



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



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ABSTRACT

This paper explores the relationship between past climate and prehistoric Mediterranean agriculture by adapting a process-based dynamic vegetation model to estimate potential agricultural productivity under climate scenarios that characterize the extremes of Mediterranean climate in the Holocene. We adapt LPJmL (the Lund-Potsdam-Jena-managed-land model [Bondeau et al., 2007]), a process-based dynamic vegetation model, to the modeling of potential agricultural productivity in the past. Calibrating this model for past crops and agricultural practices and using a downscaling approach to produce high spatiotemporal resolution paleoclimate data, we produce quantitative estimates of potential yields under past climatic conditions derived from four Holocene climatic extremes (warm/wet, warm/dry, cold/wet, and cold/dry) under two different assumptions (approximate high and low limits) about the intensity of agricultural practice. We here discuss this process with reference to a case study in Provence, examining the methodology and data requirements for modeling past agriculture using LPJmL and considering the implications of the range of variability in potential agricultural productivity under distinct climate conditions. We focus particularly on comparing the range of variability induced by climatic shifts with that achievable through changes in agricultural practices as a means of approaching questions of past vulnerability and resilience.

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1. Introduction

Agriculture is one of the most directly climate-vulnerable of human activities, and agricultural productivity thus a lynchpin of cautionary tales about both current and impending climate change impacts and consequences of past climatic shifts documented both

historically and archaeologically. At the same time, the impacts of past climate change on agricultural productivity are difficult to quantify, and more often asserted than substantiated with quantifiable evidence of changing harvests. In the literature linking past climatic changes to putative societal collapses, the role of declining agricultural productivity often remains implicit, at least partly as specific mechanisms of collapse are generally underexplored. This paper addresses this difficult but vital interface of climate and human activity by exploring the range of climatically-determined variability of past agricultural productivity under the climate conditions of the Holocene in the western Mediterranean.

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We adapt LPJmL (the Lund-Potsdam-Jena-managed-land model), a process-based dynamic vegetation and agro-ecosystem model, to the modeling of past agricultural productivity. LPJmL builds on a process-based dynamic natural vegetation model (Sitch et al., 2003) to include agro-ecosystems (Bondeau et al., 2007; Fader et al., 2015), adding the possibility of modeling various crop functional types (CFTs) as well as established plant functional types (PFTs) representing natural vegetation. To model prehistoric agriculture we calibrate these CFTs for past crops and agricultural practices, and produce spatially-explicit estimates of potential agricultural productivity (PAgP) under the temperature and precipitation extremes (warm/wet, warm/dry, cold/wet, and cold/dry) of past (Holocene) Mediterranean climatic conditions, focusing on an approximately 1400 km² case study area in Provence (see Fig. 1). This study area offers topographic and bioclimatic diversity, capturing at least some of the pronounced geographic diversity for which Provence is well known (cf. Blondel et al., 2010, Ch.5).

Four sequences of high-resolution climate data (monthly temperature, precipitation, and cloudiness, at a spatial scale of 30 m × 30 m grid cells), based on the regional Holocene extremes, are produced by downscaling a low spatial and temporal resolution Mediterranean climate reconstruction for the Holocene (Guiot and Kaniewski, 2015), using relatively high-resolution geographic data and high temporal resolution modern climate data for the latter half of the 20th century (see Contreras et al., 2018). With these inputs, we are able to use LPJmL to produce geospatially explicit estimates of PAgP of key prehistoric crop types (cereals and pulses) under past regimes of agricultural practice. Each model run produces a PAgP value for each pixel that represents the yield in metric tons of fresh matter per hectare (tFM/ha) that a cultivated area within that pixel would produce. Each simulation operates under the assumption that 100% of the pixel area is occupied by the CFT under consideration; hence the focus on potential rather than realized yields. The range of variation in the results constitutes a

quantified estimate of the magnitude of climate-induced variability in past agricultural productivity.

We here use comparisons between snapshots of these four periods to address three key questions:

- 1) What were the consequences for PAgP of the climatic extremes that Holocene inhabitants could have had to confront?
- 2) How were these consequences spatially structured, how spatially diverse were they, and what consequences did this have for the landscapes of agricultural potential available to inhabitants?
- 3) How much were inhabitants able to shape PAgP themselves – that is, how does climate-driven variability compare to potential practice-driven variability?

2. Why simulate prehistoric agriculture?

The impact of past climate change on human societies is now a commonly seen narrative, in both popular (e.g., Diamond, 2005; Fagan, 2004) and academic (e.g., Clare and Weninger, 2010; Clarke et al., 2016; Drake, 2012; Lemmen and Wirtz, 2014) literature. Although such accounts are often criticized as environmentally determinist (e.g., Erickson, 1999; Judkins et al., 2008; Middleton, 2012), the narratives remain compelling – and, increasingly, resonant with contemporary concerns about global climate change.

Discomfort with environmental determinism notwithstanding, few would now dispute the potential for significant human consequences of climate change. Concerns about current and future impacts of anthropogenic climate change now often drive research into past human-environment interactions (cf. Lane, 2015), as the advantage of being empirically examinable over long time spans outweighs the disadvantage of mismatches between past and

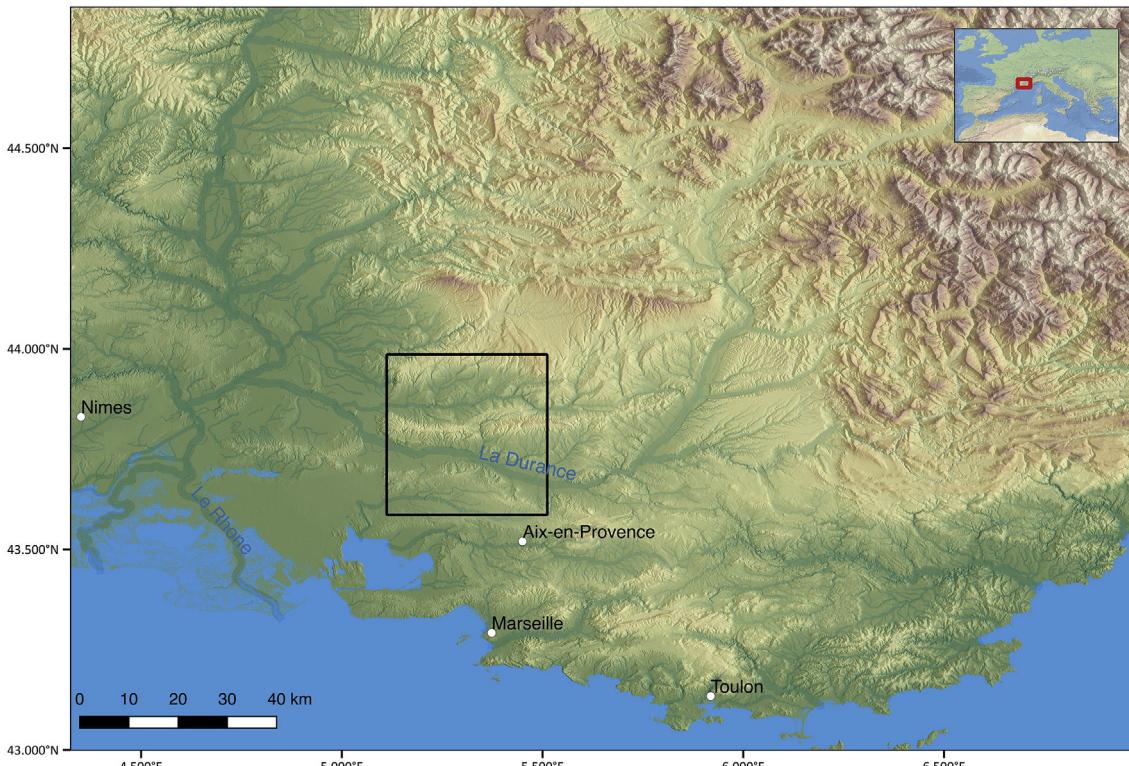


Fig. 1. The case study area. Data from SRTM30 (NASA JPL, 2013) and Natural Earth (<http://www.naturalearthdata.com/>).

modern conditions. In addition, a significant proportion of contemporary agriculture remains smallholder agriculture,¹ often in the developing world closer in character to prehistoric agricultural practices than to modern industrial agriculture. Individual smallholdings are rarely identified archaeologically, as they are less easily found or delimited than aggregated settlements or collectively modified landscapes that leave more extensive and durable remains. Nevertheless, much archaeological research concerns societies in which smallholder agriculture provides the subsistence base, making the productivity, effects, resilience, and vulnerabilities of such systems a basic archaeological concern (cf. Morehart, 2016).

Although limitations of spatial and temporal resolution continue to hamper development of detailed analyses of specific instances of climatic influence (cf. Contreras, 2017), nonetheless much research continues to assert climate-culture causal links (recently, e.g., Carozza et al., 2015; Clarke et al., 2016; Kaniewski et al., 2015; Medina-Elizalde and Rohling, 2012; Wiener, 2014). These generally appeal to approximate chronological correlation and the putatively inevitable impacts of climatic change on subsistence production, long-distance land- and sea-transport, and even cosmological understandings based on climate predictability.

Whether the assertion that such links exist is justified remains an empirical rather than theoretical question, one that has to be addressed in particular for each case. Even if it could be established for every case, however, the analytical payoff would be modest: demonstrating a clear impact of climatic change on a particular cultural trajectory would simply confirm the possibility of an environmental influence that most already suspect to be potential or even probable. Moreover, it would not provide any particular guidance for modeling the effects of *future* climate change, as such modeling efforts are based already on the conviction that climatic effects are possible. This is not to say that there is no value in investigating impacts of past climate change. However, we focus here on what we see as a more productive question: rather than asking *if* past climate change affected cultural trajectories, we explore the potential of an agro-ecosystem model to ask *how* it did so, and what were the factors that conditioned the degree and kind of effect. We use modeled PAgP under Holocene climate extremes to investigate whether climate impacts on agricultural productivity are a plausible mechanism relating climate change to cultural change, and to explore what could make agriculturalists more or less vulnerable to such change.

The mechanism often invoked (generally implicitly but occasionally explicitly) in studies of the impacts of past climate change is that of depressed subsistence production (e.g., Clare and Weninger, 2010; Drake, 2012; Pezzy and Anderies, 2003; Wiener, 2014). However, whether and how climatic shifts would have depressed harvests is rarely explored in any detail, and, as has been pointed out in both archaeological (Rosen, 1997; Wilkinson, 1997) and historical (Slavin, 2016) contexts, whether environmentally-induced shortages become famines is as much a question of social factors as environmental ones. In fact this putative link needs to be elaborated for any particular argument: why should a particular climatic change have had disastrous effects on agricultural production? To invert the question and generalize it,

how vulnerable was prehistoric agriculture to climatic change?

While agricultural production is by no means the only plausible mechanism through which climatic change might have impacted past human populations, it is an aspect that is both vital to societies' continuance and on which one might reasonably expect to see impacts (cf. Currie et al., 2015). The hypothesis that such impacts were acute can, if confirmed, provide an argument for one important way in which past human communities were vulnerable to climate change. Conversely, rejecting such a hypothesis would suggest that the elasticity of small-scale agriculture provides significant resilience (and that, in cases where strong climate-culture links are suspected, other avenues of impact need to be explored). Using modeling to explore those variables that most strongly affect such production provides one way of characterizing some of the elements vital to such resilience. While such use of modeling has been explored conceptually (e.g., Marston, 2015), operationalizing more detailed models remains challenging due to the number of variables involved and the difficulty of parameterizing models based on archaeological data that is rarely, due to challenges of preservation and sampling, complete or detailed enough to directly provide the specifications necessary for modeling (cf. Saqalli et al., 2014, p. S47).

How, then, to model the relationship of prehistoric agriculture to climate variables? Ultimately the question is one about the sensitivity of agricultural outputs (productivity) to environmental variables (temperature, precipitation, soil characteristics, etc.) and agricultural practices (land selection and clearance, tilling, manuring, crop mixtures, rotation, fallow, weeding, irrigation, etc.). Seen in this light, the question of climate impacts on agricultural productivity becomes a question of when the effects of changes in environmental variables overwhelm the potential effects of changes in agricultural practices (though environmental variables may also be altered – intentionally or not – by anthropogenic landscape modification).

The need to model both biophysical processes and human (social) behavior creates two distinct challenges. The former (relating agricultural productivity to environmental variables) has received significant attention in ecological modeling (e.g., Challinor et al., 2010; Rosenzweig et al., 2014; Waha et al., 2013), but those efforts have focused primarily on contemporary and future scenarios (though crop models [e.g., Lee et al., 2006; Meister et al., 2016] and agricultural niche modeling [e.g., Bocinsky and Kohler, 2014; d'Alpoim Guedes et al., 2016; Schwindt et al., 2016] are now being applied to questions about past agricultural possibilities). Meanwhile, the activity of small-scale societies, including agricultural production, is a focus of archaeological research, a strand of which has begun to employ agent-based models (ABMs) to address questions about (among other things) dynamic socio-environmental systems over time (see recent summary and review in Wurzer et al., 2015).

Partly because the development of archaeological ABMs represents a significant series of challenges in its own right and partly because the effects of environmental change have not always been central to the research questions of modeling efforts, even the most sophisticated published archaeological ABMs have relied on relatively simple relationships between productivity and climate (and generally on spatially coarse, if not invariant, climate data [e.g., Barton et al., 2010a, 2010b; Danielisová et al., 2015; Kohler and Varien, 2012; Saqalli et al., 2014]).² Such simplified modeling of the link between environmental conditions and agricultural

¹ The term "smallholders" is variously defined but generally encompasses agriculturalists whose activities are small-scale relative to others in similar settings, who have access primarily to kin-based labor, and whose production is primarily subsistence-oriented. Such smallholders produce, for instance, 70% of Africa's food supply (IAASTD (International Assessment of Agricultural Knowledge, Science and Technology for Development), 2009) and an estimated 80% of the food consumed in Asia and sub-Saharan Africa together (IFAD, 2010). In Latin America, smallholder farmers occupy almost 35% of total cultivated land (Altieri and Kooahfkan, 2008).

² Though see (Lee et al., 2006) for an example of the opposite – an effort to model small-scale agricultural production that is climatically and biophysically sophisticated but socioeconomically simplistic.

productivity may be justified for particular environmental conditions – e.g., where agriculture is marginal and highly vulnerable to changes in precipitation or temperature – but expanding a modeling approach to examine vulnerability and resilience more broadly requires being able to specify the consequences of environmental change when they are more complex and the links less obvious. As we detail below, by modeling PAgP under past climatic conditions we are able to explore the likely impacts of past climate change.

3. The study area

Examining the human consequences of past climate changes requires considering the effects of climatic conditions at human scales. Those effects are conditioned by topography and geography, whose variability in Provence produces a marked bioclimatic diversity within short distances (cf. Blondel et al., 2010, Ch. 5). That diversity means that effects of climate changes will be spatially differentiated at scales meaningful for inhabitants and with consequences potentially detectable in archaeological settlement patterns. This increases the diversity of possible climate impacts, but also makes it likely that in the region, historically desirable for agriculture, past inhabitants would have confronted notable climatic shifts while practicing agriculture with a variety of crops and methods.

The area selected for study within the region – approximately 1400 km² – was arbitrarily delimited to encompass the various bioclimatic zones, with the goal of developing a methodology that could subsequently be applied to a larger area of Provence. There is also a practical aspect: availability of 20th-21st century high-resolution climate data makes downscaling of paleoclimate data possible (cf. Contreras et al., 2018), while rich archaeological settlement pattern data is available through *Patriarche* (the French national archaeological atlas, a continuously updated database that integrates excavation and survey data from diverse sources; cf. <http://www.culturecommunication.gouv.fr/Politiques-ministerielles/Archeologie/Etude-recherche/Carte-archeologique-nationale>).

4. Methods: using LPJmL to model prehistoric/preindustrial agriculture

4.1. A brief introduction to LPJmL

The agro-ecosystem model LPJmL simulates the carbon and water fluxes between atmosphere, vegetation, and soil, depending on the seasonal courses of key climatic variables (temperature, precipitation, solar radiation [derived from cloudiness]), atmospheric CO₂ concentration, soil type, and (for cropland and pasture areas) farming practices (Bondeau et al., 2007). The CO₂ absorbed by the canopy through photosynthesis builds carbohydrates that are stored in the different parts of the plant. For crops, one important output is the amount of carbohydrates that fill the economically interesting pool: i.e. the harvested one (grains, fruits, roots, tubers).

The responsiveness of that harvestable output to model variables has been the focus of extensive development. The model can account for irrigation, and the intensity of agricultural practices is represented through a proxy: the potential maximum leaf area index (LAI_{max}) that can be reached by the canopy without hydric stress. This value is higher when soil fertility is good, or for well fertilized fields, leading to a dense canopy. In the model, the value of this parameter is calibrated at the country scale or region scale in order to ensure that the simulated productivity fits with the observed harvest data (Fader et al., 2015). For developed countries

with intensive modern agriculture, typical values of wheat LAI_{max} range between 5 and 6, while they are kept as low as 2 for countries where poor environmental conditions and eventually degraded soil are not (or marginally) compensated by external fertilizer (organic or industrial) inputs, and where, additionally, the yield loss due to pests can be significant. As we discuss further below, LAI_{max} and plant physiological parameters are adjusted both with regard to available information about past values and in order to tune the LPJmL results to produce expectable yields for preindustrial agriculture under various assumptions about agricultural intensity.

4.2. Adjusting LPJmL parameters to model pre-industrial agriculture

The LPJmL parameters that account for crop development and growth fall into two categories: 1) those that relate to crop characteristics and vary between crop cultivars (growing degree days needed to reach the various phenological stages, sensitivity to photoperiod, vernalization requirement, harvest index, etc.), and 2) those that relate to agricultural practices (sowing dates, irrigation, proxy for intensity, residue management, etc.). Parameters from both categories are distinct for pre-industrial agriculture and the modern agriculture. The changes applied for this study are reported in Table 1 and explained below.

Landraces, rather than cultivars, should be used to speak about the crop varieties cultivated in pre-industrial agriculture. This indicates a large variability in crop characteristics as crops constantly adapt to local features and are subject to selective breeding by agriculturalists. Although details are necessarily inferential and result in ranges rather than precise values, some evidence allows us to adjust four parameters related to crop characteristics and farming practices:

First, one of the changes resulting from the breeding efforts of agricultural research institutes since the early 20th century is the increase, especially for staple cereals, in the fraction of net primary production allocated to the harvested organs, simultaneously reducing the amount of straw (typically producing, for instance, short wheat cultivars). Therefore the harvest index (HI, the proportion of NPP harvested) of pre-industrial landraces was lower than it is for modern cultivars (Krausman, 2001); this gives an upper limit for pre-industrial HI values.

Second, all wheat and barley landraces were winter varieties; spring varieties were selected only recently with the northern displacement of the crop frontier towards continental climates with very cold winters, e.g. in North America in the 20th century. In its standard version, the sowing date is calculated in the LPJmL model from the climate pattern (Waha et al., 2012), and a spring sowing date is simulated if the winter is too cold. We switch off this possibility by allowing the simulated sowing date for winter varieties to be theoretically rather early (late summer), although it is not expected that this should happen in the Mediterranean region under Holocene climatic conditions.

Third, the crop-growing period, i.e. the time required between sowing and maturity, is related to a cultivar-specific number of degree-days, defined as the phenological heat units (PHU) requirement. Phenological development comprises the succession of the different stages of a crop between emergence and physiological maturity (when the crop can be harvested), including, e.g., a juvenile stage, flowering, and senescence. The PHU requirement implies that certain cultivars will develop faster under higher temperatures, leading to a reduced number of “potential photosynthetically active days”. As the determination of the sowing-date in LPJmL defines the beginning of the phenological cycle, the model computes an optimal PHU, i.e. an optimal growing cycle length, for ensuring the best possible yields. Gervois et al. (2008) report that past cultivars showed a shorter duration in the early stage

Table 1

Parameter changes for running LPJmL for the past. Only the changes relative to the standard parameterization (available in Bondeau et al., 2007) are given. For each crop (wheat and peas, proxies for cereals and pulses more generally), two different parameterizations are provided. For Par 1 we assume the same growing period as today (and so the same PHU); only the harvest index and the LAI_{max} are modified toward low-yielding cultivars and low-input practices. Par 2 is as the same as in Par 1, but approximates the effects of minimal agricultural intervention by considering cultivars with a shorter cycle and reducing LAI_{max}. In all cases we force the model to simulate only winter-wheat varieties.

	Wheat standard	Wheat Par 1	Wheat Par 2	Peas standard	Peas Par 1	Peas Par 2
Earliest possible sowing date	September 15th	September 1st	September 1st	NA	NA	NA
Winter/summer varieties	Spring wheat possible	No spring wheat	No spring wheat	NA	NA	NA
PHU (°C-days)	[1700.0–2876.9]	[1214–2055]	[1214–2055]	2000	1700	1700
HI _{opt} (optimum harvest index reached at maturity)	0.5	0.35	0.35	0.45	0.3	0.3
Potential LAI _{max}	5	2	1	4	2	1

development, as breeding efforts have managed to extend this duration to allow significant canopy cover to be reached earlier in year. So, across cultivars and independently of climate change impacts, the duration of the phenological cycle should be shorter in modeling past agriculture, and we adjust LPJmL parameters accordingly.

Finally, despite the use of fallow, rotations, and/or manure, pre-industrial soil fertility rarely if ever reached, much less maintained, the level of the modern fields receiving large inputs of either organic or industrial fertilizers. Lacking parameters that can directly account for these practices, we adjust the proxy parameter for agricultural intensity in LPJmL (LAI_{max}) to constrain the simulated yield within the range of estimated values found in the ethnographic, historical, and archaeological literature on Mediterranean agriculture. As a result, in order to calibrate the productivity estimates for any CFT, we require explicit information regarding crop types and the estimated range of probable yields (kg/ha), as well as information regarding such management practices as manuring, tilling/plowing/weeding/hoeing, and rotation/fallowing.

Information about agricultural practices (primarily crops and estimated yields, agricultural calendar, and management practices) are derived from archaeological (e.g., Bouby, 2014; Ruas and Marinval, 1991) as well as ethnohistoric and ethnographic (Halstead, 1987, 2014) sources for the Mediterranean region, with particular attention to data more local to the study area where available. Other modeling studies from the region and nearby (e.g., Barton et al., 2010a, 2010b; Danielisová et al., 2015; Saqalli et al., 2014; Baum et al., 2016) have also been useful, particularly as these have also had to confront the problem of producing quantifiable estimates from inevitably incomplete data (cf. Kohler and Varien, 2012, Ch.6). To ensure that they are reasonable, results have been checked by reference to the literature on prehistoric agricultural practice and experimental yields (cf. Cubero i Corpas et al., 2007; Ehrmann et al., 2014; Hejcman and Hejcmanová, 2015; Reynolds, 1997, 1992, 1977; Shukurov et al., 2015). As these are largely Central or Northern European, we also use ethnographic data on yields from preindustrial farming in the Mediterranean region (Halstead, 2014, pp. 238–251). While preindustrial agriculture is not a perfect analogue for the deeper past, in conjunction with experimental studies it provides a guide to ranges of yields that might reasonably be expected (see also Araus et al., 2003).

Such an approach is imprecise but, more importantly, avoids false precision: agricultural practices will have varied not only over time but in space, and determining specific practices for a particular time and place is a research program unto itself (one, moreover, whose results will inevitably be incomplete). Rather than adopting a single reconstruction of agricultural practice (or several varying over time), we test two parameterizations: a “low” parameterization representing minimal intervention beyond planting and harvesting, and a “high” parameterization representing a maximally intensive preindustrial agriculture. We can thus model the range of possible yields available to preindustrial agriculturalists

(examining for instance whether, in a particular set of climatic circumstances, agricultural intensification might have sufficed to maintain yields).

4.3. Provision of input data

Using LPJmL in past contexts requires paleoclimatic data that is spatially continuous and of high (monthly) temporal resolution, because growing-season temperatures and amounts of precipitation – rather than annual means – are vital to a process-based model. LPJmL requires input data on monthly means of temperature, precipitation, and cloudiness, as well as CO₂ concentration and soil texture – and information about agricultural practices. The specifics of data inputs will vary depending on the time period and location for which the model will be used; we here review the requirements with particular reference to our Provençal case study.

The need for data evenness and resolution mandates downscaling and interpolation of paleoclimate data. We use here data downscaled from a century-scale paleoclimate dataset derived from inverse modeling of pollen data for the Mediterranean throughout the Holocene (Guiot and Kaniewski, 2015).³ Guiot and Kaniewski use a large collection of pollen sites from the European Pollen Database in a Bayesian inversion of the vegetation model BIOME4, considering vegetation as a function of soil type, CO₂, and climate and validating with modern observations. For use in LPJmL at scales appropriate for examining climate effects on prehistoric agriculture, this data is downscaled by establishing relationships between geographic variables (elevation, distance from the sea) and climate variables (temperature, precipitation, and cloudiness) based on 20th–21st century climate data (detailed in Contreras et al., 2018). The resulting spatially variable 300 m pixel rasters (downscaled from the original 30 m DEM to reduce computation loads) capture monthly estimates of temperature, precipitation, and cloudiness throughout the Holocene.

CO₂ concentration is estimated by interpolation from the Antarctic Taylor Dome data (cf. Guiot and Kaniewski, 2015, p. 3), producing a single value for the study area that changes in centennial steps throughout the Holocene. A soil texture raster for the region under consideration is derived based on modern data (sand/silt/clay percentages from <http://soilgrids.org/index.html>) reclasped using raster algebra to derive FAO/USDA textural classes.⁴ Soil depths are modeled in GRASS (using *r.soildepth*, which models soil depths based on hillslope curvature; cf. <http://isaacullah.github.io/GRASS/>) based on watershed topography derived from a modern digital elevation model.⁵ Soil organic matter is simulated within

³ Available in the OT-Med data catalog at <http://database.otmed.fr/geonetworkotmed/srv/eng/search#|54b9bf34-57ae-45ea-b455-9f90351e538f>.

⁴ cf. ftp://ftp.fao.org/fi/cdrom/fao_training/FAO_Training/General/x6706e/x6706e06.htm#55a.

⁵ The 30 m SRTM DEM (NASA JPL, 2013), available at <https://lta.cr.usgs.gov/SRTM1Arc>.

LPJmL as a product of decomposition of above- and below-ground vegetative matter. The high and low parameterizations thus represent in part effects of changes in soil organic matter, but the actual soil organic matter content of each pixel is simulated within the model based on the modeled vegetation.

4.4. Substantiating LPJmL outputs

Precise estimates of past productivity are difficult to validate; partly for this reason we focus our analyses of model results on a) relative contrasts, and b) ranges encompassed by high/low extremes rather than single values. Such ranges also provide a useful sense of the outcomes of the variety of agricultural strategies available to past inhabitants.

The plausibility of these ranges relies on the accuracy of the plant physiology models that underpin LPJmL; these are well-established through extensive development and peer review over >10 years (cf. <https://www.pik-potsdam.de/research/projects/activities/biosphere-water-modelling/lpjml>). The archaeological relevance of the results can be tested with settlement data and analysis of settlement patterns vis-a-vis agricultural productivity. Fully exploring the archaeological implications of reconstructed PAgP via diachronic spatial analysis is beyond the scope of this paper, but simple plotting of archaeological settlement pattern data (derived from the *Patriarche* database; see Section 3) demonstrates that the PAgP estimates generated by LPJmL successfully capture some aspect of landscape variability that was important to past inhabitants: Fig. 2 shows that domestic and agricultural settlements newly established in the Late Iron Age preferentially selected areas with high modeled PAgP for wheat. The archaeological sites included in this analysis are those identified as domestic settlements and agricultural installations (excluding, for instance, funerary and ritual sites whose locations would presumably be less responsive to PAgP) and dated as newly established in the Late Iron Age in *Patriarche*. Fig. 3 argues that the restricted distribution of Late Iron Age sites is not simply a reflection of broader preference for areas of lower elevation or shallower slope: it is specifically the domestic and agricultural sites whose distribution is restricted to areas of low elevation, shallow slope, and high PAgP. To the extent that high PAgP is coincident with shallower slopes and lower elevations, we cannot tease apart the relative importance of these factors in site location, but it is at least clear that the LPJmL output is coherent with archaeological settlement patterns. That is, archaeological sites established in the Late Iron Age are not distributed randomly with respect to reconstructed PAgP, but are notably restricted in their distribution to areas of relatively high potential yields. Minimizing interannual yield variability, in contrast, does not appear to have been a concern; while settlements are preferentially located in cells with higher mean values, those same cells also have higher standard deviations (see Fig. 3). Although analysis of site distributions is complicated by diachronic biases in documentation and landscape taphonomy, as well as coarse archaeological chronologies, these results argue for the ability of LPJmL results to capture an aspect of environmental variability relevant to past inhabitants, and their utility for investigating settlement distribution patterns.

5. Results

For each of the four climate extremes (warm/wet, cool/wet, warm/dry, cool/dry; 6500 BP, 3000 BP, 4000 BP, and 5700 BP, respectively) of the Holocene for the study area (Fig. 4), we generate 30 year sequences of annual LPJmL estimates of PAgP for two CFTs (representing cereals and pulses) and both high and low

assumptions about the intensity of agricultural practices, at 300 m pixel resolution. The value for each pixel represents the expected yield, if it were farmed in a given year, in kg/ha. These values are of course dependent on our assumptions about prehistoric agricultural practices. We address this limitation by examining the range resulting from our high and low assumptions, and by focusing more on relative comparisons than on specific values.

The results, summarized by comparing the densities of the mean cell values across each period, show that the contrasts between periods are robust across both CFTs and parameterizations (Fig. 5). We focus hereafter on the contrasts between periods for Parameterization 1 of wheat (W1): archaeological evidence suggests that cereal crops were a more important staple than pulses (Bouby, 2014), yield estimates with which to calibrate LPJmL are more reliable and precise for cereals as they have been the primary focus of archaeological, ethnohistoric, and experimental research (see Section 4.2), temperate cereal parameterizations have been the subject of greater development (Bondeau et al., 2007, Table 1), and (most importantly) contrasts within a given parameterization are the most robust. We return below to comparisons between parameterizations as a means of assessing the potential of changes in agricultural practices as adaptations to climate change.

For W1, the results show notably higher PAgP for 3000 BP, relatively modest variability in PAgP between 6500 BP and 5700 BP, and notably lower PAgP for 4000 BP (see Fig. 5). These differences and their spatial distribution can be seen in Fig. 6, in which the value of each 300 m pixel for each period is the 30-year mean of annual PAgP in tFM/ha (metric tons of fresh matter per hectare). The 30-year means for the landscape in aggregate vary from 1.23 to 1.3 tFM/ha across the four periods, or 6% of the overall landscape mean. The uneven spatial distribution of differences result in much higher variability in some areas (Fig. 7 illustrates the differences between 3000 BP – the optimum period for agricultural productivity – and the three other periods); individual pixels can range by as much as four times the difference in landscape means. The probability that these differences in 30-year means between periods are significant can be represented by pixelwise p-values, where the 30-year time-series for each pixel constitutes a sample whose mean and variance can be calculated and compared to the corresponding pixel for another time-series (Fig. 8 displays pixelwise p-values for comparisons between the means whose differences are illustrated in Fig. 7).

The most widespread contrasts are between the cool/wet (3000 BP) optimum and the warm/dry (4000 BP) extreme, though the most marked per-pixel contrasts are with the warm/wet (6500 BP) extreme. In the case of the former, the difference in potential mean productivity across the study area is .06 tFM/ha. Potential productivity under extreme Holocene conditions, that is, could vary by as much as 4% averaged across the landscape, and by as much as .16 tFM/ha (10% of the landscape mean) in the most variable pixels. The differences between time periods (Fig. 7) are not evenly distributed spatially, but generally differences are most acute at higher elevations (though under the dry conditions of 4000 BP changes in floodplain productivity are also likely significant). It is also notable that the highest-yielding areas also generally display higher interannual variability (Fig. 9). Comparison of the high-yielding areas (Fig. 10) shows that the expansion and contraction of these areas is dramatic, with the 4000 BP warm/dry extreme notably impoverished in possibilities for high-yielding harvests, which are abundant for the 3000 BP cool/wet extreme. It is also clear that at least some areas maintain relatively high mean PAgP for all periods, though for the 4000 BP extreme these areas are extremely restricted.

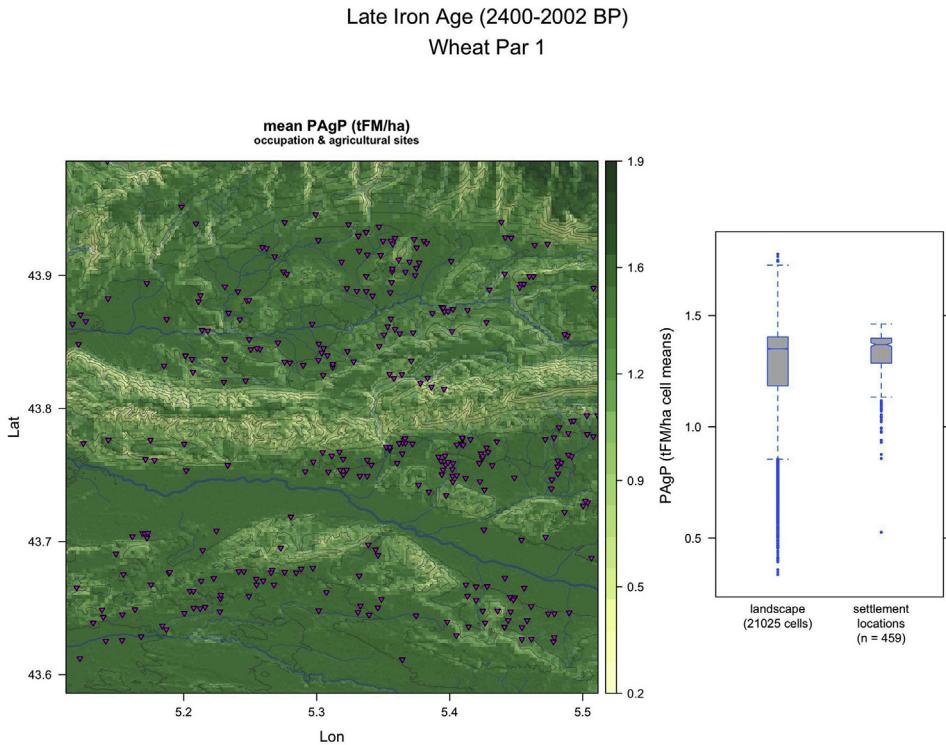


Fig. 2. Late Iron Age settlements (newly settled occupation and agricultural sites only), plotted on a landscape of mean PAgP (wheat, Par 1) over the course of the period (2400–2002 BP). The boxplot summarizes PAgP values for every cell in the plot (left) and mean values within 200 m buffers around settlement locations (right); settlement locations are derived from *Patriarche*. Here and in all subsequent figures 100m contours are derived from SRTM30 DEM.

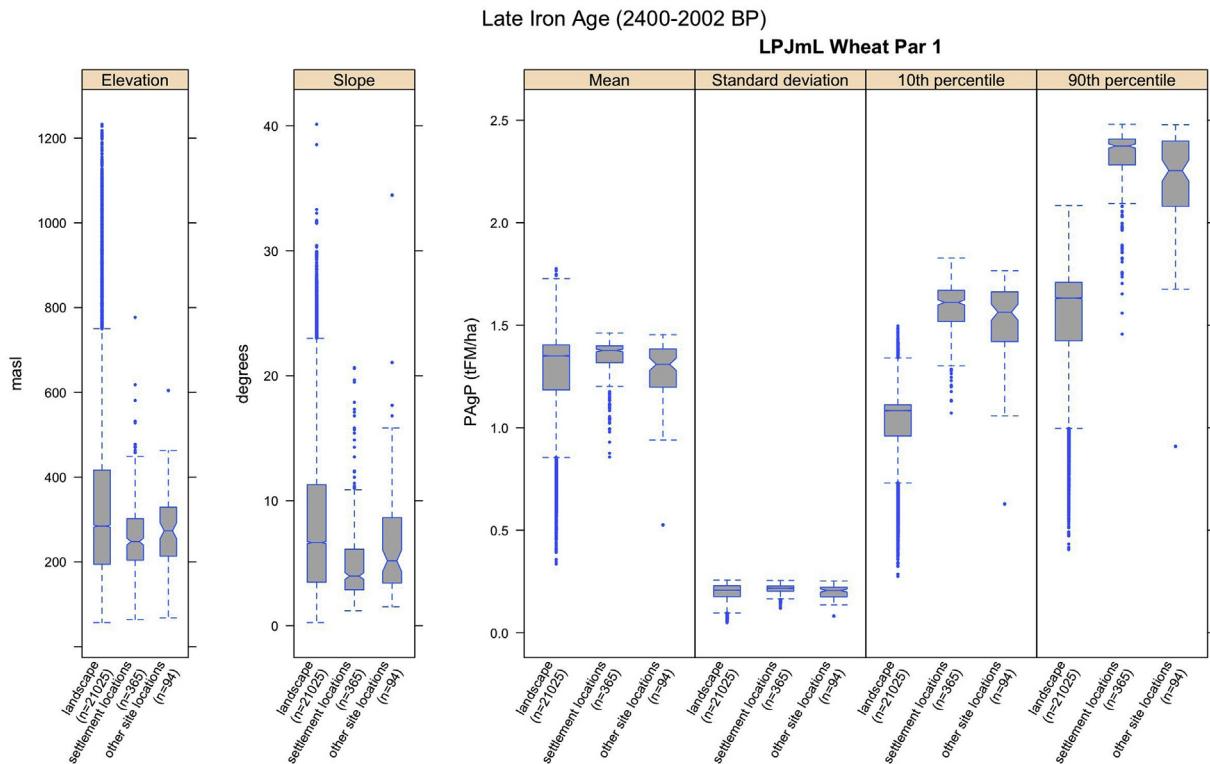


Fig. 3. Comparison of Late Iron Age site locations (shown in Fig. 2) with landscape characteristics. Locations of domestic and agricultural sites are distinct from those of other types of sites and non-random with respect to the landscape as a whole; they are preferentially associated with comparatively low elevations and slopes, and comparatively high mean W1 PAgP (even at the expense of higher standard deviations – i.e., greater interannual variation in yields).

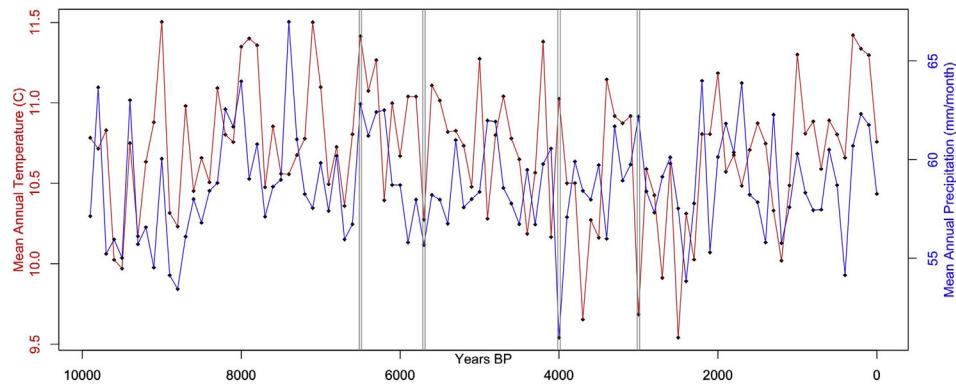


Fig. 4. Annual means (calculated from monthly values for each centennial timestep) of Holocene climate and temperature for the study area, from the Guiot and Kaniowski 2015 dataset. Data on % cloudiness is also included, but not plotted here. Vertical gray lines mark the 30-year windows examined for the Holocene extremes (warm/wet, cool/dry, warm/dry, cool/wet; 6500 BP, 5700 BP, 4000 BP, and 3000 BP, respectively). These are combinations of temperature and precipitation are not unique in the magnitude of either variable, but are representative of the most extreme combinations of these variables throughout the Holocene.

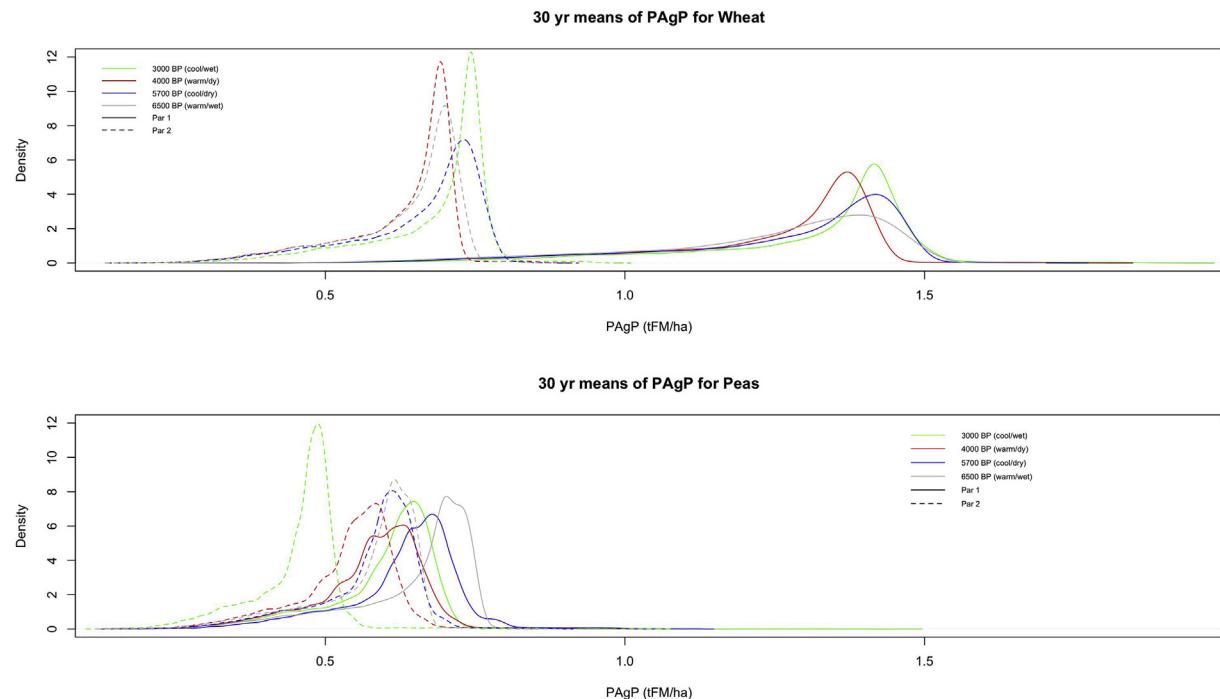


Fig. 5. Density plots of the mean PAgP values (for each period and parameter, 30-year means in tFM/ha for each of 21025 cells) for both parameterizations and both CFTs, across all four time-periods.

6. Discussion

While the modern tendency is perhaps generally to think of pre-industrial agriculture as precarious, and carefully tailored to particular environmental conditions, in fact an abundance of ethnographic, ethnoarchaeological, and archaeological study demonstrates that agriculturalists have an array of adaptive strategies available to them (cf. Halstead, 2014; Netting, 1993; van Gijn et al., 2014; Wilken, 1990), and various lines of evidence argue that this was similarly true in the past (cf. Bogaard et al., 2013; Halstead, 2000, 1987; Thurston and Fisher, 2007). These include, for instance, intensification through inputs of human and/or animal labor, crop diversification or switching, complementary trade between distinct eco-climatic zones, incorporation of pastoralist and/or foraging subsistence components, and residential mobility. Such flexibility becomes more tightly circumscribed geographically as population

densities increase and systems of land tenure and usufruct solidify, and more or less tightly circumscribed socially as social/political/economic relationships tie farmers into relationships which place particular demands on production (quantity, type, calendar) and/or alter the availability and scheduling of human and animal labor.

As a result, the geographic variability and distribution of PAgP (both average potential yields and interannual variability therein) can be significant in determining the consequences of climatic changes. The significance of a drop in mean PAgP across a landscape, for instance, might depend on whether productivity were uniformly depressed spatially; a small number of high-productivity areas might suffice for a relatively small and/or flexible population to maintain production. The levels of production which inhabitants must maintain are also critical to the significance of any climate-driven change: high target productivity generally increases vulnerability.

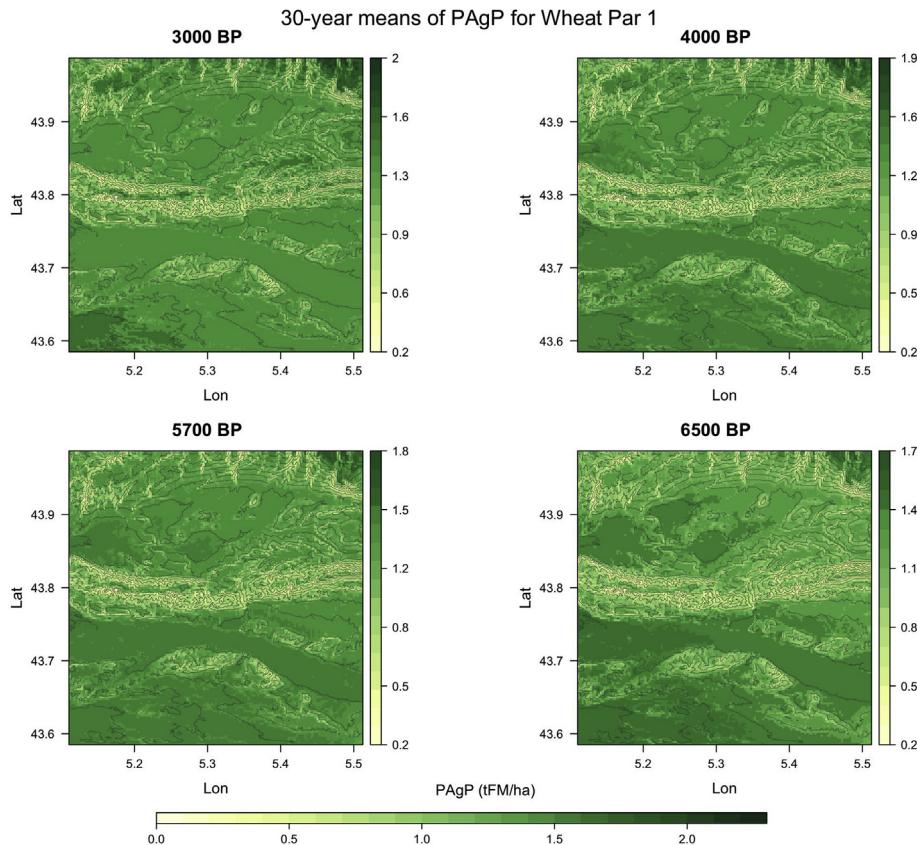


Fig. 6. Per-pixel mean PAgP in tFM/ha for 30-year periods with the high parameterization of wheat (W1), across all four time-periods. 100 m contours derived from SRTM30 DEM.

The difficulty of estimating particular productivities in the past can be sidestepped by examining the ranges and considering the sensitivities of agricultural production. What external and internal factors could drive prehistoric/pre-industrial agricultural productivity up and down? To what was it particularly sensitive? How sensitive was it to climatic shifts, and what kind(s) of climatic shifts had more or less impact (magnitude, temperature vs. precipitation, duration)? How much latitude (i.e., risk buffer) could have been provided by flexible agricultural practices and labor inputs? By developing the means to apply LPJmL to past agricultural productivity at human temporal and spatial scales, we have begun to produce robust answers to those questions.

Although the LPJmL results cannot stand alone as guides to past agricultural productivity – the variability of agricultural productivity is a function not only of environmental parameters but also of agricultural practices, land-use decisions, and labor inputs – they do provide an indicator of *potential* yields. The *significance* of the contrasts in PAgP described here is dependent on a variety of other factors, contingent as much on the target production per hectare for the region's inhabitants, as well as the location and flexibility of agricultural plots, as on the magnitude, character, and duration of the climatic change.

Agricultural practices are sufficiently variable (both diachronically and synchronically) that their interplay with particular climatic conditions for a specific period would constitute a significant research project unto itself, but examining extremes provides a range of possibility. Under a 'high' assumption about intensity of agriculture (W1), even in 4000 BP (the warm/dry extreme) almost all areas maintain PAgP values sufficient to make them viable for subsistence (here defined as producing yields of more than 1000 kg/ha; this is employed as an indicator of the extent of less

productive land rather than a literal measure of viability),⁶ though yields below 1.0 tFM/ha are significantly more widely distributed for 4000 BP (see Fig. 11). Under a low assumption about the intensity of agriculture yields very rarely rise as high as 1.0 tFM/ha (see Fig. 5), suggesting that a) viable agriculture in the region likely necessarily involved some degree of human intervention (W2 assumes minimal intensification – i.e., sowing but not tending plants), and b) intensification may have served to manage risk as well as produce surplus. It is also worth noting that interannual variability in PAgP may have been at least as much of a problem for agriculturalists as any depression in mean PAgP (Abbo et al., 2010 go so far as to argue that in fact yield stability was the critical factor driving early domestication).⁷

Intensification is not the only option: crop selection is another axis of adaptability, as both crop species and particular cultivars or landraces may be selected at least partially with environmental conditions in mind (and flexibility in crop selection may be circumscribed by both subsistence and sociopolitical imperatives). We

⁶ A threshold based on Halstead's (2014, pp. 247–248) ethnographic work in 20th century Greece on what cereal yields could sustain subsistence farmers. This presumes subsistence primarily dependent on agriculture, household needs of approximately 1000 kg/year of grain, and cultivation limited by available household labor to approximately 1 ha/household/year. This value is presumably somewhat elastic, but the contrast between parameterizations varies little as the threshold value changes.

⁷ Note that due to evidentiary limitations we simulate interannual variability based on modern (1951–2005) climatic variability (see Contreras et al., 2018 for details). Interannual variability throughout the Holocene apparently did not always match modern magnitudes (cf. Büntgen et al., 2011), but for most of the Holocene proxy data of resolution sufficient to reconstruct interannual variability is not available.

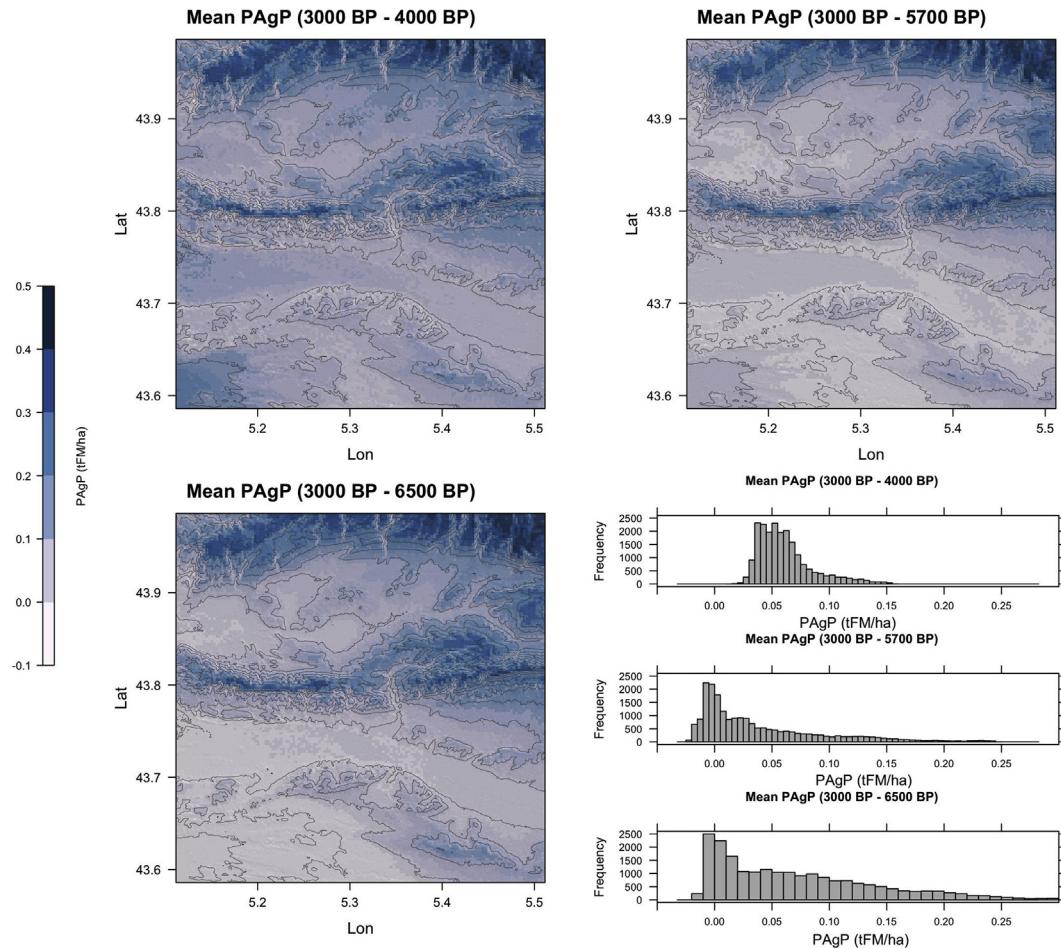


Fig. 7. Differences from optimum conditions: raster algebra illustrating the differences between the 30-year PAgP means for 3000 BP (cool/wet conditions) and the other three time periods.

have focused here on wheat as a proxy for cereal crops generally, with a limited consideration of pulses – but in principle our approach might be extended to other CFTs for which parameterizations have been developed, e.g., olive and grapevine (Fader et al., 2015). At the same time, although our estimates of the range of practice-driven variability do not include further crop diversification and should be considered conservative estimates, archaeological and historical evidence suggests that cereals and pulses have been dominant in Mediterranean subsistence agriculture since the Neolithic (Bouby, 2014; Ruas and Marinval, 1991).

Further axes of adaptability – e.g., labor inputs, cultivation location and residential mobility, individual and communal food storage, non-agricultural subsistence components, reciprocal kin- or community-based exchange, etc. – have not been modeled here, as they are aspects of human behavior and social/political/economic arrangements, requiring distinct modeling approaches. As mentioned above (Section 2), agent-based models are a promising tool for investigating the interplay of these variables. In particular they are able to address the question of how much environmental variability can be managed through changes in subsistence practices and residential strategies, as well as buffered through mechanisms like trade and exchange (cf. Crabtree, 2015; Danielisová et al., 2015; Wilkinson et al., 2007). Whereas agricultural practices can be specified to an extent in LPJmL by varying the

calibration of the input parameters, land-use decisions and labor inputs, as well as feedbacks (legacy effects of land-use, e.g., vegetation changes and anthropogenic erosion) resulting from land-use have to be modeled via other means (e.g., through dynamically linking to an ABM) in order to address the vulnerability and resilience of past agricultural production to environmental changes.

The modeling process highlights the fact that the question of whether Holocene variation was of such magnitude that it inevitably would have impacted inhabitants is in part a question about population, population density, and agricultural practice. Assessing the impacts of past climate change, then, depends also on assessing other factors as well: e.g., how constrained were inhabitants in where they could farm; how much they could intensify; what were their production imperatives; how much labor was available; what technologies, practices, and crops were available to them; what possibilities did they have for buffering shortages through storage and/or exchange? For instance, mean PAgP (Fig. 6) highlights the vital role of precipitation for agriculture in this relatively arid region: yields are most impacted for the 4000 BP warm/dry extreme. Agriculture in the region would have been particularly water sensitive before the introduction of irrigation, which was certainly widespread and significant by the Gallo-Roman Period and likely in at least modest use much earlier (cf. Leveau, 1998).

In addition to such social and technological factors, simple

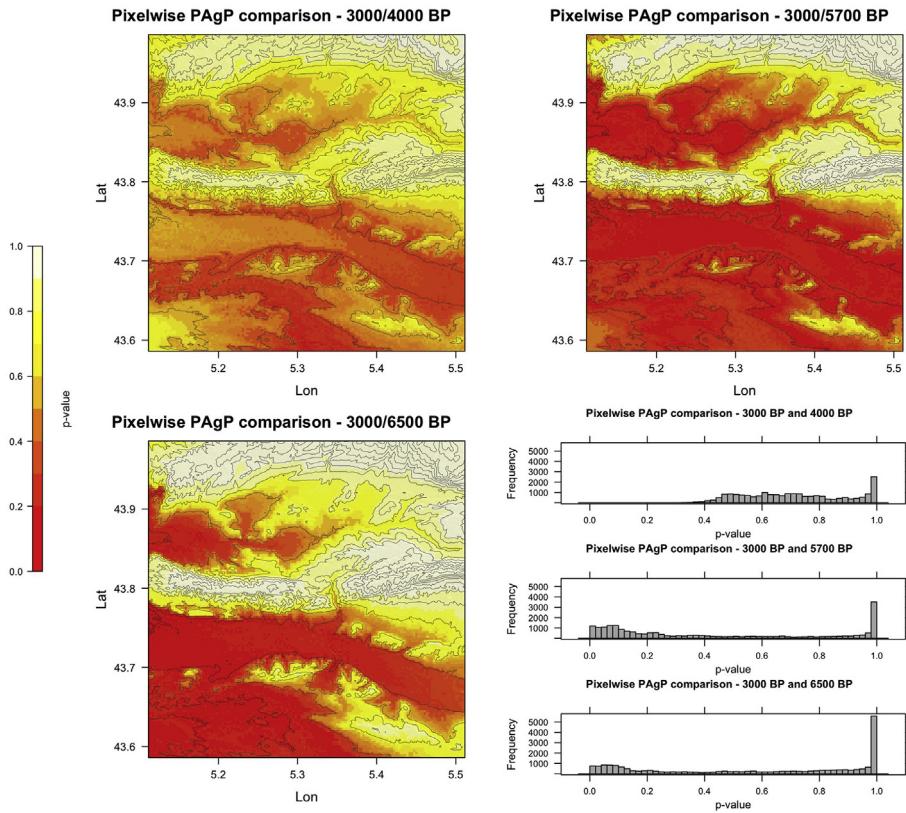


Fig. 8. Pixelwise p-values comparing the 30-year mean PAgP values for 3000 BP and the other three time periods, where p is the probability that the mean values for the 30-year sequences at that pixel are different. Each pixel represents a p -value calculated by Welch's Two Sample t -test, where the two 30-year time-series for each pixel comprise the two samples.

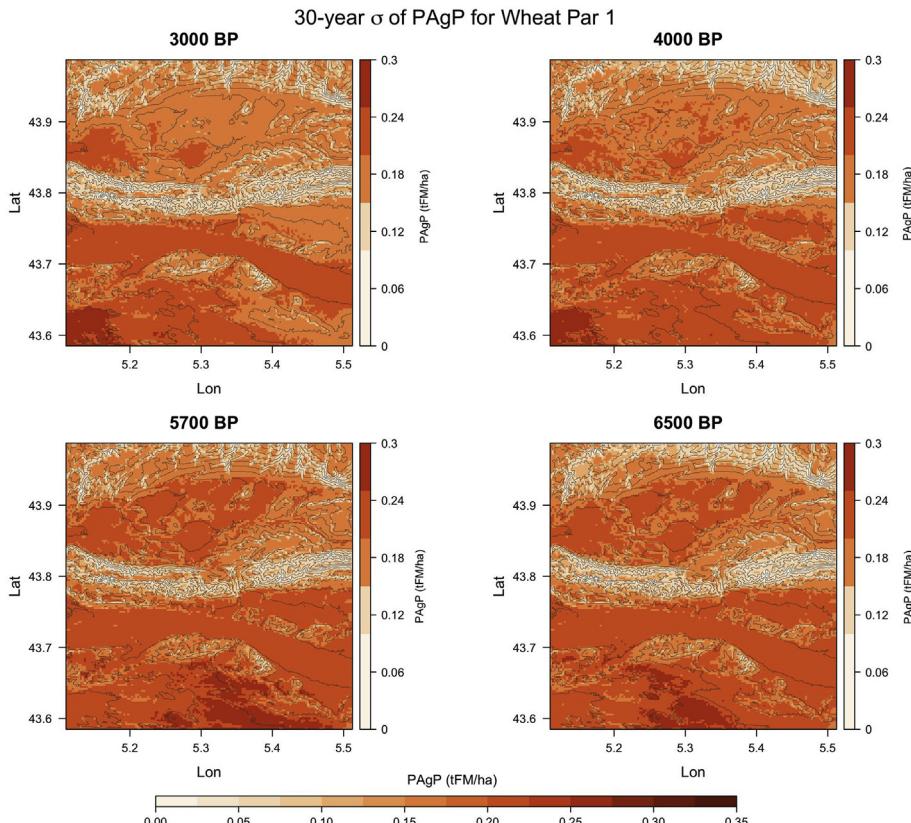


Fig. 9. Per-pixel σ PAgP in tFM/ha for 30-year periods with the high parameterization of wheat (W1), across all four time-periods. 100 m contours derived from SRTM30 DEM.

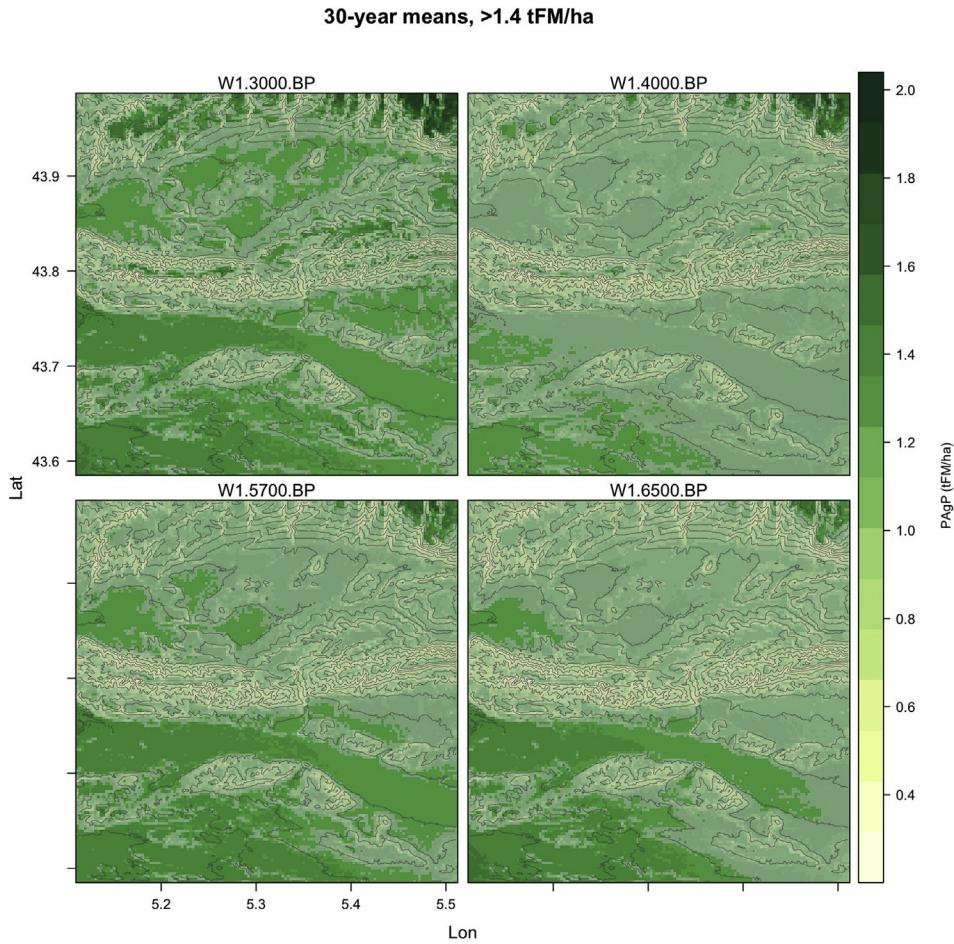


Fig. 10. Spatial distribution of relatively high yields (30-year mean PAgP > 1.4 tFM/ha; other areas are greyed-out) for each period.

subsistence diversification can also be significant. We model here the agricultural consequences of different climate scenarios; the effects of these on societies themselves would certainly depend on the importance of agriculture relative to pastoralism, foraging, exchange, etc. Nevertheless, by establishing a baseline range of agricultural productivities under varying climatic conditions, this modeling provides a firm foundation from which to consider climatic impacts on subsistence production. As we have suggested above, a vital question is *under what societal conditions* climatic changes would have been significant for inhabitants.

7. Conclusions

By developing an approach that simulates the local and annual effects of climatic change on the yields realizable by prehistoric farmers given the array of crops, practices, and strategies available to them, we are able to quantitatively assess the potential impacts of Holocene climate change. Our aim is to improve upon commonsensical explanations and explore the extent to which impacts to subsistence production can be identified as the mechanism linking past climate changes to archaeologically and/or historically visible effects.

We continue to refine the parameters guiding the application of LPJmL to agriculture in the past, and expect that the accuracy and precision of our estimates should improve at least marginally as we do so. At the same time, the number of unknowns involved will

keep uncertainties high, making consideration of ranges of possibility and relative contrasts the most practical and appropriate use of model outputs. Ultimately what is required is some way of relating kg/ha to human experience – i.e., approaching the problem of what these values meant for everyday life. What we are working to understand is the envelopes of possibility within which past inhabitants of the region would have operated – and how those envelopes expanded and contracted over time due to both climate forcing and human activity.

With respect to our case study, the Holocene extremes in this study area in Provence suggest that, a) even in the worst conditions of the Holocene, it would likely have been possible to maintain production at levels above a 1.0 tFM/ha level in most years – but in more spatially restricted areas and with a greater risk of low yields under dry climatic conditions, b) possibilities for relatively high-yield (> 1.4 tFM/ha) agriculture were also spatially circumscribed and variable according to climatic conditions, and c) areas of higher potential yields were more heavily water-dependent, and produced more variable yields. The absence of widespread decreases in PAgP below viable subsistence levels, coupled with the marked increases in PAgP achievable through intensification, suggest that in this environment small-scale agriculture *per se* was resilient to Holocene climate changes. Vulnerability to Holocene climate change was evidently primarily conditioned by social, political, and economic factors.

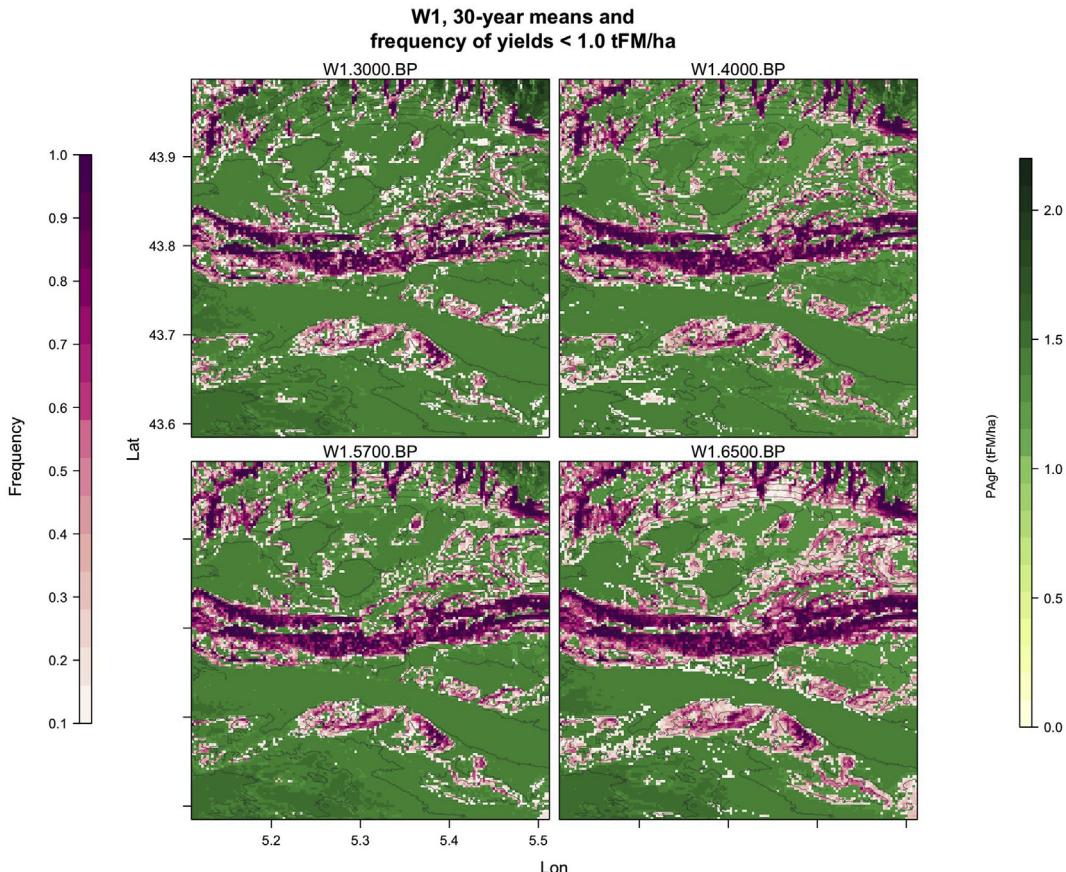


Fig. 11. For W1 in each period, 30-year PAgP means and, for areas in which the frequency of low (<1.0 tFM/ha) yields is greater than .1, frequencies of low yields.

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