Title:

Combining historical and archaeological data with crop models to estimate agricultural productivity in past societies.

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Abstract:

Carrying capacity, population pressure, and agricultural productivity are of central importance to understanding key innovations in human social and cultural evolution. In this paper we outline how crop yield models can be combined with the historical and archaeological information about past societies compiled by Seshat: Global History Database to infer how agricultural productivity and potential have changed over time in different parts of the world. To aid comparative research we focus on developing a method for calculating the carrying capacity of a particular region based on a number of simplifying assumptions. Here we present two case studies demonstrating the calculation of ancient crop yields and carrying capacity for the regions of Latium (Italy) and Oaxaca (Mexico); regions selected to illustrate a number of different features of past agricultural systems, as well as different staple crops. We outline the strengths and weaknesses of this approach and discuss ways in which it could be adapted to address a range of research questions, e.g. relating to archaeological demography and anthropogenic change. Comparison of our reconstructed carrying capacity series with independent estimates of ancient population from these regions demonstrate broadly good agreement with some notable mismatches as well, highlighting a fruitful area of focus for future studies exploring the gap between achieved population and potential carrying capacity.

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Introduction:

Population pressure, agricultural productivity, and carrying capacity have all been regarded as 'Prime Movers' in a number of theories in human social and cultural evolution. These concepts are interdependent but distinct. Carrying capacity refers to the theoretical upper limit on the number of humans who could be sustained within a landscape. Population pressure describes the relationship between the total population and carrying capacity, while agricultural productivity refers to the actual yield of crops realized by agriculturalists.

Population pressure has been invoked as an explanatory variable in the origins of food production (Cohen, 1977), and in the origins of social inequality and stratification (Carneiro, 1970). Agricultural productivity has also been invoked as a prime mover in the emergence of social complexity, with the development of an agricultural surplus allowing the differentiation of society along occupational lines (Johnson & Earle, 2000). These two factors, though, approach the problem of innovation in the human past from opposite directions. In the case of population pressure, it is the scarcity of food resources in a landscape given limitations in carrying capacity that drives humans to innovate in order to survive. By contrast, agricultural productivity as a prime mover may describe periods of great abundance where the ability to produce an agricultural surplus with a fraction of the population enables the development of specialized artists, priests, warriors, etc. Thus, it is important to understand both population pressure and agricultural productivity in order to understand the mechanisms behind innovations in the human past.

Attempts to reconstruct actual population trends in the past have generally focused on the material record left behind by ancient populations. A number of different approaches have been used to try to elucidate the size of archaeological populations, such as the radiocarbon 'dates as data' method (Rick, 1987; French & Collins, 2015), and reconstructions based on site counts and densities of artefacts. These reconstructions based on the archaeological method can give us an idea of relative fluctuations in population size. However, without a good measure of agricultural productivity and, thus, carrying capacity to compare to the demographic data, population pressure itself cannot be understood.

A number of high resolution crop yield models have been developed to provide such estimates, but in most cases are focused on modelling crop yields for modern and future conditions, with less attention given to predicting crop yields in the past. Oyebamiji (2015) derived a palaeoemulator, to hindcast crop yields in the Holocene, up to the present day, back-projecting the LPJmL crop yield model

(Bondeau et al, 2007) for future conditions into the past. Hindcasting crop yield models in this way can provide a useful anchor point for ancient agricultural productivity, but we know that human activity since the Neolithic can dramatically alter crop yields from this baseline level. Currie et al (2015) outlined a method for combining crop yield models with historical and archaeological data in order to predict the crop yields that would result when human agricultural techniques and practices are taken into account.

Here we expand on Currie et al's (2015) methodological work, and outline a method for predicting crop yields in two ancient regions. We combine the results of Oyebamiji's (2015) palaeoemulator, with historic and archaeological information relating to crop yield management in the past, derived from the Seshat Global History Databank (Turchin et al, 2015). We outline the method in relation to two worked case studies, selected to exemplify a range of human land management practices, as well as two distinct staple crops.

Method:

The method combines data from archaeology, history, climatology, and the agricultural sciences to predict crop yields and carrying capacity in the ancient world. Climatological data provides a 'starting point' for analysis, giving spatially delineated crop yield estimates for each time slice. Archaeological-historical data reveals which agricultural practices were employed in each region and at each time slice, while the agricultural data informs us how these practices might have elevated, or depressed, crop yields from the initial 'starting point'.

Simplifying assumptions

Estimating potential agricultural productivity on a global scale and over long time periods is highly challenging. As with all model-based approaches, it is therefore necessary to employ simplifying assumptions. As we are interested in the total availability of calories, rather than the diversity of foodstuffs available, one such simplification is to focus on a single major carbohydrate source for any given region. Previous population estimates for the Oaxaca Valley were based on the major carbohydrate source in Central America, maize (Nicholas, 1989), while other studies modelling carrying capacity for Europe used the temperate cereals of wheat and rye (Turchin, 2005; Scheidel, 2001). The different histories and climates of different regions will mean that a different focal crop may be of interest in each study location, and some locations may make use of more than one major carbohydrate source, for example Japan where barley and rice have both been substantial sources of calories at various points in history (Crawford, 2011).

Climate-based crop modelling

The Lund-Potsdam-Jena managed land model (LPJmL) is a dynamic global vegetation and crop model (Bondeau et al, 2007). While LPJmL was developed to predict future global vegetation patterns under possible climate change scenarios, Oyebamiji et al. (2015) take this framework and establish a flexible and robust emulation technique to predict future global crop yields from climate variables. This approach was modified and adapted in the construction of paleoclimate emulators which are capable of making backward predictions of potential crop yields in the past climate. The palaeoemulator essentially emulates the relationship between climate and crop yields, as seen in the model, and uses this relationship to predict crop yields for past time slices that are not covered by LPJmL. The model can be configured to produce results for both rainfed and irrigated agricultural systems. Projected yields from LPJmL also depend on a parameter that represents the level of management applied. Here we use the lowest value of management input, appropriate in present-day simulations to traditional subsistence agriculture less-developed regions. The crop yield emulator requires detailed information on past climate as input. We produced an estimate of past climate through the Holocene using the statistical emulator of the PLASIM-ENTS climate model developed by Holden et al. (2014). The PLASIM-ENTS emulator was originally constructed to emulate future climate based on simulations of future warming, but given the relatively small amplitude of climate change through the Holocene, error resulting from extrapolation outside of the envelope of the forcing should be small. To convert climate output from PLASIM-ENTS, at approximately 5° to the high spatial resolution required by LPJmL (0.5°), the output was filtered through the ClimGen tool, which applies anomalies to observed high-resolution climatology (Osborn, 2009).

We ran the palaeoemulator for each time step and extracted the 'lowest input' (in terms of management practice) rainfed results for the case study NGAs (Natural Geographic Areas): Latium, and the Oaxaca Valley.

Historical and archaeological data on agricultural practices

The Seshat: Global History Databank is an interdisciplinary project aiming to codify archaeological and historical variables in order to allow comparative analysis of human social evolution (Turchin et al, 2015; François et al. 2016; Turchin et al. 2018). The databank currently features codified information on the past 10,000 years within thirty bounded geographic regions, termed Natural Geographic Areas (NGAs, selected to provide good geographic breadth as well as encompass a range of historical societies, from chiefdoms to empires. The databank currently contains coded data relating to a

number of variables, spanning themes including social complexity and ritual behaviour. Here we are concerned with data pertaining to agriculture-related variables.

In outlining the need for an archaeologically-driven approach to estimating agricultural productivity in past societies, Currie et al (2015) describe features of ancient crop management practices that can be evidenced through archaeological data. Archaeological evidence for the use of nitrogen-fixing crops, for example, may come in the form of the presence of beans or legumes in the palynological record (eg van Joolen, 2003), while the variety of crop species at archaeological sites may indicate multi-cropping and crop rotation strategies. Remnants of ditches and earthworks provide evidence for irrigation works (Leigh et al, 2003). Where available, historical records detailing practices, or artworks depicting cultivation, can supplement archaeological data. In order to quantify how ancient crop management practices would have directly improved crop yields it is necessary to look to modern agricultural studies. Experimental studies from the agricultural sciences provide quantitative measures of how crop yields can be improved through the addition of fertilizer, irrigation practices, and intercropping (Akhtar et al, 2013; Celik et al, 2010; Chapagain & Good, 2015). These quantitative studies provide us with values with which we multiply the palaeoemulator output on a cell-by-cell basis to obtain the estimate of potential yield, after human management. Tables 1 summarizes key modern studies relating to the improvement of wheat and maize yields that are of relevance for the method.

1 Modern experimental agricultural data

Table 1: Cereals, modern experimental studies into yield improvement.

Crop	Technique	Source	Summary
Wheat	Manuring	Zhao et al (2009)	25-year comparison of wheat yields under different manuring systems. Unfertilized wheat (control) yields 65% lower on average than for wheat fertilized with a mixture of farmyard pig manure and with N and P derived from urea and phosphate.
Wheat	Intercropping with pea	Kadziuliene et al (2011)	Experimental work investigating effect of intercropping cereals with pea in Lithuania. Data from 2007, 2008 and 2009. On average the 1000 grain weight is 2% higher when wheat is grown alone, compared to when intercropped with peas. However, on average the individual grain weight of wheat is 14% higher when intercropped with peas, across the three years of the study.
Maize	Polyculture	Gliessman (1985)	Maize-beans-squash polyculture raises maize yields by +66% compared to monoculture.
Maize	Manuring	Celik et al (2010)	Long term experiment looking at soil properties and organic fertilizers in the Mediterranean. Maize yields found to increase by 178% with

			the addition of animal manure, compared to the control group. NB: based on a wheat-maize intercropping system.
Maize	Irrigation	Meng et al (2013)	Potential modelled difference between irrigated and rainfed maize yields of 15.76%

Land suitability/availability

In many cases archaeological and historical evidence attests to the form of fallowing practiced. In order to assess the productivity of the land used, we took data from the UN FAO GAEZ crop suitability classifications. While these land classifications relate to the modern world, they provide a reasonable guide for ranking the productivity of land in a relative manner. We used these land suitability classifications as a guide for estimating the likely length of the fallow period at each patch of land in antiquity (Figures 2 and 6).

Many agricultural developments do not directly influence yield per hectare, but will still increase the total yield within a region. This is because some agricultural practices will increase the amount of cultivable land available. We can count terracing and ploughing among these developments; terracing allows steep land to be cultivated while ploughing technology can allow less fertile soils to be sufficiently turned to enable them to be cultivated. Increasing the cultivable land in this way will increase the total crop yields for a region and in turn increase the overall carrying capacity, but can have no effect on or even decrease per hectare yields since less marginal lands are being cultivated. Land classifications, in terms of modern land suitability for potential agriculture are obtained from the UN FAO GAEZ, and area attributed to each classification ('excellent', 'good', 'moderate') are calculated for each NGA. The total available agricultural land in each NGA at each time slice of interest is calculated on the basis of these classifications. The smallest unit of analysis across the layers is that of the FAO GAEZ data, with pixel-size 89km². For every grid square of area 89km² the total crop yield for that square is calculated through combining the slope, palaeoemulator results, adjustments to crop yield based on agricultural practices, and data on fallowing practices. Where data regarding fallow periods are not available, reasonable estimates based on ethnography are used instead.

Method: Energy Requirements

The United Kingdom's National Health Service recommends that adult females consume 2000 calories a day (1 kilocalorie = 4,184 joules), and that adult men consume 2500 (NHS, nd). While it might seem that energy requirements for hunter-gatherer populations would be considerably greater than for industrial populations, Pontzner et al (2012) observed that total energy expenditure among industrialized westerners averaged 2347 and 3053 for females and males respectively, while pre-

industrial farming populations averaged 2469 and 2855. Thus, the average energy expenditure of pre-industrial farming societies, and relatively sedentary Westerners may not actually be as different as one might expect, especially after body size is taken into account. We therefore selected a value of 2500 calories/day as the typical daily calorie requirement of a preindustrial agriculturalist adult.

Figure 1: Summary of data sources and processes used in the calculation of carrying capacity. Rounded rectangles represent inputs/data sources, rectangles represent outputs, and cylinders represent procedures.

Case Study Results: Latium

The early Neolithic in the Mediterranean region is characterized by the cultivation of domestic wheat and barley, and the herding of sheep and goats (Barnett, 2000) and cattle (Scheu et al, 2015). The Neolithic is first introduced into southern Italy around 6000 BCE, spreading to northern Italy around

200/300 years later (Zeder, 2008). We can summarize the development of cereal cultivation in Latium in terms of six major events of relevance to the models here (Table 2). The first key event in the trajectory of agricultural development in Latium is the introduction of cereal cultivation at 6000 BCE (Zeder, 2008). The next major event is the introduction of the light plough in the Bronze Age at 2000 BCE (Forni, 1997), alongside the introduction of light manuring (Forni, 2000). Both of these practices are likely to have significantly increased the proportion of available land, reducing the requirement for long fallow periods. Rotation of wheat with legumes in order to fix nitrogen appears at 600 BCE, and would raise yields by approximately 14% (Kadziulienė et al, 2011). Around 750 BCE agriculture takes on a more permanent character; with the establishment of permanent fields and an increase in the intensity of manuring to support this (van Joolen, 2003). At 600 BCE the heavy plough is introduced (Spurr, 1986), and at 500 BCE there is an increase in crop rotation, manuring and the introduction of terracing, resulting in an overall increase in the area available for cultivation. A major development occurs at 300 BCE, with the introduction of irrigation systems, as evidenced through the extensive network of aqueducts dated to this era (Cech, 2010). However, it is worth noting that temperate cereals in Italy are unlikely to require irrigation, and irrigation may therefore have only been applied to crops other than wheat.

Table 1: Key developments in the history of agriculture, Latium

Year	Era	Agricultural innovations	Notes on land use
6000 BCE	Neolithic	Cereal farming introduced to Italy (Zeder, 2008)	Shifting cultivation with long fallow periods between use of field, heavy soils make agriculture difficult in some places
2000 BCE	Bronze Age	Introduction of light plough (Forni, 1997), light application of manure to fields (Forni, 2000)	Shorter fallow periods in best quality land, light plough increases land that can be tilled and used for agriculture
750 BCE	Iron Age	Increasing application of manure (van Joolen, 2003)	Shorter fallow periods (“permanent fields”) in better quality land

600 BCE		Introduction of heavy plow (Spurr, 1986)	Shorter fallow periods (“permanent fields”) in better quality land, heavy plough further increases land that can be tilled and used for agriculture
500 BCE	Roman era	Terracing, crop rotation with nitrogen-fixing legumes (van Joolen, 2003), and increased manuring	Intensified land use and further reductions in fallow periods in best land, sloped land becomes available due to terracing
300 BCE		Emergence of irrigation practices (Cech, 2010)	
500 CE	Medieval period	Intensity of agriculture is reduced but technologies and practices are still retained	Potential decrease in fallow period (Partner, 1972; Wickham, 1981) –uncertainty incorporated into estimates

S2.1.2 Cultivable Land: Latium

To assess the distribution of cultivable land within each NGA we looked at modern crop yield data from UN FAO GAEZ suitability index classes for rainfed wheat. Patches within Latium are classified in terms of their suitability for wheat production, from marginal to very high suitability. We regrouped these classifications into ‘high/very high’, ‘good/moderate’, and ‘marginal’. The distributions of these patches are shown in the map in Figure 2. The suitability of the land for agriculture is likely to be a determining factor in the length of fallow period required, and we therefore assume that fallow periods would be shorter in ‘excellent’ land, compared to ‘marginal’ land.

Figure 2: Distribution of land patches according to suitability for low input rainfed wheat cultivation, Latium. Data from the UN FAO GAEZ.

S2.1.4 Raw palaeoemulator results, Latium

To illustrate the effect of climate alone on agricultural yields, prior to human interference, the raw palaeoemulator results for Latium are shown here. Figure 3 depicts the average palaeoemulator output for yields of temperate cereals for all patches within the Latium region. Without human intervention, the crop yields in the region show a steady decline from 9000 BCE to 0 CE, before a slight increase in yield is seen.

Figure 3: Average raw palaeoemulator output for all patches, Latium

Latium: Results

Figure 4: Modelled carrying capacity for Latium.

Figure 5: Spatial variation in wheat yield, 6000 BCE Latium

Carrying capacity in Latium rises slowly from the origins of agriculture to 1000 BCE. Following a shift in fallow period, the carrying capacity dramatically rises at around 500 BCE. At 0 CE, at the beginning of the Roman imperial period, the total carrying capacity for the entire Latium region is approximately 3 million. Historical uncertainty as to the form of fallow system used following the fall of the Roman Empire results in divergent minimum and maximum carrying capacity into the post-Roman era.

A history of agriculture in Oaxaca

Maize agriculture first appears around 5000 BC in Mexico, and the earliest direct dates on maize in Oaxaca specifically come from Guila Naquitz Cave, where the oldest surviving maize kernels date to 4200 cal BC (Benz, 2001). Elsewhere in Mexico, the earliest direct date for domesticated maize is 5100 cal BC (Pope et al, 2001). It is clear that maize agriculture in Mexico has a long history, however it was not the first crop to be domesticated in the country; squash was domesticated shortly before maize, with beans domesticated shortly afterwards. Remains of domestic squash from Guila Naquitz Cave are dated to between 8000 and 6000 cal BC (Smith, 1997). Maize, beans and squash polyculture are vital to modern Mexican agriculture, functioning as a triad that can raise overall crop yields compared to monoculture. The earliest direct date on beans in Mexico is 2300 cal BC from the Tehuacan Valley (Smith, 2001), neighbouring Oaxaca. Thus the apparent sequence of domestication of the three plants is squash, maize, with all three crops cultivated together by 2300 cal BC.

Considering the evidence for the prehistory of agriculture in Oaxaca, key inputs for the model are: the origins of maize cultivation around 4200 BCE and the presence of maize-beans-squash polyculture from 2300 BCE. Earthworks appear at 1400 BCE with the construction of dams, while low-level irrigation is evidenced from between 1000 BCE and 500 BCE. Further earthworks appear at 300 BCE with residential terracing and extensive irrigation technology.

A landmark study comparing simulated maize yields to recent experimental and indigenous-led agricultural yields in the Southwestern United States (Bocinsky & Varien, 2017) highlighted the extent to which maize yields can be highly variable, from year to year, and between patches within a small locale in the same year. Despite the use of local indigenous knowledge to select patches for farming, and the application of indigenous farming techniques, such as deep-planting of maize seeds, and the use of 9 different varieties of corn, experimental maize yields were very low in most clusters and patches, with high yields occurring in far fewer patches. Yields in the experimental patches tended towards zero, but with very high variance. While the Southwestern United States is a very different landscape to Oaxaca, we should be mindful of the high degree of variance in maize yields indicated by Bocinsky & Varien (2017).

Oaxaca Cultivable Land

In terms of available cultivable land, the Oaxaca Valley can be divided into three zones, ranked from marginal to excellent. Very few patches are ranked as 'marginal'.

Figure 6: Distribution of patches according to land quality, Oaxaca. Data from the UN FAO GAEZ.

S2.3.3 Palaeoemulator results

Figure 7: Average raw palaeoemulator output, all patches, Oaxaca

Maize agriculture first evidenced in Mexico around 5000 BC, and the earliest direct dates on maize in Oaxaca specifically, come from Guila Naquitz Cave, where the oldest surviving maize kernels date to 4200 cal BC (Benz, 2001). Interestingly, the raw palaeoemulator yields (Figure 7) indicate that a trough would be seen in maize yields, without human intervention, at around 5000 BC, based on the palaeoclimate data alone. Is it possible that a short-lived climatic downturn from 5000 to 2000 BC forced ancient people to turn to cultivation in this period?

Table 3: Agricultural history of Oaxaca

Date	Era	Agricultural Innovation	Notes on land use
4200 BCE	Palaeolithic/Palaeoindian	Start of maize cultivation (Benz, 2001)	

2300 BCE	Archaic	Maize-beans-squash polyculture possible after beans finally domesticated at 2300 BCE (Smith, 2001)	Positive impact on maize yields. Reduction in fallow period.
1400 BCE	Tierras Largas	Earthworks/terracing (Leigh et al, 2013)	Increase in cultivable land. Positive impact on total yields within NGA.
500 BCE/ 1000 BCE	Monte Alban	Low-level irrigation (date uncertain) (Kirkby, 2013)	Positive impact on maize yields.

Figure 8: Modelled carrying capacity for Oaxaca.

Figure 9: Spatial variation maize yield, Oaxaca Valley, 0 AD

Carrying capacity in Oaxaca increases only slightly following the introduction of the three sisters polyculture system at 2300 BCE as modelled here. Instead it is irrigation, introduced between 1000 and 500 BCE that most dramatically affects the carrying capacity of the region. Inclusion of the calories obtained from beans and squash, as part of the polyculture triad, would substantially raise the carrying capacity from 2300 BCE.

Discussion and Conclusion

In this paper we have presented a novel method for inferring the carrying capacity, population pressure, and potential agricultural productivity of past human societies. The case studies covered in this paper provide an illustration of the method and begin to demonstrate how we can use such data to make comparisons between different regions and time periods, to assess the role of population pressure and productivity in social development.

Here we have focussed on estimating carrying capacity and potential productivity, rather than actual historical yields. This is important to bear in mind when comparing the estimates from this model with estimates of past population sizes. For example, from our estimates of the underlying potentially productivity and available techniques we have estimated the carrying capacity of Latium during the early Roman Empire to be approximately 7 million people. However, the actual population at this time could potentially have been much larger. Food is likely to have been imported from elsewhere within the Roman Empire and, indeed, regions outside of Italy such as Egypt and North Africa are noted by historians as being 'breadbaskets' supplying grain and other produce (notably grapes and olives in the form of wine and oil) (Hoyer 2018; Venit, 2012). An interesting effect of our approach is that acquiring food through trade or other means (taxation of imperial provinces, for instance), trade or any then estimates based on the crops grown just within the boundary of a given NGA are likely to be underestimates of the actual potential carrying capacity.

Conversely, our method may overestimate population size when people have not cleared all available land, or are using land for purposes other than growing carbohydrate staple crops. Indeed, our models suggest that a population of 1 million could easily be supported by food sourced from within Latium alone, without even drawing on resources from across the Empire and beyond, yet historical estimates of the population of Rome at the height of the Empire range from 440,000 (Storey, 1994) to 1,000,000 (Brunt, 1971), vastly undershooting our estimated carrying capacity. Similarly, for Oaxaca, our carrying capacity estimate of around 250,000 people is ten times greater than that estimated by Kirkby (1973) on the basis of corn yield data, and in even greater excess of estimates based on archaeological data alone, suggesting that our carrying capacity estimate is either too generous, or is far from being achieved in Oaxaca. These mismatches belie any simple analysis equating actual, realized historical populations from the carrying capacities estimated by our model. However, these mismatches themselves raise important questions about the dynamics of social and economic development in these NGAs; for instance, in Latium the Roman imperial period was marked by incredible urban growth and the development of large, unproductive estates by imperial elites, reducing the amount of potentially productive land that was actually utilized (Bowman and Wilson 2011). Further, our

estimates do not account for the significance of the non-human population that was fed on these same agricultural resources, such as horses used in cavalry warfare and draught animals; horses in particular have been shown to play a critical role in social development, and should be more explicitly included in studies assessing the use of a given region's agricultural yields (Turchin, 2009). We should consider also the high degree of variance seen in maize yields under traditional agricultural techniques (Bocinsky & Varien, 2017). It may be that Liebig's law of the minimum is applicable; with the potential for extreme variability in maize yields within a small geographic area and from year-to-year, and the maximum population that could be supported overall would not necessarily correspond to the maximum population that could be supported in a specific year of plenty.

Our carrying capacity estimates are most likely to align with actual population in cases where most of the available arable land is being exploited and there is not an imbalance in the amount of calories flowing into and out of the NGA. Our method is flexible enough so that in future these relationships and flows of goods can be explicitly examined to more precisely estimate realized population size.

In addition to providing information on demographic trends and socio-cultural dynamics, our methods provide a realistic estimation of a region's carrying capacity, which provides a window into population pressure and social stability in the past. By comparing carrying capacity to realized population size, as evidenced through other methods and data, we can get a measure of population pressure (the difference between carrying capacity and population). Such a measure is important for testing hypotheses about how societies respond to resource stress, where such stress is viewed as a prime mover in social conflict (e.g., Zhang et al, 2007), and may also help in assessing issues relating to the sustainability of socio-environmental systems in the past (Diamond, 1994).

While we have provided quantitative estimates of carrying capacity, at this stage it is important to treat these "absolute" values with caution. However, they provide quantitative estimates of possible carrying capacity that may allow us to compare the productive potential of different NGAs, or the relative stress on resources at any particular point in time within an NGA by comparing trends in carrying capacity to trends in population size. Our method also allows for inter-regional comparison of a kind that is not possible with alternative methods in archaeological demography, such as the 'dates as data' method (Rick et al, 1987; Tallavaara et al, 2010; French & Collins, 2015).

It is important to acknowledge the many challenges that are faced when trying to systematically estimate features of past societies across space and time. Due to the nature of the historical and archaeological records there are many gaps in our knowledge of past societies, and certain biases in our records of the past. While we have to work with the available information, our general strategy is to make as clear as possible the assumptions involved in defining and coding these variables, and other

stages in the modelling process, and be aware of potential limitations and sources of error. This allows other researchers to engage with the different aspects of the model and suggest improvements and refinements; accordingly, we are ready and willing to update our understanding and incorporate new information. The Seshat Project engages with academic historians and archaeologists, who are involved in the process in a number of ways, from helping design the codes being used, through to checking the data and helping with interpreting the patterns that emerge. Notably the process and our approach to data collection allows us to incorporate disagreements between academics about their interpretation of the past (see Turchin et al. 2018 for details). More could be done in the future to incorporate uncertainty. For example, the figures show a number of “step-like” changes in carrying capacity, which are a result of treating the estimated starting point of an innovation as certain. In future we aim to incorporate uncertainty into the analysis, for example by plotting multiple trajectories where the start date of an innovation is uncertain, or the magnitude of an agricultural improvement is unknown. Likewise, Bocinsky & Varien (2017), in highlighting the extreme variability of maize yields, call for crop yield models to approximate this variability, and we may treat the extreme variance seen in maize yields under traditional agriculture as another form of uncertainty that we should try to incorporate into future iterations of the model.

Modelling the past over long periods of time and large geographic regions also involves making a number of simplifying assumptions. Here, for example, we have made the decision to model carrying capacity based on calories obtained from a primary carbohydrate staple. This assumption could be challenged in Oaxaca and Latium, however, as other crops have also been prominent in traditional agricultural practices (i.e. olives and grapes in Latium and Mediterranean cultures more generally, and beans and squash in Oaxaca and other parts of Mesoamerica). Modelling the cultivation of these other crops more explicitly would require extra assumptions and information about how much land was assigned to different crops, and potentially what different practices were employed for different crops. Given that land devoted to other crops would not be available for growing our focal crop then the actual change in estimated yield is not likely to be great, though this remains an assumption in need of empirical testing. There are further complications involving polyculture than just different crop yields. Notably, in the Mexican polyculture beans-squash-maize triad the different plants interact such that productivity in each is increased by growing them together. In our Oaxaca case study we have taken this into account by adjusting the yield based on the overall improvement in yield across all three crops. In other words, we factor in the effect of polyculture without explicitly modelling the details of each component part.

Another potential criticism of our approach is that we have focused on the energetic content of food and not considered other aspects of nutrition, such as protein, vitamins, and minerals that are also

required to live and affect the health of a population. In particular, a more realistic model could explicitly model the sources of protein exploited by societies (e.g. wild animals, certain crops, and domesticated animals) and the trade-offs involved in assigning land to different functions in order to achieve sufficient levels of protein. Such a model would again involve several more assumptions and increase the amount of information that would need to be collected and incorporated into the model. All models involve a trade-off between realism and tractability. Given the myriad challenges faced in estimating potential agricultural productivity in the past we feel that it is important to start off with a simple model that is understandable. The model presented here can be built upon in future; different assumptions can be explored and the effects of adding in more complexity can be investigated.

One major advantage of our approach is that we are able to extend climate models into the deep past. Climatic explanations for events in human history have proven popular in recent years (e.g. Kennett et al, 2014). Our method allows us to assess the relative contributions of climate and agricultural innovations to changes in crop yield over long time periods. Interestingly, we find that changes in carrying capacity due to climatic changes and their effects on crop yield are relatively small. Changes in agricultural practices, at least in the way we have modelled them here, produce more substantial changes in yields, and by extension carrying capacity. This should not be taken as saying that climate is unimportant for understanding changes in socioenvironmental systems. Small changes in climatic conditions may push productivity down below that needed for current population levels, and could therefore lead to substantial deaths, migration, or changes in socio-political strategies in order to secure extra resources (e.g. establishing trade connections, or invading neighbours). Furthermore, we do not explicitly model shorter term changes in climatic changes and therefore miss higher frequency fluctuations in climate and weather that may have important consequences. Indeed, one assumption of our approach is that carrying capacity can be meaningfully inferred based on the mean climatic conditions. However, if conditions vary over shorter time scales then carrying capacity may be more closely linked to minimum conditions. This issue can be explored further as the methodological approach is developed in the future, and highlights the need to focus scholarly effort on refining the temporal resolution of paleoclimatic models.

In using these data in future statistical analyses, we can also explore whether there are interactions with other environmental variables as would be predicted if there were systematic biases in carrying capacity estimates. Currently, using average conditions is justified based on the data available at the moment and the fact that we apply this consistently to all our world regions. Our initial crop yields are determined by the LPJmL paleoemulator (Bondeau, 2007; Oyebamiji et al, 2015). This has been an important first step, but future models could improve on this through extending this approach so that it produces a range of estimates based on the various sources of uncertainty, primarily the past climate

reconstructions and the modelled relationships between climatic inputs and yields. In future it will be valuable to assess results produced by different crop models and also different reconstructions of paleoclimatic conditions. Future iterations of our approach will incorporate data on changes in the productive potential of crop types themselves as they have been shaped by artificial selection over the years. Recent experiments comparing landraces with wild progenitors suggest that domestication itself may have increased yields by around 50%, principally a result of increased plant size and reduced chaff (Preece et al. 2016). Currently most crop models are designed by simulating crop production under modern conditions and using modern cultivars. An ideal scenario for a future crop model would be to incorporate the kind of historical factors outlined in this paper directly into the simulation process. Recent work by Turchin et al (2020) takes crop yield modelling in this direction, by including the effects of crop domestication into the model.

Overall the method outlined here can be readily applied to any region or time period of interest and result in estimates of the productive potential of past societies. We have developed this method primarily for testing hypotheses about human cultural and social evolution, and in particular for investigating the emergence of large complex societies over the last 10,000 years. Initial results from the study regions of Latium and Oaxaca correlate reasonably well with archaeological and historical evidence for settlement intensification and social complexity. Our approach is useful for a variety of other areas of comparative research. For example, this method allows for direct comparability between regions and time periods in a way that is not possible with other methods in archaeological demography, due to the fact that the relative population trends recreated from the changing proportions of artefacts over time within regions do not allow for inter-regional comparisons (French & Collins, 2015). Our method of incorporating archaeological and historical data explicitly into our estimates can be built upon in a number of ways, and may be particularly valuable in addressing other questions surrounding human history such as the long-term effects of anthropogenic changes on the environment, which currently rest on very rough estimates of global population trends and rather opaque means of translating these estimates into changes in agricultural practices and land cover (McEvedy & Jones, 1978). In general, it is desirable to see closer connections between earth system scientists on the one hand, and expert historians and archaeologists on the other, and to produce estimates of the past that incorporate the various existing sources of uncertainty. Reconstructing trends in ancient food production, carrying capacity, and population pressure over the long *durée* can provide social scientists with an ideal laboratory in which to test exciting theories relating to human social evolution. The approach outlined in this paper hopefully proves a proof-of-concept that can aid

comparative analyses and help us understand more about historical trends in agricultural productivity and population.

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