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### ► To cite this version:

Nicolas Bernigaud, Alberte Bondeau, Joel Guiot, Laurent Bouby, Frédérique Bertoncello, et al.. Reconstructing vineyard's geography, yields and profitability of wine production in Roman empire: new insights of spatial-analysis, Agent-based modelling, and climate-vegetation models. Emlyn Dodd; Dimitri Van Limbergen. *Methods in Ancient Wine Archaeology, Scientific approaches in Roman contexts*, Bloomsbury, pp.215-226, In press. halshs-03924342

**HAL Id: halshs-03924342**

**<https://shs.hal.science/halshs-03924342v1>**

Submitted on 10 Feb 2025

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# Reconstructing vineyard's geography, yields and profitability of wine production in Roman empire: new insights of spatial-analysis, Agent-based modelling, and climate-vegetation models

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## Introduction

Historical and archaeological research carried out in the various countries of the Mediterranean and Western Europe gradually allows us to expand our knowledge of the genesis, development, and geography of viticulture in the Roman Empire. While it is worth highlighting the progress made in recent decades, our knowledge in this area is still lacking and geographically disparate. Viticulture is often difficult to identify based on sometimes tenuous archaeological evidence, and the intensity of research varies greatly from one country to another.

The modelling methods developed in the fields of spatial archaeology and geosciences offer the possibility of freeing ourselves from these various archaeological biases that blur or make very lacking our vision of ancient viticulture. These methods now make it possible to reconstruct the geographical extension and spatio-temporal dynamics of wine regions, but also to analyse the historical, socio-economic, and environmental causes of their evolutions, punctuated by phases of boom and fall.

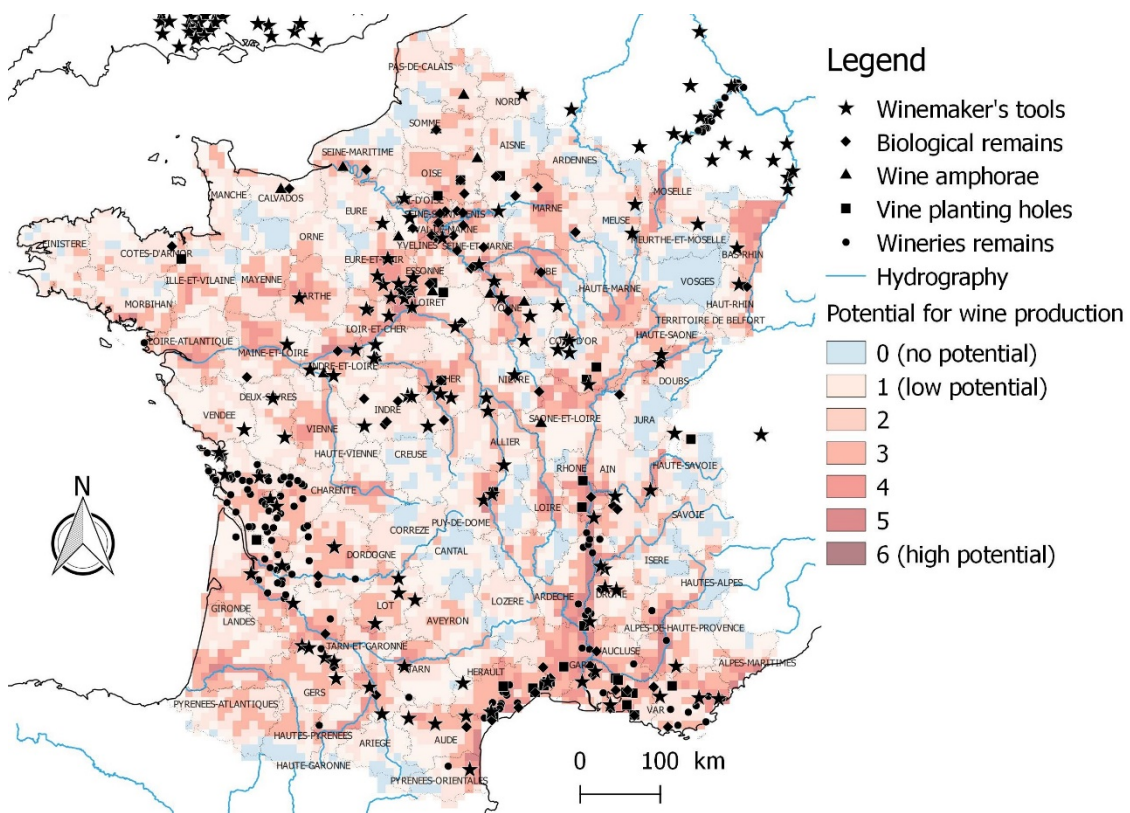
In this chapter, we will present different types of modelling that we have developed to reconstruct the geography of areas potentially favourable to ancient viticulture, as well as to assess the impact of climate change on yield variations, profitability, and geography of wine production. This work is based on spatial analysis methods, as well as other particularly innovative types of modelling such as agro-ecosystem and climate-vegetation models developed by geosciences, but also agent-based modelling (ABM). Most of the works presented here have Roman Gaul as their geographical framework, but these methods can be used for other study areas and at other geographical scales such as the Roman Empire.

## 1. Reconstructing spatial extension of viticulture: spatial analysis and suitability map processing

For more than thirty years, tools and methods of spatial analysis derived from geography have been applied in archaeology to develop models to predict the location of human occupations of different periods in different landscape units (e. g. Verhagen and Withley 2020). Mainly used from a heritage management perspective, these methods have great potential to work on more specific scientific issues such as the reconstruction of the geography of wine production areas in the different provinces of the Roman Empire, such as Hispania Tarraconensis where first work has been carried out (Stubert et al. 2020).

We have designed and developed for Gaul a suitability map for vineyards with the R software (and the raster package). This cumulative model (Bernigaud, Bondeau and Guiot 2021) is based on the addition of six geographical, environmental, and climatic criteria considered favourable to the establishment of a commercial vineyard in the Gallo-Roman period: temperatures over 18 °C in July (1), land oriented to the south and east (2)<sup>i</sup>, proximity (< 5 km) to the coastline (3), to a major road (4) and river (5) to facilitate the export of production. Finally, the proximity (< 30 km) to an urban capital of a city (6), constituting a major place of consumption and redistribution<sup>ii</sup>.

The suitability map obtained for the High Empire makes it possible to distinguish areas where the variable value of potential (from 0 to 6) is proportional to the number of criteria stacked in each cell. While the high-altitude zones (Alps, Pyrenees, Massif Central) show expected zero potential (= 0 criteria), as some northern plains (Orne, Seine-Maritime, Somme), the most favourable areas to viticulture (> 3 criteria) appear in the southern Mediterranean, the Rhone-Saone axis, the Rhine Valley, the south-west as well as further north the Paris Basin and the Pays de Loire (Fig. 1).



**Figure 1.** Suitability map for the establishment of vineyards in roman Gaul (from 0 to 6) in the High Empire. Locations of (bio)archaeological data attesting to viticulture are overlapped (after Bernigaud et al. 2021).

The robustness of this model was evaluated by geographical comparison with data attesting to viticulture<sup>iii</sup>, using the statistical test of relative gain, the simplest and most frequently employed in predictive modelling (Verhagen 2008). The values obtained with this index (from -2.04 to 0.73) for each of the seven levels of potentiality (from 0 to 6) indicate a very good geographical correlation between the results of the model and the archaeological data (Bernigaud, Bondeau and Guiot 2021).

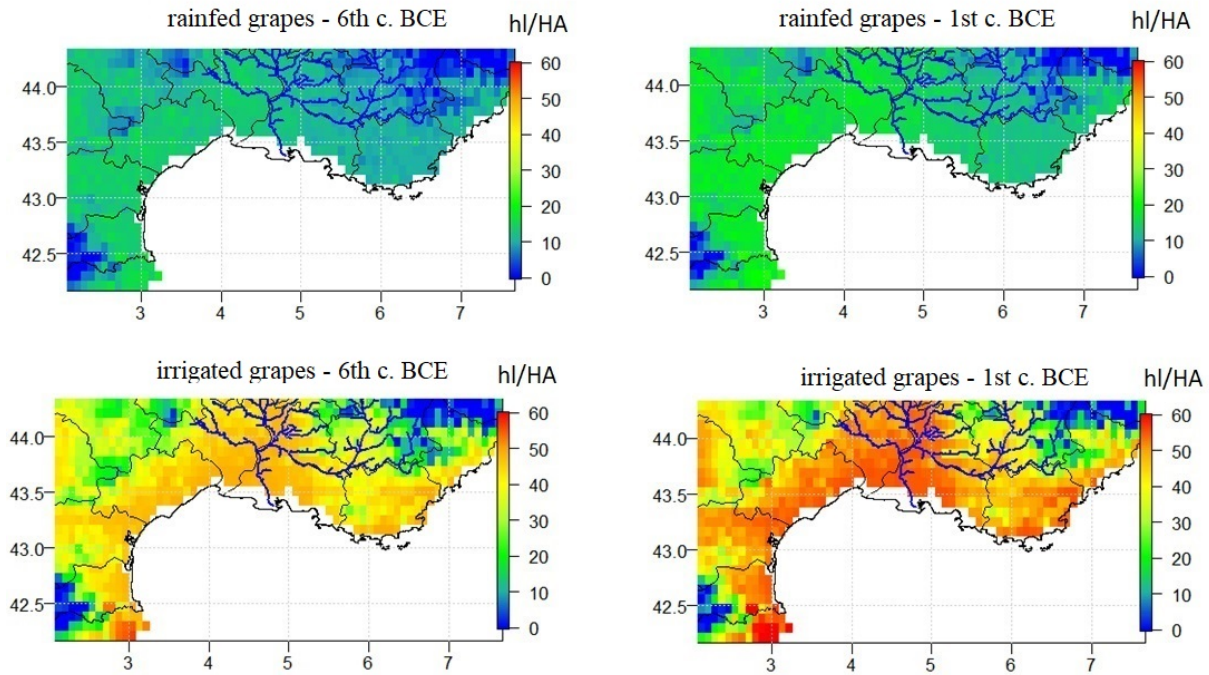
The main interest of this robust model is to highlight as favourable, areas where archaeological data attesting to viticulture are apparently scarce or absent. This is particularly the case in several departments of the south-west (Pyrénées-Atlantiques, Landes) and the north-western quarter (Loire-Atlantique, Sarthe, Mayenne, Ille-et-Vilaine) of France (Fig. 1). It is questionable whether viticulture was not practised in these regions or whether it could rather be a research bias. It should be recalled that in France, as elsewhere, our current state of knowledge is based on publications of regional syntheses that are still far from exhaustive. Therefore, the apparent data vacuum in some regions could simply be explained by a lack of publication or research on the subject. The archaeological visibility of viticulture is also geographically more or less good because of the diversity of winemaking techniques used, for climatic and environmental reasons. If the vinification was for example carried out in southern Gaul in *dolia* cellars - whose remains are easily identifiable - it was done in temperate Gaul in wooden barrels, which have only very rarely been preserved. In general, viticulture therefore remains more difficult to identify by archaeology in the northern regions than in the south.

For those regions where data are scarce or absent while the model nevertheless has good potential, these results can be considered to have predictive and heuristic value. These will be able to stimulate archaeological research in the field, but also in reports of unpublished excavations (preserved in the Regional Archaeology Services) in search of clues on viticulture.

## **2. Reconstructing areas favorable to viticulture and potential yields from climate-vegetation models: LPJmL and the Viticulture Index**

### **2.1. Lund-Potsdam-Jena-managed-Land (LPJmL) agro-ecosystem modelling: reconstructing potential wine yields as a function of climate**

Lund-Potsdam-Jena-managed-Land (LPJmL) agro-ecosystem modelling was initially designed by German and Swedish environmental scientists to model current carbon and water cycles on a global scale, as well as yields of the main crops based on daily climate data (temperatures, precipitation, cloudiness) and environmental data (porosity and soil water reserve) (Bondeau et al. 2007, Fader et al. 2015). Very recently, LPJmL has been adapted to study past situations, using paleoclimatic data to calculate potential yields for cereals during Protohistory in southern France (Contreras et al. 2018, Contreras et al. 2019).



**Figure 2.** Maps of potential yields of vine calculated by LPJmL (for irrigated and rainfed cultivation) in southern Gaul according paleoclimatic data (after Bernigaud et al. 2021).

On the methodological basis of this pioneering work, we conducted first trials with LPJmL to measure the impact of Roman Climate Optimum (RCO) (McCormick et al. 2012) on wine yields (Bernigaud, Bondeau and Guiot 2021). Potential yields were calculated (for a rainfed crop and an irrigated crop) from values of temperature, precipitation, and cloudiness. These paleoclimatic data were reconstructed from a modelling of the current climate of France (ALADIN-climate), modified with anomaly values extracted from a paleoclimatic reconstruction carried out on a European scale (Guiot and Kaniewski 2015).

Calculations made for the coldest century (6th century BCE) and the hottest century (1st century BCE) of the last three millennia indicate large differences in value. For the sixth century BCE, the potential yields of the vine are between 0 and 20hl/ha while they reach up to 30 hl/ha in the first century BCE in rainfed cultivation, i.e., one third more (Fig. 1). In irrigated cultivation, they increase from 30-45 hl/ha in the coastal plains to 45-60 hl/ha, which represents a growth of one third to one-half, depending on the sector. In both cases, the potential yields decrease with altitude to reach zero values in the Massif Central, the Alps and the Pyrenees. They still appear the highest in the Languedoc and Roussillon plains, in the middle and lower Rhone valley as well as on the Var coast (Fig. 2). These areas of higher potential, only based on biophysical criteria, coincide well with the results of our predictive model built with other criteria (Fig. 1). However, some differences should be noted: the high potential that emerges from the predictive model in the Alpes-Maritimes appears for example much more moderate with LPJmL (Fig. 2).

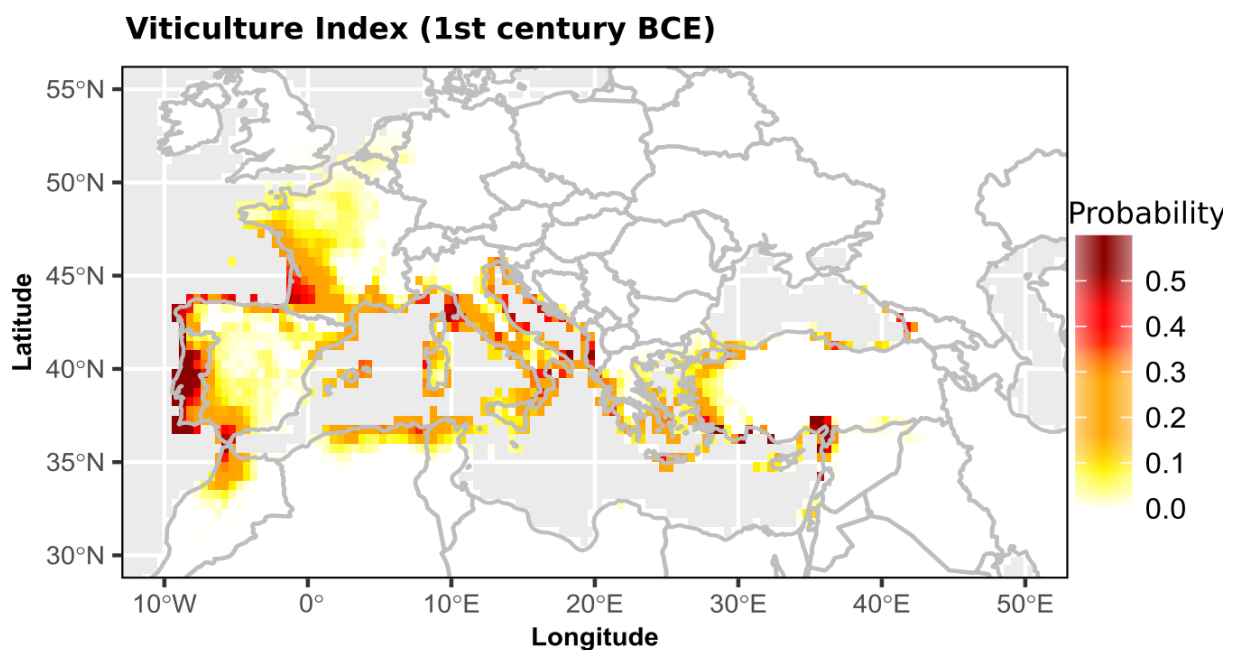
In general, according to the first results obtained with LPJmL the potential yields of the vine could have increased very sharply, from a third to double, between the coldest century (6th century BCE) and the hottest century (1st century BCE) of the last three millennium. For Gallia Narbonensis, where viticulture reached its peak during the High Empire, archaeological investigations show that this development occurred from the first century BCE (Carrato 2017). If this development appears to follow the Roman conquest of southern Gaul (in the 120s BC), the results of our models now let

envisage that the climatic factor could have played, in concert with this historical event, a decisive role for the growth of this commercial viticulture.

## 2.2. The Viticulture Index (VI)

Very recently developed, the Viticulture Index (VI) is another innovative method for defining areas favourable to the development of the vine according to the bioclimate. This index (whose values vary between 0 and 1) is calculated from threshold annual values of precipitation, temperature, evapotranspiration, and values of net primary production (Guiot et al., submitted). The climate data used are produced from an ensemble of Earth System Models (ESMs) (Kay et al. 2014) coupled to a global vegetation model (Biome 4) (Kaplan et al. 2002) constrained by paleoclimatic reconstruction carried out from pollen data already mentioned (Guiot and Kaniewski 2015).

Viticulture Index was calculated for different periods of the Holocene at the scale of the Mediterranean and Western Europe to assess the impact of climate change on the biogeography of the vine. The results obtained with the climatic characteristics of a century of the Roman period (1st century BCE) show for example the highest probabilities in the Mediterranean islands (Balearic Islands, Corsica, Sardinia, Sicily, Elba, Crete, Cyprus, Rhodes,...), on the continental coasts of the Tyrrhenian, Adriatic, Ionian, Aegean seas, as well as on the Levantine, Tunisian, Algerian and Moroccan shores. The values also appear high on the Atlantic coast (Portuguese, Spanish and French coasts). On the other hand, they are low or zero on the African coasts of the eastern Mediterranean (Libyan and Egyptian coasts) and continental areas, with the notable exception of the Iberian Peninsula and a large part of the French/Gaul territory which show both potential in the large river valleys (Tagus, Ebro, Douro, Rhone, Loire) (Fig. 3).



**Figure 3.** Map of climatic potential for viticulture (according to the Viticulture Index/VI) in the Mediterranean and Western Europe for the first century BCE (after Guiot et al., forthcoming)

To measure more precisely the predictive potential of this index on the geography of vineyards, it would be useful to compare it with an exhaustive mapping of archaeological and historical data at the scale of the Roman Empire. While this long work of data collection remains to be undertaken, it can already be roughly seen that viticulture is attested by archaeological evidence and texts in many areas where the model indicates that climatic conditions allowed the development of the vine. This is



the case for the well-known wine regions of Hispania Tarraconensis and Betica (e. g. Martín i Oliveras et al. 2017, Brun 1997), those of Gaul (Narbonensis, Aquitania, Belgica) (Fig. 1), Tyrrhenian, Adriatic-Ionian, Aegean, and Levantine coast (e. g. Komar 2016, Dodd 2020). The viticulture of most Mediterranean islands is also relatively well attested by historical and archaeological data (e.g. Galymore *infra*, Hadjisawas *infra*, Komar 2016).

To our knowledge, however, no, or few data are known for regions where this index nevertheless displays high values. This is for example the case on the northwest coast of Spain, in the Ebro Valley, in the north of Morocco, Algeria and Tunisia. In addition, if viticulture is identified in Lusitania/Portugal (Brun 1997), the importance of the production perceived by archaeology - all in all moderate - is not related to the very high climate probabilities of the Index (Fig. 4). Conversely, it should also be noted that the probabilities appear rather modest in the Eastern Mediterranean where important wine regions were located, particularly in Egypt and Israel (Dzierzbicka 2018 and *infra*, Ayalon et al. 2009, Fuks et al. 2020).

For regions with good probabilities but where data are scarce or absent, efforts may be made to verify on a case-by-case basis whether this deficit could not be linked to research bias. To take up the case of northern Morocco, Mauretania Tingitana remains undoubtedly often perceived as a province producing olive oil rather than wine. But recent excavations conducted on the tell of Rirha in the region of Sidi Slimane (near the ancient city of Volubilis) have uncovered a press whose wine function is perfectly ensured thanks to the identification of many remains of charred grape seeds, as well as biochemical analyses (Carrato et al. 2020). This discovery therefore gives first insights into a wine production – unnoticed for a long time - in this Roman province where our Viticulture Index (VI) indicates precisely a good climatic potential. Conversely, the identification of a few areas where the index gives zero values but where viticulture is nevertheless clearly attested (Egypt, Israel) should make it possible to resume and improve the calibration of this index. These discrepancies may also be caused by local conditions favourable to vine but falling within the large pixels of the analysis (about 50 km size) and/or technical adaptation to climatic constraints (i. e. irrigation in Egypt).

### **3. Calculating the potential benefits of winemaking: using the Agent-Based model ROMCLIM**

Developed in the United States since the 1990s in the field of archaeology to analyse the causes of the rise and fall of Native American societies, agent-based modelling (ABM) has been developing in Europe for about ten years. ABM make it possible to carry out dynamic simulations through the programming of agents that interact with each other and with their environment, thus producing phenomena that we try to reproduce, or unexpected phenomena called "emerging" (e.g. Lake 2020, Romanowska, Wren and Crabtree 2021).

We developed the ROMCLIM agent-based model to simulate at the scale of southern Gaul the impact of global warming in the Roman period (RCO) (McCormick et al. 2012) and then the cooling of Late Antiquity (LALIA) (Büntgen et al. 2016) on agricultural production and its potential income (Bernigaud et al., forthcoming)<sup>iv</sup>. This model, in which the agents are virtual farms, has the particularity of reproducing in a simplified way the more complex functioning of the agro-ecosystem modelling LPJmL (§ 2.1.).

The wineries we have programmed operate with a staff of 16 people and operate an area of 100 jugera (25 ha), which takes up the main characteristics given by the agronomist Varron (*De Agri cultura*, XI) in the first century BCE in Italy. For each century of the chronological period considered (6th century BCE – 7th century CE) the annual production (averaged by century) is calculated by multiplying the area exploited by the value of the potential wine yields, returned by an emulation function of LPJmL. The market value of the annual wine production is then calculated by multiplying

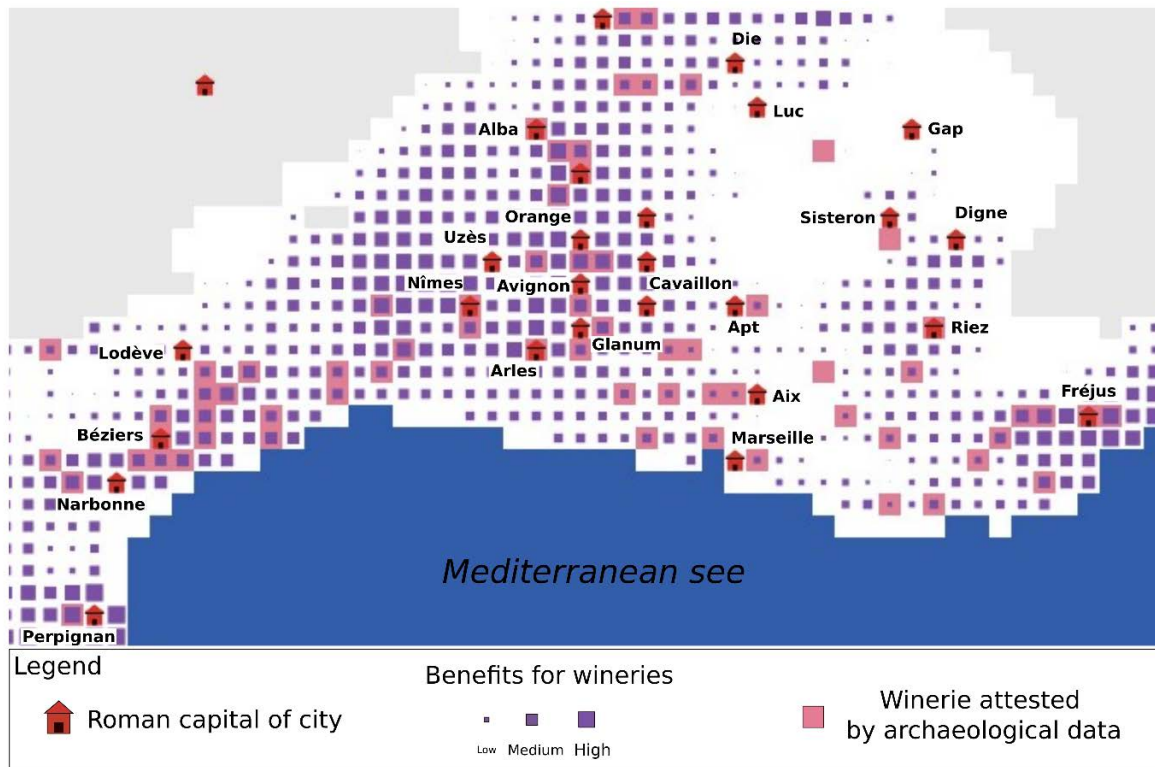
its quantity by a market selling price. This price is chosen by the user in an interval [0.57-240 sesterces/litre] that we have established from figures provided by historical sources<sup>v</sup>. The profits generated (in sesterces) by each of these wineries are finally obtained by subtracting from this market value operating and transport costs to the nearest city capitals<sup>vi</sup>.

According to multiple simulations carried out, the yields and potential incomes of the vine appear particularly sensitive to climate change. Overall, the results indicate a sharp increase in yields and potential benefits as early as the third century BCE (beginning of the RCO) before a decrease during Late Antiquity (4th-7th c. CE) due to LALIA. The graphical interface of the model shows the areas where the profitability of the wineries is higher or lower depending on the climate, but also their distance to the capitals of cities (proportional to transport costs).

In general, simulations carried out with the climatic characteristics of the High Empire (Fig. 4) show that the Roman colonies located in the Rhone valley (Orange, Avignon, Glanum) as well as Gard area (Nîmes, Uzès) and pre-Alpine foothills (Vaison, Carpentras, Cavaillon) form the heart of the most profitable area, which extends to the west into the Languedoc (Béziers, Narbonne) and Roussillon (Perpignan) plains. This strongest potential is also emerging in the south-east of Narbonensis (Fréjus), as far as the Alps (Digne, Riez). On the other hand, it appears unsurprisingly close to zero at high altitude (Pyrenees, Hautes-Alpes), but also in a region east of Aix-en-Provence and Marseille (Fig. 4).

It should be noted that much viticulture evidence from archaeological surveys conducted in recent decades (Buffat et al. 2001, Brun 2001, Jung et al. 2013) have been found in these areas of highest potential (middle and lower Rhone valley, plains of Languedoc and Roussillon, Var). On the other hand, it is interesting to note that little or no data are known in some of the regions favourable according to the model. This is particularly the case of the Cevennes hinterland (west of Nîmes and Uzès), the city of Antibes (east of Fréjus), the alpine area between Riez and Digne, or the Perpignan area (southwest). For these sectors, the results have a heuristic value that raises new questions and encourages new research. This will allow an effort to verify whether the scarcity or absence of archaeological data is not related to a lack of research or publications. The good potential displayed, however, could also be an artifact of the model, unless it has not been exploited for historical reasons that remain to be clarified.





**Figure 4.** Map of potential profit obtained for southern Gaul with climatic data of the first century CE (1900 BP). Each winery is represented by a purple square whose size is proportional to the profits made. The cells where viticulture is attested by archaeological data are pink.

#### 4. Conclusion and research perspectives

The different types of modelling presented in this chapter (predictive models, agro-ecosystem modelling, SMA, Viticulture Index) offer a potential for analysis that opens new perspectives for the research on ancient viticulture, by their ability to integrate climate, to which the vine is particularly sensitive. These first exploratory models could be hybridized and adapted to the scale of the Roman Empire to reconstruct the geography of wine regions, but also to analyse the causes of their development and decline. After a period of boom during the High Empire, it is well known that the vineyards of the Italic Peninsula, Iberia and Gaul were indeed affected at the turn of the third century CE by a relative waning, marked in counterpoint by the development of viticulture in North Africa and then in the Eastern Mediterranean (Cilicia, Cyprus, Gaza, Egypt, etc.) where it enjoyed great prosperity during Late Antiquity (6th-7th century CE).

The first results of the models we have developed support the hypothesis of a potential positive effect of global warming of the Roman period on the yields and profitability of commercial viticulture, which could on the other hand have been significantly affected in Gaul by the subsequent cooling of Late Antiquity. However, the rise of the eastern Mediterranean wine regions at the end of antiquity suggests on the contrary favourable climatic conditions. To try to resolve this apparent paradox, several avenues can be considered. In the warmer regions of the Mediterranean, climate cooling may have favoured the development of viticulture, to the point of making it possible in the Negev desert (Fuks et al. 2020). But it must also be considered that the climates of the western and eastern Mediterranean are contrasted (Guiot and Kaniewski 2015). The effect of climate change was therefore not necessary the same.

On the methodological basis of the exploratory examples presented in this chapter, other models could be developed to identify more broadly the different wine regions of the Roman Empire, the chronology of their spatio-temporal evolution as well as the factors at the origin of the changes. The design of a predictive model will benefit from the achievements of the one we have developed for Gaul (§ 1), but also from those also recently proposed for the Laetanian vineyards of north-east Spain (Stubert et al. 2020) and for the Adriatic region (McLean, this volume). By combining these different methods and considering an increased number of historical-geographical, environmental and paleoclimatic criteria, potential maps produced for different periods (High Empire, Lower Empire/Late Antiquity) would certainly make it possible to identify regions where viticulture is still very underestimated, or maybe even unknown. Dynamic simulations carried out with a hybridized ABM (integrating the results of predictive and agro-ecosystem models) would finally offer the possibility of analysing not only the potential role of climate change in the reorganization of the Empire's wine regions, but also that of other historical, socio-economic, demographic, and environmental factors.

### **Acknowledgement**

The research presented in this article was conducted as part of the multidisciplinary project 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) and Labex OT-Med both funded by the A\*midex Foundation of the University of Aix-Marseille (France). The authors would like to thank the other participants of this project with whom regular exchanges have made it possible to advance multidisciplinary discussions and reflections on the issue of the adaptation of ancient societies to climate change over the past three millennia: Loup Bernard (University of Strasbourg), Delphine Isoardi (CCCI-CNRS, Aix-en-Provence), Philippe Leveau (Centre Camille Jullian, Aix-en-Provence), Alan Kirman (EHESS, Paris), Sylvain Olivier (University of Nîmes), Cees Passchier (University of Mainz, Germany), Gül Sürmelihindi (University of Mainz, Germany) and Daniel Contreras (University of Florida, USA).

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<sup>i</sup> According to Columelle (*De Re Rustica* 3, 12)

<sup>ii</sup> Link to the model and input files: <https://data.mendeley.com/datasets/j4gtjy9w87/2>

<sup>iii</sup>The data used for mapping various types of (bio)archaeological data attesting to viticulture in Gaul (remains of wine-growing establishments, winegrowers' tools, planting pits, amphora workshops, grape seeds, etc.) have mainly been extracted from several regional syntheses collected in works devoted to viticulture in Gaul (e.g.: Brun and Laubenheimer 2001, Brun 2005, Brun et al. 2011), as well as various databases (including the [Outagr](#) database dedicated to agricultural tools).

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<sup>iv</sup> The NETLOGO code is available at:

<https://github.com/Bernigaud2021/ROMCLIM/blob/NETLOGO/ROMCLIM2021.nlogo>

<sup>v</sup> In 1<sup>st</sup> c. AD, Columelle (*De Re Rustica* 3.3.2) estimated that 40 urns (or 1 culléus) of wine sold for at least 300 sesterces (0.57 sesterces/litre). We have therefore chosen this value as the minimum price. The maximum is the price of the old Falerne, established at the beginning of the IV<sup>th</sup> c. AD by the edict of Diocletian at 34 denarii per sextarius (240 sesterces/litre).

<sup>vi</sup> The annual cost for the maintenance of staff is based on 140 sesterces/individual/year or 2240 sesterces/year for the 16 persons on the holding. Transport costs are defined by the user within a range whose maximum given by Diocletian's Edict is 20 denarii/mile/1200 kg (0.002 sesterces/km/kg).