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ABSTRACT

Starting as early as the 6th century BCE in southern Gaul, viticulture extended after the Roman conquest as far as the south of England. This paper presents different types of multi-proxy spatial modeling incorporating climatic, environmental and geohistorical factors to analyze the causes of the expansion of vineyards outside the Mediterranean region in the 1st century CE. The effects of the Roman Climate Optimum on potential wine production were simulated through agrosystem modeling (Lund-Potsdam-Jena-managed-Land). We also produce a predictive model of areas potentially favorable to viticulture in the 1st c. CE, based on a series of geographical, archaeological and paleoclimatic criteria. The results highlight a strong impact of climate change on potential wine production as early as 1st c. BCE and favorable conditions for the development of viticulture as far as northern Gaul throughout the Roman period, especially on soils with southern exposures, along communication routes (main roads and rivers) and close to Roman urban centers. Necessary data to build the model are available at https://data.mendeley.com/datasets/j4gtjy9w87/3.

1. Introduction

Introduced by Greek colonists c. 600 BCE, around the time they settled Marseille, viticulture was limited to southern Gaul during the Iron Age (Boissinot, 2001; Collin Bouffier, 2009). At the beginning of our era, vineyards were cultivated in Gallia Narbonensis; however, according to the description given to us by the Greek geographer Strabo, wine-grape vines grew with little success north of this province.[1]

In recent decades, archeological progress has made it possible to improve our knowledge of the history of viticulture in France due to a rapidly growing number of discoveries. Winemaking installations, such as wine storehouses, presses, and basins, tools used by wine growers, ancient vine planting holes, vegetal remains (grape pips, vine pollen), as well as wine amphora workshops and epigraphic documents have enabled us to progressively identify the area covered and the chronological development of vineyards (Brun, 2011). While it was long believed, in accordance with Roger Dion's work, that the rapid expansion of winemaking took place rather late in Roman Gaul (Dion, 1959), current data show that vineyards expanded into the northern part of the Three Gauls in the 1st c. CE, where it developed quite considerably in the following centuries in Île-de-France, the Rhine and Moselle valleys (Brun, 2010), and even in southern England (Brown et al., 2001).

Since the 1980s, progress in climate history research has revealed that a period of climate warming took place between the 2nd c. BCE and the early 3rd c. CE. Researchers have since investigated the potential effects of this Roman Climatic Optimum (RCO) or Roman Warm Period (McCormick et al., 2012) on agricultural production in general and viticulture.

What was the potential impact of the RCO on agricultural yields? This question is particularly important to understand the causes of a successful economy in the High Roman Empire (Harper, 2017). We focus here on wine production, which was one of the most rentable agricultural production (Ferdière, 2020) and was extremely sensitive to climate change (Wolkovich et al., 2017). Recent advances in modeling makes

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[1] "In all of Gallia Narbonensis, the agricultural products are exactly the same as in Italy, while as one advances north toward the Cévennes, one no longer sees olive or fig trees; the other crops, it is true, continue to thrive, but, if one advances a bit more in the same direction, one sees that grape vines, in turn, only grow with great difficulty."(Geography, 2: IV, 1,2).

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possible to develop simulations to test out different hypotheses (e.g. Morales-Castilla et al., 2020).

In this article, we quantify the impact of climate warming on wine yields in southern France using an agro-ecosystem model, which is presently the best causal approach to link climate and agricultural yields. To better understand the extension of viticulture in northern Gaul, we also present an archaeological predictive model which indicate potential location of vineyards in regions for which archeological data are scarce or lacking.

2. Lund-Potsdam-Jena-managed-Land (LPJmL) modeling: Methods and results

LPJmL is an agro-ecosystem model that simulates the biogeochemical fluxes of the entire ecosystem represented by nine natural plant functional types and up to 26 crop functional types, among other grapes (Bondeau et al., 2007, Fader et al., 2015, Schaphoff et al., 2018). Important biogeochemical fluxes between the atmosphere, the vegetation and the soil are the carbon and water fluxes, driven by the pedo-climatic conditions, which are responsible for the growth of the various plant organs, including the harvested one (fruit in the case of grapes). Controlled by the temperature driven phenological development, photosynthesis and transpiration are coupled, which leads the model to respond in a balanced way to warming, drought, and CO_2 fertilization (Elliott et al., 2014). The broader benchmarking evaluation in the context of Global Gridded Crop Model Intercomparison (GGCMI) provides evidence for LPJmL's capability of representing most relevant mechanisms of climate induced signals in observed yields (Jägermeyr et al., 2017).

The model runs at a daily time step, fed by environmental data (soil, climate, and atmospheric CO_2 concentration) and management data for agriculture (e.g. irrigation). The required climate data are daily mean air temperature, precipitation, and cloudiness (or radiation when available). Soil classification is an important input because the texture balance between sand, silt, and clay, strongly impacts the of soil water fluxes, and therefore the water available to plants. Several crop models exist for wine with specific parameterizations for different varieties (see e.g. García de Cortázar-Atauri et al., 2009). This is not the case for LPJmL, which considers a standard variety based on a buddle of parameters provided by the literature (Fader et al., 2015), but calibrates one relevant management parameter (tree density) at the regional/national level in order to fit the regional/national averaged yield. In France and Italy, this leads to a tree density of 9000–10000 trees/ha, which is considered to be a relatively high density. Provided the input data are available, LPJmL can be very easily run on any spatial domain. It has been applied for very different questions. For example, regarding wine production, Fader et al. (2016) have used the model for simulated the future water requirement of Mediterranean agriculture under different climate change and demographic scenarios. On the other hand, LPJmL was already adapted for simulating cereals and pulses production in southern France during ancient periods based on paleoclimatic data (Contreras et al., 2018a, 2019).

For our study, we used a paleoclimate reconstruction produced for the Holocene for Europe and the Mediterranean region. Using a 100-year time step, it integrates the monthly averages of numerous climatic variables such as precipitation, temperature, and cloud cover on a geographic grid with points spaced 5° longitude and latitude (Guiot and Kaniewski, 2015). The data points in this set were extracted and interpolated spatially to obtain a gridded coverage at 8 km resolution for the south of France using a downscaling method programmed with R software (Contreras et al., 2018b). By this method explained in detail in the previous reference (now quite common for the treatment of climatic data), we can convert low-resolution data in high-resolution data to fit the granularity of the model. A set of raster-type maps of the different climatic variables required for the LPJmL model was produced in this way for Provence and Languedoc. As the model requires daily climate inputs, the monthly reconstructed data are interpolated daily, accounting for the monthly number of rain days which is an important driver of the soil moisture dynamics.

Soil classes are provided by the Harmonized World Soil Database v 1.2 from the FAO (FAO/IIASA/ISRIC/ISSCAS/JRC, 2012). It distinguishes 13 related texture soil classes at five arc-minutes spatial resolution (i.e. circa 8 km in southern France), for which different parameters on water fluxes and soil temperature dynamics are considered by LPJmL. Atmospheric CO2 concentration is set at the pre-industrial concentration, i.e. 280 ppm.

To measure the impact of climate warming on wine yields between the Iron Age and the beginning of the Roman period, we worked on data from two centuries, which had extreme average temperatures compared to the last three millennia. According to the chart of climatic values for the south of France (Fig. 1), a *minimum* was reached in the 6th c. BCE (2500 BP) with annual average temperatures 1.2 °C lower than the present ones. Meanwhile, the 1st c. BCE (2000 BP), which corresponds to the beginning of the Gallo-Roman period, was marked by a peak in the average annual temperatures (+0.4 °C), a 1.6 °C increase compared to the coldest century of the Iron Age.

Agro-ecosystem modeling enabled us to calculate the potential yields for non-irrigated and irrigated vineyards for these two centuries. We point out that the practice of watering wine-grape vines was not clearly recommended by ancient Roman agronomists. The recurrent discovery of ditches, canals, and former streams linked to areas where vines were planted at various sites around Nîmes (Pomarèdes et al., 2012) and Marseille (Saint-Jean-du-Désert) (Boissinot, 2001) lead us to believe, however, that vines could have been irrigated in southern Gaul as early as the Iron Age.

The modeling results obtained based on the paleoclimatic reconstructions (Fig. 2) indicate that for the 6th c. BCE (2500 BP) potential yields for irrigated vines were generally between 40 and 50 hectoliters per hectare in the Mediterranean plains, with lower figures (0–30 hl/ha) in the mountainous areas (Cévennes, Alps). For the 1st c. BCE (2000 BP), the yields are 20% to 50% higher, frequently up to 60 hl/ha in the plains, particularly in the lower Rhone valley and Languedoc-Roussillon. The same simulations made for non-irrigated vines give lower figures than for irrigated vines, with quantities generally between 10 and 20 hectoliters per hectare in the 6th c. BCE. In the 1st c. BCE, they increase to a range of 20 to 30 hl/ha, an increase of up to 50%. According to this modeling, the Roman Climatic Optimum may have thus enabled a significant increase in wine yield potential in the south of France as of the 1st c. BCE.

3. Archaeological predictive modeling of winegrowing regions in Gaul

While climate warming seems to have had a beneficial effect on yields, it also certainly favored the expansion of Roman viticulture all the way to southern England. Our knowledge of the winegrowing geography of Gaul is still partial, as archeological studies have not yet been made for many regions. To attempt to predict where these Gallo-Roman vineyards may have existed, we created a map of potential sites by combining six geographic, environmental and paleoclimatic criteria favorable to planting them:

1. Temperatures have always played a decisive role in the geography of vineyards. Currently, the northern limit of vineyards in France seems to correspond to the 18 °C isotherm in the month of July (Chabin, 2004). Yet, this is not an impassable climatic barrier, since vineyards were still cultivated all the way to Normandy in the early 20th century. However, these vineyards produced low quality wine, and subsequently disappeared due to competition. While average summer temperatures of less than 18 °C do not completely preclude winemaking, it has certainly been an unfavorable factor in its development since antiquity (Amouretti, 1988).

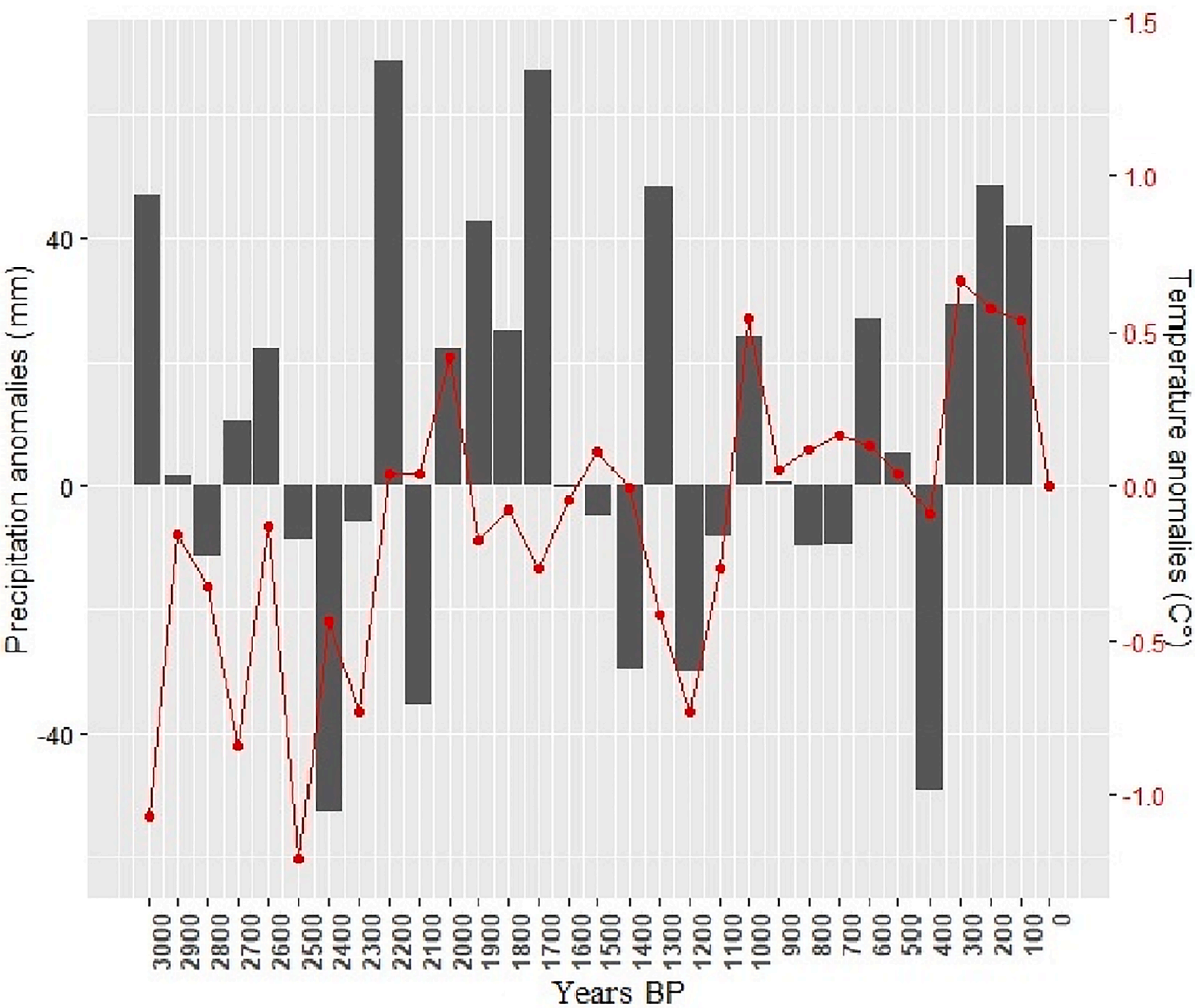

Fig. 1. Climate anomalies during the Holocene (according to 20th century mean values), i.e. differences between the century based past averages and the present (20th century). Red: temperature, black: precipitation (data after Guiot et Kaniewski 2015).

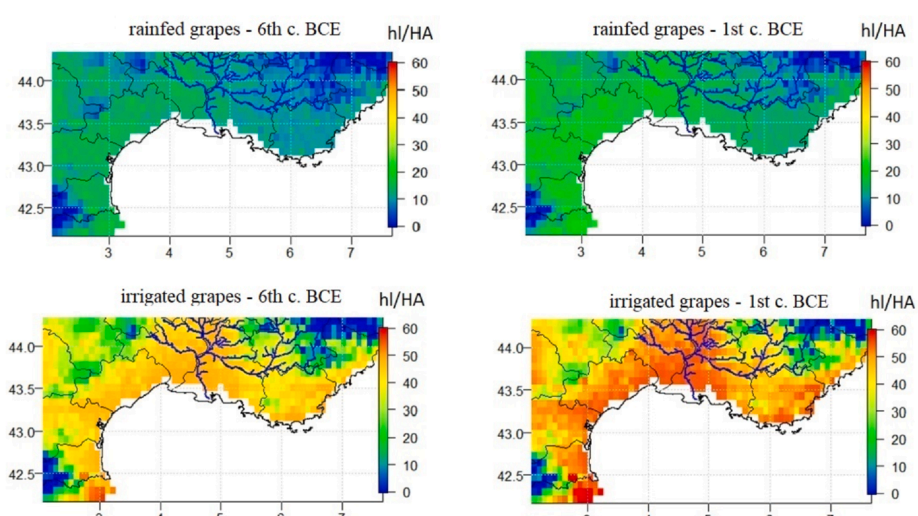

Fig. 2. LPJmL simulated potential yields of irrigated and rainfed grapes (in hl/HA) in 2500 BP (6th c. BCE) and 2000 BP (1st c. BCE) in the South of France. The comparison between the values of the two centuries shows a significant increase of potential yields between 25% and 50%.

2. A southern and eastern exposure of slopes has been identified as a favorable environmental factor. In the 1st c. CE, the Roman agronomist Columella recommended an eastern exposure of vineyards in temperate regions and a southern exposure in the coldest areas (*De Re Rust.*, III, 12).[2]
3. Placing vineyards cultivated for commercial purposes near a navigable river or stream has always been a decisive criterion. River transport has always made it possible to export the wine produced on boats toward more or less distant markets. We know that Gallo-Roman winemaking was intensive in various river valleys, such as the Rhone and the Moselle, as well as near navigable rivers like the Oise in which several ancient vine planting holes have been discovered (Toupet and Lemaître, 2003).
4. Establishing vineyards near the sea also made it possible to export the production by boat to more or less distant destinations. For example, some wines produced in Roman Gaul were sold all the way to Rome.
5. Proximity to major roads was also desirable. Part of the wine produced was transported over land by wagon. The flat-bottomed Gallic amphorae were specifically made for this kind of transport (Béal, 2006–2007).
6. Proximity to urban centers was also considered to be a favorable factor. These cities were the main places where wine was consumed. Planting vineyards as close as possible to them made it possible to reduce the transport costs and to increase the profit margins, especially for low- and medium-quality wines that could not be sold for too high a price. For example, traces of ancient vineyards have been discovered less than 2 km from the city of Bourges (*Avaricum)*, which was the capital of the Bituriges Cubi tribe during Gallo-Roman times (Dumasy et al., 2011).

To take account of these different criteria in our modeling, with an R software program we transformed and processed a set of vector layers of the Roman road network,[3] navigable rivers,[4] coast line,[5] and tribal capitals.[6] After having resized these files at the scale of Gaul, 10-km wide buffer zones[7] were created around the different entities, except for the tribal capitals for which we used a larger value of 30 km.[8] A map of the exposures was obtained by transforming a digital topography model (SRTM data[9]). The data concerning the July temperatures were processed based on the current ALADIN climate model[10] to which paleoclimatic anomalies were added (Guiot and Kaniewski, 2015) to obtain a map of July temperatures in the 1st c. CE.

The different rasterized layers were combined to obtain a map that represents the vineyard planting potential in Roman Gaul (Fig. 3). The value of each pixel is that of the number of criteria between 0 (zones with no potential) and 5 for the most favorable sectors (the six criteria were never realized at the same location). In general, the zones that were relatively close to a tribal capital and to the network of main roads, and rivers and sloping to the south or east, have the highest values. The map obtained shows the relative importance of large river valleys with well-exposed hillsides (the Rhine, Moselle, Loire, and Rhone), but also other areas like Aquitaine, Hérault, and the Southern Alps. Perhaps more astonishing, the potential appears to be quite good in northern and northwestern France (Rennes, Le Mans, Jublains, Chartres, Paris, Beauvais), regions that today do not appear to be very well-suited for viticulture.

Meanwhile, the zones with a low potential are rather far from the towns and the channels of communication and have a northern or western exposure. For those in which the average summer temperatures were also lower than 18 °C, the potential appears to be even zero. Such is the case in the Western Somme, Southern Lower Normandy, as well as most of the mountainous regions (the Massif Central, Northern Alps, Jura, and Vosges).

To assess the quality of our modeling, we overlaid a map of archeological discoveries that offers proof of winemaking activities on ours that estimates winemaking potential. We first geolocate the winemaking buildings, carpological remains, and ancient vine planting holes,[11] as well as the different winegrowing tools.[12]

By comparing the data, we observed a good geographic match between our predictions and the actual data in Western Aquitaine, in Gallia Narbonensis (the Hérault and middle and lower Rhone valley), in the Rhine and Moselle valleys, on the middle course of the Loire River (Fig. 4), as well as in Île-de-France. In the Center Region, the numerous winemaking tools discovered corresponds to an area between Orléans and Chartres with a good winemaking potential.

Viticultural buildings and other remains exist in sectors that would seem to be not very favorable for winemaking (Western Var, Indre, Maine-et-Loire). Meanwhile, very few remains have been unearthed in other regions such as Alsace that seem to have had a good potential. In the northern and northwestern parts of Gaul (Eastern Brittany, Pays de la Loire), the inventory of discoveries made still remains quite limited: grape pips were unearthed in the ancient agglomeration of Corseul (*Fanum Martiis)* in the Côtes-d'Armor (Bouby and Marinval, 2001); circular vineyards were discovered during the excavation of the Quiou villa, about twenty kilometers southeast (Arramond and Requi, 2012); in Piriac-sur-Mer, a wine press was discovered in the ruins of a rural building (Hervé-Monteil et al., 2011). Finally, wine amphora workshops (Gauloise 12) have been found in northern France (Brun, 2010).

Validation of the predictive model is based on Kvamme's Gain Statististics (Kvamme, 1988), which is one of the simplest and most frequently used validation methods in spatial archaeology (e. g. Verhagen, 2007, 2008; Danese et al., 2014). This test compares the relative proportion of each archaeological features against the relative proportion of the area covered by the different levels of modeled viticulture suitability. For example (Table 1), we have 10% of the total area with no viticulture potential (criterion = 0), among them 10 sites (2.9%) have archeological features and the corresponding Kgain is then −2.04.

The closer the index value is to 1, the better the quality of the estimate. From our estimates, the Kgain is negative (−2.04, −1.7, −0.18) for criteria 0 to 2. These criterion levels are then considered as unsuitable for viticulture. Kgain becomes positive from criteria 3 (Kgain = 0.28) to reach a maximum for 4 and 5 cumulative criteria (0.66 and 0.73). Archaeological evidence of viticulture therefore appears to be

[2] "In general, what appears to be the most advantageous exposure to recommend is southern in cold territories, and eastern in temperate regions, provided that you do not have to fear the devastating forces of the Autan and the Eurus that blow on the coasts of Baetica."

[3] File can be downloaded at: https://darmc.harvard.edu/data-availability.

[4] File can be downloaded at: https://www.eea.europa.eu/data-and-maps/data/wise-large-rivers-and-large-lakes.

[5] File can be downloaded at: https://www.eea.europa.eu/data-and-maps/data/eea-coastline-for-analysis-1/gis-data/europe-coastline-shapefile.

[6] File created by P. Ouzoulias/CNRS.

[7] According to the distances we established using GIS tools, most of the ancient winemaking tools and buildings are found within a 10-km wide strip along the main Roman roads and the major rivers.

[8] This distance, which corresponds to a day of walking, corresponds to the supply area of agricultural goods sold in ancient cities.

[9] File can be downloaded at: http://srtm.csi.cgiar.org/srtmdata/.

[10] https://www.data.gouv.fr/s/resources/indices-mensuels-de-temperature-et-nombre-de-jours-de-temperature-issus-du-modele-aladin-pour-la-periode-de-reference/20150930–200335/Tempe_REF_mensuel.txt.

[11] These different data items were largely drawn from volume 58 of *Gallia* (2001), *La viticulture en Gaule*, co-edited by Jean-Pierre Brun and Fanette Laubenheimer, as well as volume 68 of *Gallia* (2011), *La vigne et le vin dans les trois Gaules*, co-edited by Matthieu Poux, Jean-Pierre Brun, and Marie-Laure Hervé-Monteil.

[12] Data mainly extracted from the Outagr database created by A. Ferdière http://outagr.huma-num.fr/Outagr/.

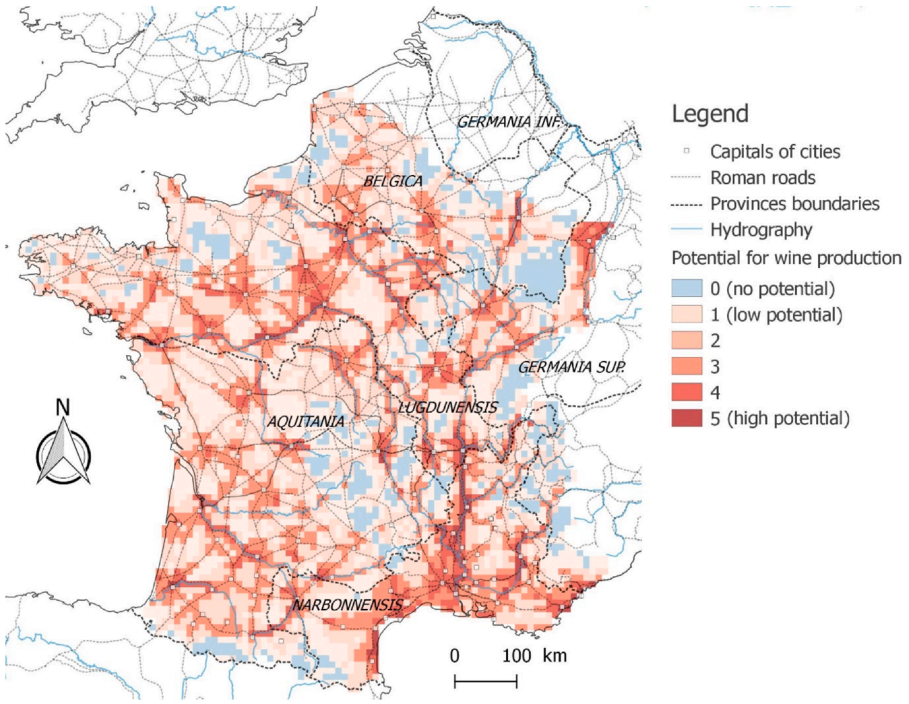

Fig. 3. Predictive spatial model: potentially favorable areas for the establishment of vineyards in Roman Gaul in the 1st c. CE according to climate, southern exposures, and proximity of important towns, of main roads and large rivers. The darker the red color, the potential for viticulture is. The blue areas indicate "no potential", i.e., without any positive factor, as predicted by the spatial model.

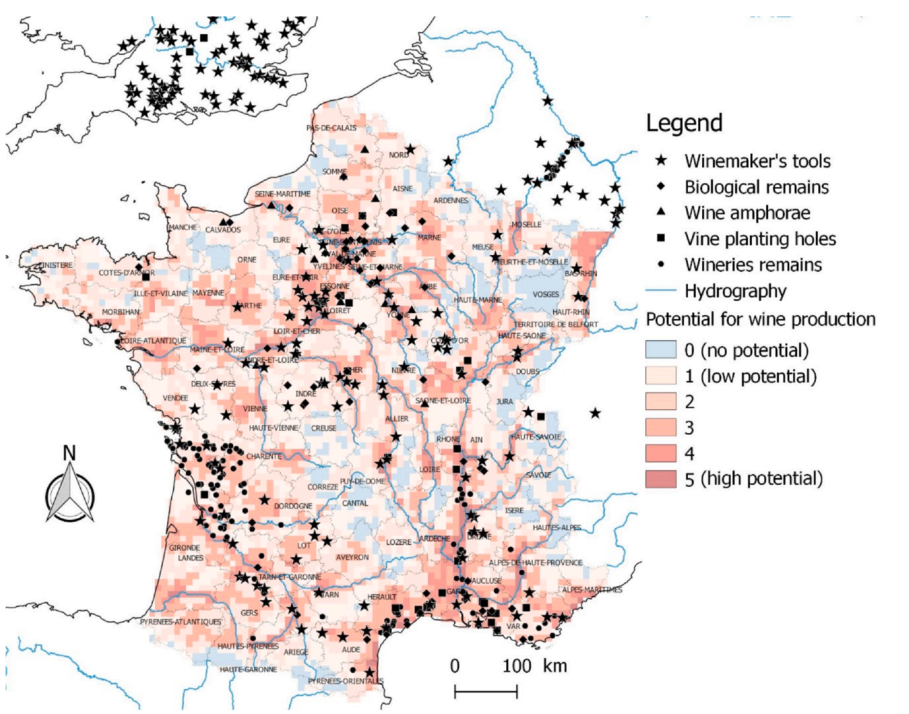

Fig. 4. Comparison of archaeological data on Gallo-Roman viticulture (1st c. CE) with the results of the predictive spatial model. The symbols represent the archeological data for the roman period. The reddish colors are an indicator of viticulture suitability based on the number of favorable factors (see Fig. 3).

under-represented in areas considered unfavorable but well represented in areas favorable to very favorable. The maximum values achieved by the Kgain can be considered very satisfactory, with this index rarely exceeding 0.7 (Verhagen, 2007). According to this test, predictive modelling is therefore in strong agreement with the geography distribution of existing archaeological data.

4. Discussion

If we accept Strabo's description alluded to in the introduction, viticulture was still restricted to the province of Gallia Narbonensis at the beginning of our era, before extending into the northern part of the Three Gauls during the 1st c. CE. This geographic expansion took place

Table 1
estimation of the quality of predictive modeling according to the statistical method of Kvamme's Gain Statistics, Kgain(c) = 1 – (% area with viticulture suitability at level c / % archeological sites).

criterion (c)	Area Percentage	Site number	Number percentage	Kgain
0 (unfavorable)	9.1%	10	2.9%	−2.04
1 (weakly favorable)	26.6%	33	9.8%	−1.7
2	33.1%	93	27.8%	−0.18
3	22%	103	30.8%	0.28
4 (favorable)	7.5%	76	22.7%	0.66
5 (very favorable)	1.5%	19	5.6%	0.73

during the phase of intense economic growth of the High Roman Empire, which was marked by strong urban development. The cities, and especially the city-states, most of which were founded under Augustus's principate, were the main places where wine was consumed. Vineyards were thus more or less successfully planted in the immediate vicinity of these urban areas, as can be seen in the ancient vineyards discovered around Bourges (*Avaricum)* as mentioned above. Other vineyards were also planted further from the cities, close to roads and rivers that made it possible to transport and sell the wine produced. The dynamic expansion of viticulture in the Moselle valley in the later Roman Empire certainly owes a great deal to its proximity to Trier, the ephemeral capital of the Empire, as well as to the urban centers of the Germanic *limes* further downstream (Schnitzler, 2011). In addition, part of the production could also be exported outside of Gaul. The residents of Rome drank wine from the Allobroges, as well as from the region near Béziers, as is attested in the stamped amphorae found at Rome in the *Castrum Pretorium* and at *Monte Testaccio* (Clavel, 1970).

4.1. The new perspectives of predictive modeling to explain the extension of viticulture

To develop vineyards in northern Roman Gaul, beyond the Mediterranean climate zone, winegrowing techniques had to adapt to colder climate conditions and earlier winters that could compromise the grape harvest. This expansion was made possible by the discovery and cultivation of new varieties that were adapted to the cooler weather of northern Gaul. In the Bordeaux region, or perhaps Bourges, *Vitis biturica* was considered to be resistant to cold weather, as was *Vitis allobrogica*, which ensured the good reputation of Vienne (currently in the Isère Department) as of the 1st c. CE (Béal and Lucas, 2011). This famous wine, popular among the Romans, was made with black grapes that ripened in frosty weather according to Pliny (*Hist. Nat.*, XIV, 26). Perhaps it came from Mondeuse grapes, which are today mainly grown in Savoie (André and Levadoux, 1964). These three different varieties may have been imported, but also mixed with other indigenous varieties found in Gaul, as suggested by the recurrent identification of wild grape pips (*Vitis vinifera* spp. *sylvestris*) in the carpological remains of blends in southern Gaul (Bouby et al., 2013). The development of viticulture in Roman Gaul thus seems to owe much to the utilization of the wild species that were growing naturally in the alluvial forests. Far from being restricted to the Mediterranean region, if the current distribution maps are correct (Arnold et al., 1998), these wild vines could have also grown in northern France.

This Gallo-Roman viticulture developed all the way to mid-mountain altitudes as we can see in the winemaking facility and wine storehouse and its *dolia* (earthen jars) built at La Bâtie-Montsaléon (763 m) in the Hautes-Alpes department (Brun, 2001a). The remains of a wine press and ancient vine planting holes dating from the 4th c. CE were also recently discovered in the Haute-Savoie department, in Thonon-les-Bains at Versoie, south of Lake Geneva (Landry, 2019)). The Roman climate warming period was certainly very favorable to this altitudinal and latitudinal expansion of viticulture, as some ancient texts suggest. According to Pliny, in 121 BCE when L. Opimius was consul, an exceptionally hot summer enabled Italy to produce a very high-quality wine (Béal and Lucas, 2011). This event was too exceptional to be interpreted as climate change; however, the Saserna (father and son), who were agronomists and winemakers in northern Italy (the current region of Piedmont or Emilia-Romagna), described milder winters in the second half of the 2nd c. BCE and increasing temperatures that made it possible to grow grapes in regions that had previously been too cold, and even to harvest a great amount of grapes there.[13] While the precise location of the regions touched by this change remains uncertain, these textual allusions correspond chronologically to the beginning of the Roman Climatic Optimum, as defined on the basis of paleoclimatic proxies.

According to the predictive model based on a combination of climatic, environmental, and geographic criteria, viticulture could have flourished widely during the Roman Climatic Optimum in northern Gaul (Brittany, Normandy, Hauts-de-France). Since the archeological evidence of this activity is still quite scarce, its importance may be considerably underestimated. Furthermore, it is more difficult to provide proof of Gallo-Roman viticultural activities in the north than in the south.

Indeed, in Gallia Narbonensis, wine was stored in *dolia* amphorae, which make it easy to recognize the wine cellars, while, in the north, wine was stored in wooden barrels (Marlière, 2002) that have generally disappeared. Identifying winemaking activities in the north then requires other forms of evidence such as presses, fermentation vats, tools, planting holes, and carpological remains, which are more difficult to find or whose role in winemaking is not always completely certain. Archeological research should be further developed in these northern regions of Gaul where modeling seems to be promising, but where concrete evidence of winemaking remains scarce.

4.2. LPJmL model confirms an increase of potential yields during the RCO

The beneficial impact of climate warming on grape harvest yields is also supported by the results of LPJmL modeling that indicate significant differences in potentials yields between the 6th c. BCE – coldest century of the Iron Age – and the 1st c. BCE, which was marked by optimum temperatures.

Due to the lack of data concerning the ancient varieties mentioned by Roman agronomists, we must specify that our modeling was conducted based on the biological characteristics of current varieties, as in Fader et al. (2015), followed by a calibration in order that the simulated yields fit within the range of the reported yields for the Roman period, that may differ from the current ones. While no historical source gives specific information on the winemaking yields in Roman Gaul, Latin authors did provide figures for Italy. In the 1st c. CE, Columella estimated that the bad vineyards could produce one culleus per juger – or about 20 hl/ha -, which was considered to be a low yield (*De Re Rust.*, III, 3). The agronomist recommended uprooting vines that produced less than three culleus / juger (±60 hl/ha), which was in his opinion a break-even point for a winemaking facility. It was indeed possible to obtain greater yields. Columella alludes to the case of one of his young vineyards that produced 100 amphorae/juger (±106 hl/ha). According to Pliny (*Hist. Nat.*, XIV, 5), in Italy in the districts of *ager Caecubus* and *Setia* (today's

[13] Indicated by Columella (*De Re Rust.*, I, 1, 5): "In this book on agriculture that [Saserna] left us, he concludes that the position of the sky changed based on this observation: regions in which previously, due to the particularly cold winters, no vines or olive trees would survive, now that the ancient cold weather has loosened its grip and the climate has warmed, produce abundant harvests of olives and Liber [Pater] (grapes)." See Jean-Pierre Brun, « Annexe, la viticulture en Gaule : *Testimonia* », in Jean-Pierre Brun, Fanette Laubenheimer (editor), *La viticulture en Gaule, Gallia*, 58, 2001, p. 221–237, see p. 234.

Sezze) such vineyards could produce up to 7 culleus/juger (±145 hl/ha), which was considered to be a high yield. Cato the Elder even claims that in the 2nd c. BCE he obtained 10 culleus/juger (±210 hl/ha), or even 15 culleus/juger (±312 hl/ha); however, Columella as well as Pliny, who mention these yields, consider them to be particularly exceptional.

Such figures should, of course, be interpreted with some caution. Sometimes copied from one treatise to another, they may contain mistakes or might be perhaps poorly converted into today's units of measure. Yet if we trust these figures despite our doubts, the yields expected by Roman winegrowers in Italy would have been from 60 hl/ha to over 100 hl/ha at the beginning of our era. These figures seem to be particularly high as the average today in France is about 60 hl/ha. But they are comparable to the current figures in Italy with an average of approximately 80 hl/ha, much higher than in France. The information provided by Roman agronomists on the wine yields in ancient Italy is of an order of magnitude close to today's figures. Using the characteristics of today's varieties, the LPJmL model can simulate values for the Gallo-Roman period in the south of France compatible with those reported. Therefore, the 25% to 50% increase in the potential production between the 6th c. BCE and the 1st c. BCE calculated by this model appears to be credible.

According to the textual examples alluded to above, the positive effects of climate warming on viticulture seem to have been perceptible in Italy in the second half of the 2nd c. BCE, which corresponds quite well to the Roman conquest of southern Gaul that was completed in 121c. BCE. Furrows and planting holes in a vineyard dating from the last quarter of the 2nd c. BCE were discovered in Nîmes 200 m to the south of the southern limit of the pre-Augustan city (Monteil et al., 1999). However, the archeological surveys conducted on a larger scale in Languedoc and Roussillon do not enable us to conclude that there was a significant development of viticulture in the 1st c. BCE, though the climate had already become very favorable. This activity only seems to have gained significance between the late 1st c. BCE and the early 1st c. CE. (Buffat et al., 2001). It would thus appear likely that there was a gap of more than one century between the beginning of climatic conditions beneficial to winegrowing and its actual development in Roman Gaul driven by the emergence of a market economy that started in the Augustan period.

Considering the potential rise of yields, winemaking probably became competitive enough in Gaul to challenge Italian wine production, but it was not straightforward. Indeed, Italian producers had been making significant profits selling wine in Gaul since the 2nd c. BCE, as is attested by the Italic amphorae found on numerous Second Iron Age sites (Bats, 1986). Domitian's famous edict of 92 CE, which stipulated that half of the vines in Gaul should be uprooted, was maybe a protectionist measure for Rome that aimed to protect the Italian production against the Gaulish competition especially strong in the late 1st c. CE. While his edict was not necessary enforced, the authorization given by Emperor Probus at the end of the 3rd c. CE for planting vineyards in Gaul very certainly encouraged this activity (Dion, 1959). In the 4th c. CE, the vineyards in Moselle and Garonne were very dynamic, according to Ausonius' poetic evocation (*Idyllia*, 10) (Schnitzler, 2011). These vineyards may have also competed with those of Gallia Narbonensis, whose decline seems to have been irremediable after the 3rd c. CE (Buffat et al., 2001).

If, according to paleoclimatic proxies, the climate in late antiquity seems to have got cooler compared to that of the High Roman Empire, it was still not yet unfavorable to winemaking. For example, Emperor Julian, who visited Île-de-France in the late 4th c. CE, praised the quality of the vines there, which he attributed to its sunny winters (Brun, 2001b).[14] Viticulture was still clearly successful in the later Roman Empire in northern Gaul.

5. Conclusion

Developed as of the 6th c. BCE in southern Gaul, especially near Marseille, viticulture expanded rapidly northward in the 1st c. CE. This phenomenon can be linked to the emergence of a market economy fueled by the urban development of the High Roman Empire that started under Augustus. While historic and economic factors played a preponderant role, it has become clear that the climate warming during this period also played a decisive role in the expansion of winemaking. According to the LPJmL modeling results presented in this article, potential yields of 60 hl/ha could have been obtained by the 1st c. BCE. While the agronomist Columella considered this figure to be the break-even point for a winemaking operation in Italy, today it corresponds to the average yield of a commercially viable vineyard in France. This sharp increase in wine yields driven by a warmer climate could have improved the profitability of wineries and encouraged the expansion of winemaking in Roman Gaul at the beginning of our era. While Pliny (*Nat. Hist.*, XIV, 68) wrote in the early 1st c. CE that the wine from Gallia Narbonensis was unknown outside of Gaul, the situation seems to have rapidly evolved during that century, as is attested by the aforementioned discovery in Rome of amphorae from Béziers dating from the 2nd c. CE.

Thanks to the favorable climate conditions during the Roman Climatic Optimum, winemaking extended outside the Mediterranean basin, reaching northern Gaul, probably especially around the main roads, large rivers, and big towns, on land with south exposure. The predictive model we have created shows that the geographic and environmental conditions were favorable for its development there, especially in the northwestern quarter. We are willing to wager that future progress in rescue archeology will make it possible to test out the validity of our prediction.

Because wine production was one of the most profitable agricultural activity in High Empire (Ferdière, 2020), our models could be used to test the potential impact of climate change on Roman economics. It can also be applied to other crops (cereals, legumes, olive trees, etc.) and at the scale of the whole Roman Empire. These methods so offer the possibility to better characterize the impact of RCO on agriculture and its role in the strong economic development of the High Empire (Harper, 2017).

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[14] "The inhabitants of the region [of Lutetia] have a sunnier winter. They have high-quality vines and some of them have already succeeded in growing figs" (p. 228).

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References

Amouretti, M.-C., 1988. La viticulture antique : contraintes et choix techniques. Revue des Études anciennes 90, 5–17. https://doi.org/10.3406/rea.1988.4316.

André, J., Levadoux, L., 1964. La vigne et le vin des Allobroges. Journal des Savants 3 (1), 169–181. https://doi.org/10.3406/jds.1964.1078.

Arnold, C., Gillet, F., Gobat, J.-M., 1998. Situation de la vigne sauvage *Vitis vinifera* ssp. *silvestris* en Europe. Vitis 37, 159–170. https://doi.org/10.5073/vitis.1998.37.159-170.

Arramond, J.-C., Requi, C., 2012. Arboriculture ou viticulture ? Le cas de la *villa* gallo-romaine du Quiou. Archéopages (34), 6–9. https://doi.org/10.4000/archeopages10.4000/archeopages.37110.4000/archeopages.375.

Béal, J.-C., 2006–2007. Transporteurs et propriétaires terriens en Gaule romaine : un bilan. Revue archéologique du Centre de la France (45-46), URL : http://journals.openedition.org/racf/775.

Bats, M., 1986. Le vin italien en Gaule aux IIe-Ier s. av. J.-C., problèmes de chronologie et de distribution. Dialogues d'histoire ancienne 12, 391–430. https://doi.org/10.3406/dha.1986.1732.

Béal, J.-C., Lucas, G., 2011. La viticulture dans la partie occidentale du territoire allobroge. Révision de quelques données archéologiques et des sources textuelles. In Jean-Pierre Brun, Matthieu Poux et Marie-Laure Hervé-Monteil (dir.). La vigne et le vin dans les Trois Gaules, Gallia 68, 215–235.

Boissinot, Ph., 2001. Archéologie des vignobles antiques du Sud de la Gaule. In Jean-Pierre Brun, Fanette Laubenheimer (dir.), La viticulture en Gaule, Gallia 58, : 45-68. https://doi.org/10.3406/galia.2001.3173.

Bondeau, A., Smith, P. C., Zaehle S., Schaphoff, S., Lucht, W., Cramer, W., Gerten, D., Lotze-Campen, H., Müller, C., Reichstein, M., Smith, B., 2007. Modelling the role of agriculture for the 20th century global terrestrial carbon balance, Global Change Biology, 13. https://doi.org/10.1111/j.1365-2486.2006.01305.x.

Bouby, L., Marinval, P., 2001. La vigne et les débuts de la viticulture en France : apports de l'archéobotanique. In Jean-Pierre Brun, Fanette Laubenheimer (dir.). La viticulture en Gaule, Gallia 58, 13–28. https://doi.org/10.3406/galia.2001.3171.

Bouby, L., Figueiral, I., Bouchette, A., Rovira, N., Ivorra, S., Lacombe, T., Pastor, T., Picq, S., Marinval, P., Terral, J.-F., 2013. Bioarcheological insights into the process of domestication of grapevine (*Vitis Vinifera* L.) during Roman Times in Southern France. PLoS ONE 8 (5), e63195. https://doi.org/10.1371/journal.pone.0063195.

Brown, A.G., Meadows, I., Turner, S.D., Mattingly, D.J., 2001. Roman vineyards in Britain: stratigraphic and palynological data from Wollaston in the Nene Valley, England. Antiquity 75 (290), 745–757. https://doi.org/10.1017/S0003598X00089250.

Brun, J.-P., 2001a. La viticulture antique en Provence. In Jean-Pierre Brun, Fanette Laubenheimer (dir.), La viticulture en Gaule, Gallia 58, 2001 : 69-89. https://doi.org/10.3406/galia.2001.3174.

J.-P. Brun La viticulture en Gaule : Testimonia. In Jean-Pierre Brun, Fanette Laubenheimer (dir.) La viticulture en Gaule, Gallia 58 2001 221 237 https://www.persee.fr/doc/galia_0016-4119_2001_num_58_1_3181.

Brun, J.-P., 2010. Viticulture et oléiculture en Gaule. In Pierre Ouzoulias et Laurence Tranoy (dir.), Comment les Gaules devinrent romaines, Paris, La Découverte :231-253. URL : https://www.cairn-int.info/comment-les-gaules-devinrent-romaines–9782707159076-page-231.htm.

Brun, J.-P., 2011. La viticulture en Gaule tempérée. In Jean-Pierre Brun, Matthieu Poux et Marie-Laure Hervé-Monteil (dir.), La vigne et le vin dans les Trois Gaules, Gallia 68, Paris : 1-12.

Buffat, L., Pellecuer, C., Mauné, S., Pomarèdes, H., 2001. La viticulture antique en Languedoc-Roussillon. In Jean-Pierre Brun, Fanette Laubenheimer (dir.). La viticulture en Gaule, Gallia 58 (1), 91–111. https://doi.org/10.3406/galia.2001.3175.

Chabin, J.-P., 2004. L'excellence aux limites… ou le paradoxe des vignobles septentrionaux français d'après l'exemple côte-d'orienThe excellence at the margins... or the paradox of the French northern vineyards from the "Côte d'or" exampleDas Hervorragende im Grenzgebiet... oder das Paradoxon der nördlichen französischen Weinbaugebiete am Beispiel der Côte d'Or. Revue Géographique de l'Est 44 (1-2), 9–16. https://doi.org/10.4000/rge10.4000/rge.86810.4000/rge.916.

Clavel, M., 1970. Béziers et son territoire dans l'Antiquité. Paris, Les Belles-Lettres, Centre de Recherche d'Histoire Ancienne. https://doi.org/10.3406/ista.1970.1013.

Collin Bouffier, S., 2009. Marseille et la Gaule méditerranéenne avant la conquête romaine. Pallas, Revue d'études antiques 80, 35–60. https://doi.org/10.4000/pallas.1751.

Contreras, D.A., Hiriart, E., Bondeau, A., Kirman, A., Guiot, J., Bernard, L., Suarez, R., Vand Der Leeuw, S., 2018a. Regional paleoclimates and local consequences: integrating GIS analysis of diachronic settlement pattern and process-based agroecosystem modeling of potential agricultural productivity in Provence (France). PLoS ONE 13 (12), e0207622. https://doi.org/10.1371/journal.pone.0207622.

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

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

Danese, M., Masini, N., Biscione, N., Lasaponara, R., 2014. Predictive modeling for preventive archaeology: overview and case study. Central Eur. J. Geosci. 6(1), 42-55 (2014). https://doi: 10.2478/s13533-012-0160-5.

Dion, R., 1959. Histoire de la vigne et du vin en France des origines au XIX[e] siècle. Flammarion, Paris.

Dumasy, F., Gandini, C., Bouchain-Palleau, I., Rouquet, N., Troadec, J., 2011. *Vitis biturica*, cépage des Bituriges Cubes ? L'archéologie de la vigne dans le Berry antique. In Jean-Pierre Brun, Matthieu Poux, Marie-Laure Hervé-Monteil (dir.). La vigne et le vin dans les Trois Gaules, Gallia 68, 111–150.

Elliott, J., Deryng, D., Müller, C., Frieler, K., Konzmann, M., Gerten, D., Glotter, M., Flörke, M., Wada, Y., Best, N., Eisner, S., Fekete, B.M., Folberth, C., Foster, I., Gosling, S.N., Haddeland, I., Khabarov, N., Ludwig, F., Masaki, Y., Olin, S., Rosenzweig, C., Ruane, A.C., Satoh, Y., Schmid, E., Stacke, T., Tang, Q., Wisser, D., 2014. Constraints and potentials of future irrigation water availability on agricultural production under climate change. Proc. Natl. Acad. Sci. 111 (9), 3239–3244. https://doi.org/10.1073/pnas.1222474110.

Fader, M., von Bloh, W., Shi, S., Bondeau, A., Cramer, W., 2015. Modeling Mediterranean agro-ecosystems by including agricultural trees in the LPJmL model. Geosci. Model Dev. 8 (2015), 3545–3561. https://doi.org/10.5194/gmd-8-3545-2015.

Fader, M., Shi, S., von Bloh, W., Bondeau, A., Cramer, W., 2016. Mediterranean irrigation under climate change: more efficient irrigation needed to compensate increases in irrigation water requirements. Hydrol. Earth Syst. Sci. 20, 953–973. https://doi.org/10.5194/hess-20-953-2016.

FAO/IIASA/ISRIC/ISSCAS/JRC, 2012. Harmonized World Soil Database (version 1.2). FAO, Rome, Italy and IIASA, Laxenburg, Austria.

Ferdière, A., 2020. Agriculture in Roman Gaul. In David Hollander and T. Howe (eds), A Companion to Ancient Agriculture. https://doi.org/10.1002/9781118970959.ch22.

García de Cortázar-Atauri, Iñaki, Brisson, Nadine, Gaudillere, Jean Pierre, 2009. Performance of several models for predicting budburst date of grapevine (Vitis vinifera L.). Int. J. Biometeorol. 53 (4), 317–326. https://doi.org/10.1007/s00484-009-0217-4.

Guiot, J., Kaniewski, D., 2015. The Mediterranean Basin and Southern Europe in a warmer world: what can we learn from the past. Front. Earth Sci. Frontier Media 3, 28. https://doi.org/10.3389/feart.2015.00028.

Harper, K., 2017. The Fate of Rome: Climate, Disease, and the End of an Empire. Princeton, Princeton University Press.

Hervé-Monteil, M.-L., Dagmar, L., Monteil, M., Dietsch-Sellami, M.-F., Archer, A., Lecler-Huby, E., Le Maho, S., Mortreau, M., 2011. La viticulture dans l'ouest de la Gaule Lyonnaise : les pressoirs de Parville (Eure) et de Piriac-sur-Mer (Loire-Atlantique). In Jean-Pierre Brun, Matthieu Poux, Marie-Laure Hervé-Monteil (dir.). La vigne et le vin dans les Trois Gaules, Gallia 68, 163–214.

Jägermeyr, J., Pastor, A., Biemans, H., Gerten, D., 2017. Reconciling irrigated food production with environmental flows for Sustainable Development Goals implementation. Nat. Commun. 8, 15900. https://doi.org/10.1038/ncomms15900.

Kvamme, K., 1988. Development and testing of quantitative models. In: Judge, W., Sebastian, Lynne (Eds.), Quantifying the Present and Predicting the Past: Theory, Methods and Application of Archaeological Predictive Modelling. 325–428, Denver.

Landry, C., 2019. Du vin antique sur un versant haut-savoyard ? Le vignoble et le pressoir de Versoie à Thonon-les-Bains. In Jean Duma (dir.). Des ressources et des hommes en montagne [on line], Paris, Éditions du Comité des travaux historiques et scientifiques, https://doi.org/10.4000/books.cths.5646.

Marlière, E., 2002. L'outre et le tonneau dans l'Occident romain, Monographies Instrumentum. Éditions Monique Mergoil, Montagnac.

McCormick, Michael, Büntgen, Ulf, Cane, Mark A., Cook, Edward R., Harper, Kyle, Huybers, Peter, Litt, Thomas, Manning, Sturt W., Mayewski, Paul Andrew, More, Alexander F.M., Nicolussi, Kurt, Tegel, Willy, 2012. Climate change during and after the Roman Empire: reconstructing the past from Scientific and Historical Evidence. J. Interdiscip. History 43 (2), 169–220.

Monteil, Martial, Barberan, Sébastien, Piskorz, Michel, Vidal, Laurent, Bel, Valérie, Sauvage, Laurent, 1999. Culture de la vigne et traces de plantation des II[e]-I[er] s. av. J.-C. dans la proche campagne de Nîmes (Gard). Revue archéologique de Narbonnaise 32 (1), 67–123. https://doi.org/10.3406/ran.1999.1521.

Morales-Castilla, Ignacio, García de Cortázar-Atauri, Iñaki, Cook, Benjamin I., Lacombe, Thierry, Parker, Amber, van Leeuwen, Cornelis, Nicholas, Kimberly A., Wolkovich, Elizabeth M., 2020. Diversity buffers winegrowing regions from climate change losses. Proc. Natl. Acad. Sci. USA 117 (6), 2864–2869. https://doi.org/10.1073/pnas.1906731117.

Pomarèdes, Hervé, Mazière, Florent, Séjalon, Pierre, Bel, Valérie, Breuil, Jean-Yves, Ginouvez, Olivier, Jung, Cécile, Maufras, Odile, 2012. Territoires languedociens de la Protohistoire au Moyen âge. Nouvelles données sur les campagnes de Nîmes. Lodève et Béziers. Archéopages (34), 10–21. https://doi.org/10.4000/archeopages10.4000/archeopages.37110.4000/archeopages.378.

Schnitzler, Bernadette, 2011. Aux origines de la vigne et du vin dans les vallées du Rhin et de la Moselle de l'époque celtique à la fin de la période romaineThe origin of vineyards and wine in the Rhine and Moselle valleys from the Celtic to the late Roman periodsGeschichte der ersten Reben und des Weins im Rhein- und Moseltal, von den Kelten bis zum Ende der Römerzeit. Revue d'Alsace (137), 13–32. https://doi.org/10.4000/alsace10.4000/alsace:105610.4000/alsace:1062.

Schaphoff, S., von Bloh, W., Rammig, A., Thonicke, K., Biemans, H., Forkel, M., Gerten, D., Heinke, J., Jägermeyr, J., Knauer, J., Langerwisch, F., Lucht, W., Müller, C., Rolinski, S., Waha, K., 2018. PJmL4 – a dynamic global vegetation model with managed land – Part 1: Model description. Geosci. Model Dev. 11, 1343–1375. https://doi.org/10.5194/gmd-11-1343-2018.

Toupet, C., Lemaître, P., 2003. Vignobles et modes d'exploitations viticoles antiques dans le Nord de la Gaule. L'exemple de Bruyères-sur-Oise (Val d'Oise): une relecture. In Sébastien Lepetz et Véronique Matterne (dir.). Cultivateurs, éleveurs et artisans dans

les campagnes de Gaule romaine, Revue archéologique de Picardie 1–2, 209–226. https://doi.org/10.3406/pica.2003.2368.
Verhagen, P., 2007. Case studies in archaeological predictive modelling. Leiden.
Verhagen, P., 2008. Testing Archaeological Predictive Models: A Rough Guide, in: Posluschny, A., K. Lambers and I. Herzog (eds.) Layers of Perception. Proceedings of the 35th International Conference on Computer Applications and Quantitative Methods in Archaeology (CAA), Berlin, Germany, April 2–6, 2007 (Kolloquien zur Vor- und Frühgeschichte, Vol. 10). Dr. Rudolf Habelt GmbH, Bonn, pp. 285-291.
Wolkovich, E.M., Burge, D.O., Walker, M.A., Nicholas, K.A., Gibson, David, 2017. Phenological diversity provides opportunities for climate change adaptation in winegrapes. J. Ecol. 105 (4), 905–912. https://doi.org/10.1111/jec.2017.105.issue-410.1111/1365-2745.12786.