that landowners demonstrate a certain rationality[5]. Indeed, in the model, the landowners decide what to do with each of their agricultural holdings according to the profit they derive from it or expect to derive if they create a new one.

This profit is related firstly to the production capacity of the holding, which depends on its environmental context. At this first stage of the model development, five very stylized types of environmental units were selected: alluvial plain, foothills, plateaux, sedimentary basins, hillslopes; each one is credited with a productive potential. The profit also takes into account the cost of transporting the goods to the nearest marketplace, i.e. the agglomerations. In the model, two types of agglomeration were distinguished to account for historical reality: one city capital and three smaller towns, with no administrative role (the so-called "secondary agglomerations").

The model was instantiated in a specific spatio-chronological context which is the territory of the Roman colony of Forum Iulii, the actual Fréjus in South-East of France, where archaeological and palaeoenvironmental studies have been conducted for over 20 years (Bertoncello 1999; Bertoncello et al. 2012; Bertoncello et al. 2014). This instantiation helped calibrating some model parameters (such as, for example, the relative proportions of towns, villas and farms in the settlement system) and will also allow to place the simulation in a realistic environment, based on the actual landscape of this area, although it is not fully implemented yet in the ABM.

The model also aims to integrate the impacts of two factors external to the settlement system on the production capacity of the rural holdings. The first one is the macro-economic context within the Roman Empire, which might have influenced the economic power of the landowners, for example through the fluctuations of the taxation and the state of the market. This economic factor has not been implemented yet in the model. The second element is the climate, which has an impact on land fertility. For the moment, climate change is simulated in a very coarse manner by randomly increasing or decreasing the landscape units' fertility, but it is planned to combine the ABM with a palaeoclimatic model.

The Model Dynamics (Figure 2)

At each iteration, the landowners' decision-making regarding each of their holdings depends on the combination of the evolution of their economic power and the profit derived from this particular farm/villa. The economic power of the landowners is not considered in its absolute value but in terms of evolution: at each iteration, their revenue (drawn from all their holdings) can be equivalent, superior or inferior to their revenue at the previous iteration. There are many intervening factors in the profit produced by an agricultural holding: the type and size of the domain, the amount of workforce, the size and efficiency of the agricultural equipment, the type of agricultural productions, the environmental conditions, etc. Due to the complex interactions between these elements, estimating the profit derived from each agricultural holding would require developing a specific model dedicated to this goal. This is envisioned as a medium-term perspective but at this stage, we accepted to use very rough estimators for the profit produced by each villa or farm in the model, in order to focus on the model structure. Thus in the model, the profit derived from each holding at each iteration can be "high" or "low" with respect to a theoretical average value fixed at 600 (tokens) for the farms and 6000 (tokens) for the villas. This value is the average between the minimal and maximal

5 Concerning the debate on rationality in Ancient economy, see for example Andreau et al. 2004.

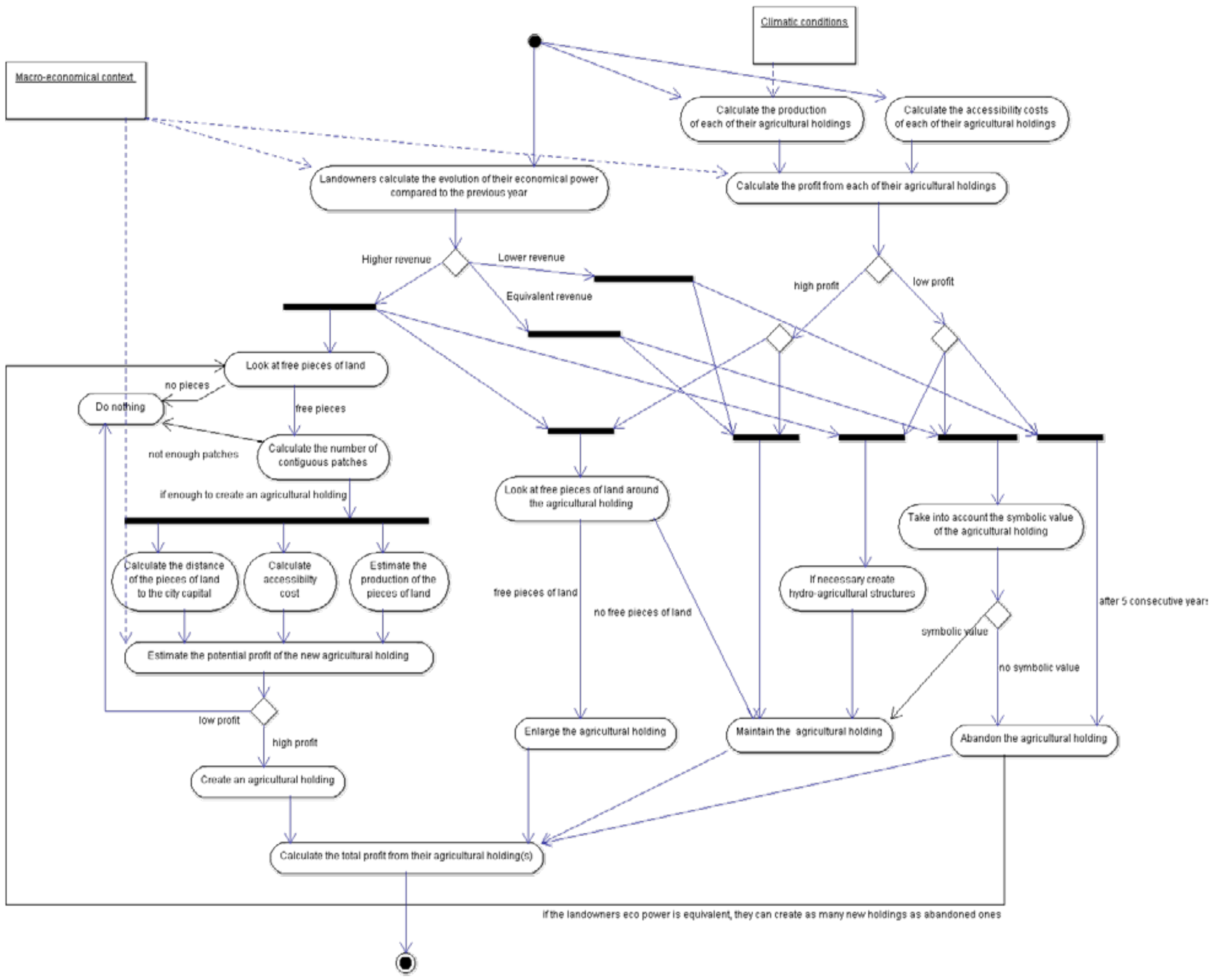

Figure 2. Flowchart of the model dynamics using the UML formalism.

profit values possible for each type of holdings (farm/villa) which depend on their size (i.e.: 10 to 50 ha for a farm and 50 to 500 ha for a villa) and on their production capacity, related to their environmental context (see above).

Table II shows the range of actions that can be performed by the landowners according to the evolution of their economic power and the profit derived from each holding. In the simplest case, when the landowner's revenue is lower than his previous one and the profit from his holding is high, he will maintain it without change. On the contrary, if the profit is low, he will abandon this farm or villa, but only after five consecutive years of low profit. This delay was introduced to take into account the variability of the agricultural production from one year to another and to avoid too much instability of the system; the five-years timescale is one of the parameters to be tested.

As farmers cannot own more than one farm, new agricultural holdings can only be created by big landowners and aristocrats, when their revenue is superior or equivalent. In this last case the landowners can only create new holding(s) if they abandon the same number of holding(s). Sufficient contiguous patches of land must be available to create a new estate, within the size intervals defined for farms and villas. According to their socio-economic status, landowners were assigned different spatial behaviour (Table I). As they can only improve or enlarge their existing farm, the farmers' range of action is limited to their holding. The aristocrats can create settlements anywhere but they are specifically attracted by the city-capital, as it is the place where they exercise their political functions. Indeed the Roman magistrates had to reside in the city-capital during their annual office, but they were also required to have at least one property in the territory, in order to guarantee

Landowner's economic power (t+1)	Profit derived from each agricultural holding		Possibility of creating new holdings (only for big landowners and aristocrats)
	High profit (Farm: > 600 tokens; Villa: > 6000 tokens)	Low profit (Farm: < 600 tokens; Villa: < 6000 tokens)	
Equivalent (=)	Maintain	Maintain	No
		Abandon	Yes
Higher (>)	Enlarge or Maintain	Improve or Maintain	Yes
Lower (<)	Maintain	Abandon	No

Table II: The actions performed by the landowners according to the evolution of their economic power and the profit derived from each agricultural holding.

their ability to assume their public responsibilities (see Berrendonner 2005: 83 who quotes the Law of Taranto which gives this information). Therefore, in the model, the aristocrats must have at least one holding in a radius of 10 km from the capital: according to ethnological studies, this distance corresponds to a two-hour walk. When they want to create a new holding, the patches of land located within this 10 km radius are granted an extra attractiveness value. In order to simulate various spatial behaviours, we hypothesize that the big landowners have a more « local » range of action than the aristocrats: they can only create new holdings within a radius of 20 km from any of their existing estates.

When the landowners' revenue is superior to the previous one, they can choose to maintain their settlement without change, enlarge it or improve it. By improvements, we mean various hydro-agricultural structures such as irrigation or drainage ditches, land terraces, stone clearance, etc., which can be created to improve the production of the land. This generates feedbacks between agents' behaviour and the properties of their environment, as they can improve land productivity. If such an "improved" domain comes to be abandoned, the presence of these hydro-agricultural structures is considered as an advantage to create a new agricultural holding on these lands, as they reduce the initial investment necessary to exploit them. In the model this is expressed by a higher value of attractiveness given to these patches.

Another feedback loop is introduced in the model by degrading land productivity after five years of consecutive exploitation.

Beside the economic value of the agricultural holding, its symbolic value is also taken into account. This refers to the attachment of some landowners to one specific settlement. We have mentioned the attractiveness of the city-capital for the aristocrats. Ancient texts and epigraphical documents also suggest that the owners attached particular importance to the estate where the family grave was located (see the example of the funerary monument of the Domitii family, located at Rognes, 15 km from the city-capital Aquae Sextiae /Aix-en-Provence, whose members belonged to the municipal aristocracy of the colony: Burnand 1975). In the model, this symbolic value will push the landowners to keep their holding even if its profit is low.

Expected Outputs

According to these processes, the repeated landowners' decision-making produces a changing macro-level settlement pattern, in terms of number, type and location of the settlements (Figure 3).
In order to explore the respective role of the chosen environmental (i.e. fertility of the various simulated environmental units, climatic conditions) and social (economic power and symbolic behaviour of the landowners, distance to the nearest town, macro-economic context) factors in the evolution of the settlement pattern and dynamics, various scenarios will be tested. The basic ones will be to run the model first without any climatic nor macro-economic variations, then to introduce climatic change or economic fluctuations, then both of them.

This raises the tricky question of estimating the validity of the various simulated scenarios. One way to do this in our case is to compare the simulated out-

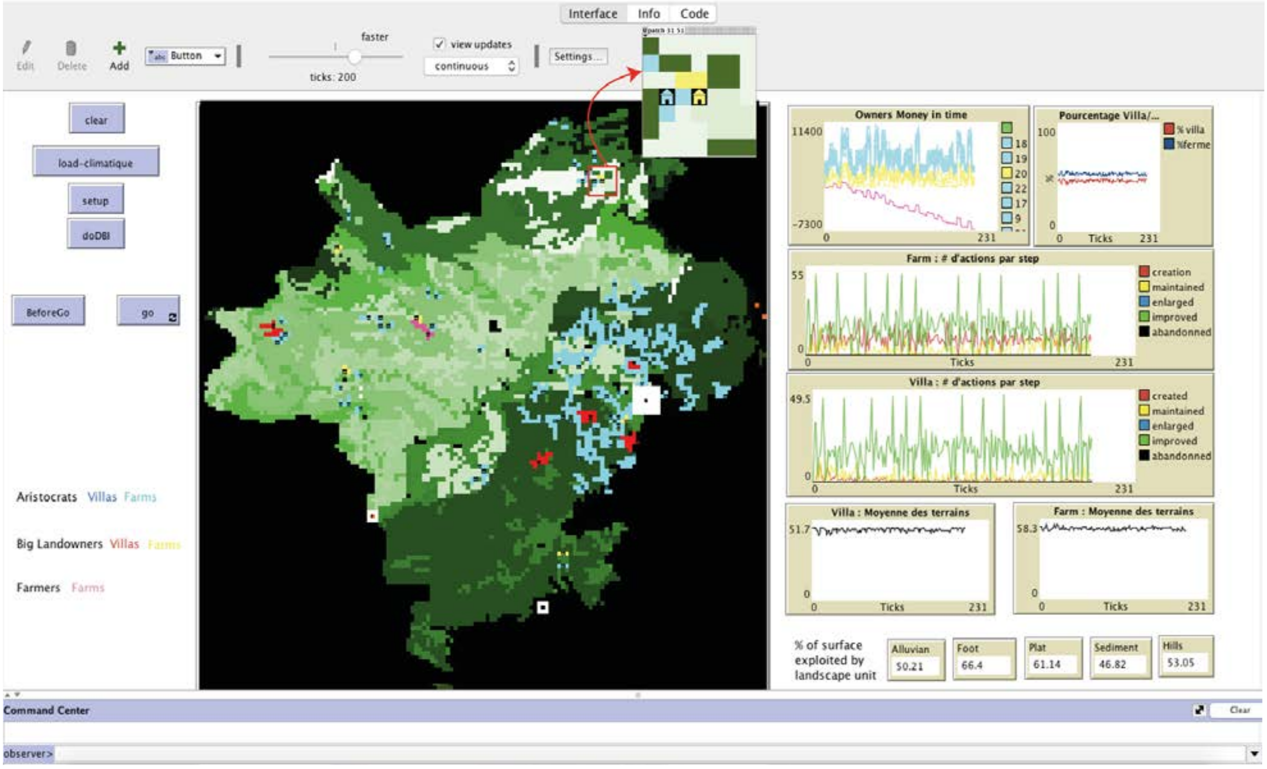

Figure 3. Screenshot of a simulation of the model on the NetLogo Platform, with a zoom on some patches.

puts with the archaeological records. This implies to produce outputs which are comparable to the quantitative, spatial and hierarchical indicators available to describe the settlement pattern and dynamics in the area of Fréjus during the Roman period (see Figure 1 above and Bertoncello et al. 2012; Ouriachi & Bertoncello 2015). The model will thus calculate, at each iteration, the proportion of villas and farms per type of landowner and per type of landscape units; the proportion of settlement maintained, enlarged, improved, abandoned or created; the minimum, average and maximum size of the estate for each type of settlement by type of owner; the minimum, average and maximum distance of each type of settlement by type of owner to the city capital and to the closest smaller town, etc.. In order to compare them to empirical data, these values will be compiled for a chosen number of iterations supposed to correspond to an archaeologically relevant period of time. It is obvious though that a good match between the simulated outputs and empirical data is not sufficient to draw firm conclusions on the causalities involved in the settlement dynamics. But this can help us to select which ones of our hypotheses are the most plausible. In that sense, modelling is a tool to think. It provides a testing of an hypothesis of process rather than a proof of the existence of process (« c'est une mise à l'épreuve plus qu'une preuve » : Tannier et al. 2017, 406).

Concluding Remarks and Perspectives

A first version of the ABM has been implemented and is now in the testing phase. Besides the unavoidable and necessary adjustments of the model, we would like to mention further developments that are envisioned in the near future. The first one concerns the ABM itself and more specifically the agents' behaviour. For the moment, the actions of the landowners are defined by fixed rules: according to the combination of these rules they react in one way or another. In opposition to these « reactive agents », the integration of « cognitive agents » in the model is currently tested in order to better take into account the complexity of human behaviour. The BDI model (Beliefs, Desires and Intentions: Bratman 1987) allows to assign agent beliefs about itself (for example in our case, its economic power) and its environment (estimation of lands' fertility), as well as desires (for example, creating a villa close to the city-capital), which will determine what actions the agent will initiate to reach its goal. Possibility Theory (Dubois & Prade 1988) is used to weight and prioritize the various desire generation rules, allowing to better account of the gradual nature of reasoning and deliberations of a cognitive agent in a context of uncertainty (da Costa Pereira & Tettamanzi 2010). Using such cognitive agents in our model opens interesting perspectives to integrate more nuanced perceptions of land productivity, of the impact of hydro-agricultural structures, of the macro-economic context, etc.The two other main developments planned for the model relate 1) to past climate and climatic changes, and 2) to the functioning of Ancient agrosystems. Each of these items requires a model per se, and the issue is thus to couple our ABM with both a palaeoclimatic and an agrosystemic models. This is the goal of the RDMed project which started in September 2018.[6] Based on the previous work done by the team of Joël Guiot at University Aix-Marseille, this project aims to simulate the response of Ancient societies to climatic change by developing an integrated model coupling our Agent-Based Model, an agroecosystemic model for agricultural production (adapted from the LPJmL model to Ancient agriculture: Contreras et al. 2019), an erosion model to simulate the effect of human activities on the landscape, and a palaeoclimatic model combining modern and palaeoclimatological data using a statistical downscaling technique to provide the appropriate temporal and spatial resolutions (Contreras et al. 2018). The prototype of the ABM we presented in this paper is thus a small preliminary brick in a more ambitious and long term project.

6 The RDMed (« Resilience and adaptation to Droughts and extreme climate events in the MEDiterranean: lessons learnt from past on a 1.5°C or more warmer world") project is directed by Joël Guiot (CEREGE, Aix-en-Provence) and supported by AMidex – Aix-Marseille University.

Reference

Andreau, J, France, J, Pittia, S 2004 *Mentalités et choix économiques des Romains.* Bordeaux: Ausonius Scripta Antiqua 7.

Berrendonner, C 2005 Les patrimoines fonciers des sénateurs de l'Italie républicaine: l'apport des sources épigraphiques. *Cahiers du Centre Gustave Glotz*, 16: 79-99. DOI: https://doi.org/10.3406/ccgg.2005.882

Bertoncello, F, 1999 *Le peuplement de la basse vallée de l'Argens et de ses marges (Var) de la fin de l'Age du Fer à la fin de l'Antiquité.* Unpublished thesis (PhD), University of Provence I, Aix-en-Provence.

Bertoncello, F, Devillers, B, Bonnet, S, Guillon, S, Bouby, L, Delhon, C 2014 Mobilité des paysages littoraux et peuplement dans la basse vallée de l'Argens (Var, France) au cours de l'Holocène. *Quaternaire*, 25 (1): 23-44. DOI: 10.4000/quaternaire.6893

Bertoncello, F, Fovet, E, Gandini, C, Trément, F, Nuninger, L 2012 The spatio-temporal dynamics of settlement patterns from 800 BC to 800 AD in Central and Southern Gaul: models for an interregional comparison over the long term (Chapitre 3). In: Gandini, C, Favory, F, Nuninger, L (eds.) *Settlement Patterns, Production and Trades from the Neolithic to the Middle Ages. ARCHAEDYN, Seven Millennia of Territorial Dynamics, Final Conference, Dijon, 23-25 june 2008. British Archaeological Reports Int. Series*, 237. pp. 51-64.

Bratman, M 1987 *Intentions, Plans, and Practical Reason.* Cambridge: Harvard University Press.

Buffat, L 2010 Fermes et villas en Gaule Narbonnaise. In: Ouzoulias, P and Tranoy, L (eds.) *Comment les Gaules devinrent romaines.* Paris: La Découverte. pp. 177-188.

Burnand, Y 1975 Domitii Aquenses. *Une famille de chevaliers romains de la région d'Aix-en-Provence. Mausolée et domaine. Revue archéologique de Narbonnaise*, suppl. 5. Paris: De Boccard.

Compatangelo, R 1995 Prospection archéologique et domaine: modèles historiques et réalités de terrain. In: *Du Latifundium au Latifondo. Un héritage de Rome, une création médiévale ou moderne?* Actes de la Table ronde internationale du CNRS organisée à l'Université Michel de Montaigne - Bordeaux III, les 17 - 19 décembre 1992. Paris: Publication du centre Pierre Paris. pp. 45-65.

Congès, G and Lecacheur, P 1994 Exploitation et domaine sur la côte varoise à l'époque romaine : exemple de la plaine de Pardigon (Cavalaire, Croix-Valmer, Var). In: Favory, F and Fiches, J-L (eds.) *Les campagnes de la France méditerranéenne dans l'Antiquité et le haut Moyen Age.* Etudes microrégionales. Paris: Éditions de la Maison des Sciences de l'Homme. pp. 279-288.

Contreras, D, Guiot, J, Suarez, R, Kirman, A 2018 Reaching the human scale: a spatial and temporal downscaling approach to the archaeological implications of paleoclimate data. *Journal of Archaeological Science*, 93: 54-67. https://doi.org/10.1016/j.jas.2018.02.013

Contreras, D, Bondeau, A, Guiot, J, Kirman, A, Hiriart, E, Bernard, L, Suarez, R, Fader, M 2019 From palaeoclimate variables to prehistoric agriculture: Using a process-based agroecosystem model to simulate the impacts of Holocene climate change on potential agricultural productivity in Provence, France. *Quaternary International*, 501: 303-316. https://doi.org/10.1016/j.quaint.2018.02.019

Da Costa Pereira, C, Tettamanzi, A 2010 An Integrated Possibilistic Framework for Goal Generation in Cognitive Agents. In: van der Hoek, W, Kaminka, G, Lésperance, Y, Luck, M, Sen, S (eds). *Proc. of the 9th International conference on autonomous agents and multiagent systems* (AAMAS 2010). Toronto, pp. 1239–1246.

Dubois, D, Prade, H 1988 *Possibility Theory*. New York: Plenum Press.

Durand-Dastès, F, Favory, F, Fiches, J-L, Mathian, H, Pumain, D, Raynaud, C, Sanders, L, Van der Leeuw, S 1998 *Des oppida aux métropoles. Archéologues et géographes en vallée du Rhône*. Paris: Economica.

Favory, F (dir.) 2012 *Le Tricastin romain : évolution d'un paysage centurié (Drôme, Vaucluse)*. Lyon: DARA.

Grimm, V, Berger, U, Bastiansen, F, Eliassen, S, Ginot, V, Giske, J, Goss-Custard, J, Grand, T, Heinz, S, Huse, G, Huth, A, Jepsen, JU, Jørgensen, C, Mooij, WM, Müller, B, Pe'er, G, Piou, C, Railsback, SF, Robbins, AM, Robbins, MM, Rossmanith, E, Rüger, N, Strand, E, Souissi, S, Stillman, RA, Vabø, R, Visser, U, DeAngelis, DL 2006 A standard protocol for describing individual-based and agent-based models. *Ecological Modelling*, 198: 115–126. https://doi.org/10.1016/j.ecolmodel.2006.04.023

Grimm, V, Berger, U, DeAngelis, DL, Polhill, JG, Giske, J, Railsback, SF 2010 The ODD protocol: A review and first update. *Ecological Modelling*, 221: 2760–2768. https://doi.org/10.1016/j.ecolmodel.2010.08.019

Mauné, S, Durand, B, Carrato, Ch, Bourgaut, R 2010 La villa de Quintus Iulius Pri(…) à Aspiran (Hérault). Un centre domanial de Gaule Narbonnaise (Ier – Ve s. apr. J.-C.). *Pallas*, 84: 111-143. DOI: 10.4000/pallas.3383.

Ouriachi, M-J, Bertoncello, F 2015 An 'alphabet' to describe the spatio-temporal dynamics of settlement systems: a relevant representation of time? In. Giligny, F, Djindjian, F, Costa, L, Moscati, P, Robert, R (eds.) *CAA 2014 - 21st century Archaeology: Concepts, Methods and Tools. Proceedings of the 42nd Annual Conference on Computer Applications and Quantitative Methods in Archaeology.* Oxford, Archaeopress, pp. 393-398.

Ouzoulias, P 2006 *L'économie agraire de la Gaule: aperçus historiographiques et perspectives archéologiques.* Unpublished thesis (PhD), University of Franche-Comté, Besançon.

Tannier, C, Franc, A, Ouriachi, M-J, Zadora-Rio E 2017 Entre modèles et récits, les transitions dans les systèmes de peuplement. In: Sanders L (ed.). *Peupler la terre. De la préhistoire à l'ère des métropoles.* Tours, Presses Universitaires François Rabelais, 2017, p. 387-407.

Van der Leeuw, S, Favory, F, Fiches, J-L 2003 *Archéologie et systèmes socio-environnementaux : études multiscalaires sur la vallée du Rhône dans le programme Archaeomedes.* Paris: CNRS éd. (CRA monographies, 27).

Wilensky, U 1999 *NetLogo. http://ccl.northwestern.edu/netlogo/*. Center for Connected Learning and Computer-Based Modeling, Northwestern University, Evanston, IL.