Agricultural productivity in past societies: toward an empirically informed model for testing cultural evolutionary hypotheses

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current or future conditions. In this paper, we argue for a "bottom-up" approach that estimates productivity, or potential productivity based on information about the agricultural practices and technologies used in past societies. Of key theoretical interest is using this information to estimate the *carrying capacity* of a given region, independently of estimates of population size. We outline how explicit crop yield models can be combined with high quality historical and archaeological information about past societies, in order to infer the temporal and geographic patterns of change in agricultural productivity and potential. We discuss the kinds of information we need to collect about agricultural techniques and practices in the past, and introduce a new databank initiative we have developed for collating the best available historical and archaeological evidence. A key benefit of our approach lies in making explicit the steps in the process of estimating past productivities and carrying capacities, and in being able to assess the effects of different modelling assumptions. This is undoubtedly an ambitious task, yet promises to provide important insights into fundamental aspects of past societies, and will enable us to test more rigorously key hypotheses about human socio-cultural evolution.

Agricultural Productivity in Past Societies: Toward an Empirically Informed Model for Testing Cultural Evolutionary Hypotheses

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Abstract

Agricultural productivity, and its variation in space and time, plays a fundamental role in many theories of human social evolution. However, we often lack systematic information about the productivity of past agricultural systems on a scale large enough to test these theories properly. The effect of climate on crop yields has received a great deal of attention resulting in a range of empirical and process-based models, yet the focus has primarily been on current or future conditions. In this paper, we argue for a "bottom-up" approach that estimates potential productivity based on information about the agricultural practices and technologies used in past societies. Of key theoretical interest is using this information to estimate the *carrying capacity* of a given region independently of estimates of population size. We outline how explicit crop yield models can be combined with

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Introduction

For the vast majority of our evolutionary history, humans subsisted by hunting animals and gathering plants. Around 12,000 years ago, we began to take a more direct role in the process of food production, domesticating animals and cultivating crops in order to meet our nutritional requirements (Mazoyer and Roudart 2006). This subsistence revolution is thought to have occurred independently in a limited number of places (a list would include *at least* the Fertile Crescent region of the Near East, China, Mesoamerica, South America, and New Guinea). This new way of life is arguably the most important process in human history, and its dramatic consequences have set the scene for the world we live in today. Agricultural productivity, and its variation in space and time, plays a fundamental role in many theories of human social evolution, yet we often lack systematic information about the productivity of past agricultural systems on a scale large enough to test these theories properly. Here, we outline how explicit crop yield models can be combined with high quality historical and archaeological information about past societies in order to infer how agricultural productivity and potential have changed temporally and geographically.

The paper has the following structure: First, we introduce the ways in which agriculture is involved in theories about human social evolution, and stress the need to scientifically test between competing hypotheses. Second, we outline what information we need to model about past agricultural systems and how potential agricultural productivity and carrying capacity can provide a useful way of comparing societies in different regions and time periods. Third, we discuss the need for a systematic, comparative framework for collecting data about past societies. We introduce a new databank initiative we have developed for collating the best available historical and archaeological evidence. We discuss the kinds of coded information we are collecting about agricultural techniques and practices in order to inform our modelling efforts. We illustrate this task by presenting three short case studies summarizing what is known about agricultural systems in three different regions at various time periods. We discuss the challenges confronting this approach, and the various limitations and caveats that apply to the task at hand. Fourth, we outline how we can combine a statistical approach of modelling past crop productivity based on climate inputs with the kind of historical information we are collecting.

The Role of Agriculture in Theories of Human Social Evolution

The development of agriculture and the ways it has spread and intensified are fundamental to our understanding of the human past. Agriculture plays a central role in many important and influential hypotheses about human history. For example, authors such as Renfrew, Bellwood, and Diamond (Diamond and Bellwood 2003; Renfrew 1992; Bellwood 2005; Bellwood, Renfrew, and Research 2002) argue that early agricultural societies enjoyed a demographic advantage over hunter-gatherers, which fueled a series of population expansions resulting in agriculturalists spreading out to cover much of the world, taking their culture and languages along with them. At the beginning of the European age of exploration, agricultural societies had pushed the distribution of forager populations in the Old World to only those places that were marginal for agriculture. Widespread forager populations were present in the Americas and Australia, but these too eventually gave way to agricultural populations of European origin. Agriculture raised the carrying capacity of the regions in which it developed and spread, leading to people living at higher densities with a more sedentary way-of-life than was previously possible.

However, the development of agriculture did not stop there. Further improvements in agricultural technologies and techniques, and processes such as artificial selection further raised the productivity of agriculture and the size of the population that could be supported in any one region. These improvements ultimately enabled humans to live in large urban conglomerations with extremely high population densities. Influential models of agricultural innovation, starting with the work of Esther Boserup (Boserup 1965), argue that advances occur in response to increases in population, and the subsequent decreasing availability of land. This drives farmers to invest more labor in producing food. In other words, there is feedback in the system that leads to the increasing intensification of agriculture. These processes of intensification, whatever their cause, can occur in a number of different ways (Kirch 2000) and have had important consequences. From the fields and hedgerows of Northern Europe to the mountainside rice terraces of the Ifugao of the Philippines (Conklin 1980), through to the deforested slopes of Easter Island (Stevenson et al. 2006), agricultural populations have dramatically altered the landscapes around them.

Agriculture is central to many theories about how larger-scale complex societies evolved. Under functionalist views of social complexity more productive agricultural systems allowed for 'surplus' production, and enabled a more extensive division of labor (Johnson and Earle 2000). This surplus production allowed for individuals who did not grow their own food, enabling the creation of specialized managers and rulers, and *occupational* artists and artisans. It is argued that this division of labor increases efficiency and coordination, enabling more complex societies to out-compete less complex societies either directly or indirectly. Under this view, not only is a rich resource base a necessary condition for the emergence of complex societies, but it is also a sufficient one. If this is correct, it follows that differences in agricultural productivity can explain why some regions developed more complex societies than others.

Changes in agricultural intensity have also been linked to changes in the ritual and religious life of human groups. It is argued that hunter-gathers and early agriculturalists, who lived in small groups and faced high risks from hunting of large animals, tended to participate in dysphoric, "imagistic" rituals that, although rarely experienced, are typically emotionally intense (Atkinson and Whitehouse 2011; Whitehouse 2004). Such rituals act as a mechanism for creating social cohesion via 'identity fusion' (Swann et al. 2012). A greater dependence on agriculture led to increased group sizes, and required different forms of cooperation and coordination in order to successfully produce food. New ritual forms developed that were organized around daily or weekly cycles but with less intense emotional experiences. It is argued that this 'routinization' enabled strangers to recognize and identify with others as members of a common in-group, enabling trust and cooperation on a hitherto unknown scale (Whitehouse et al. 2013; Whitehouse and Hodder 2010).

It is clear that agriculture is of fundamental importance to studies of the human past. The ideas outlined above represent just a flavor of the ways agriculture and agricultural productivity enter into our understanding of the long-term patterns and processes of human history. Importantly, these ideas are hypotheses that require testing against other plausible narratives. For example, it has been argued that an important factor driving the evolution of complex societies was intensive forms of conflict between nomadic pastoralists and settled agrarian societies that selected for increasingly larger and more cohesive societies (Turchin et al. 2013; Turchin 2009). Thus, complex societies tended to emerge on the border of the Eurasian Steppe and spread out from there. Under this view, agriculture is seen as necessary but not sufficient to explain the observed variation about where and when such societies developed. When attempting to understand the past we should seek to test between competing hypotheses, rather than simply focusing on a single favored idea. In order to do this, it is important to have relevant data on past agricultural systems and their productivity and potential. These systems exhibit a great deal of variation, and are of varying levels of intensity. To enable more direct comparisons across different regions and time periods, it will be important to have explicit models that translate different agricultural systems across space and time into a common currency. This will allow us to perform statistical analyses so that we can directly test alternative hypotheses.

Agricultural Productivity and Potential in the Past

The relationships between crop yields, weather and climate have been the focus of a great deal of attention in the Earth system science literature. This is due to concerns about securing food supplies for our growing populations and the potential challenges that climate change poses (Oyebamiji et al. 2015). Most studies have been concerned with establishing the current relationships between climate and crop yields, or making projections about changes in crop yields due to future climate change rather than extending this approach back into the past. Where historical information is used, it tends to be on a relatively recent time scale (Ramankutty and Foley 1999). Recently, researchers have attempted to infer the location and intensity of agricultural production during the Holocene on a global scale (Klein Goldewijk et al. 2011; Kaplan et al. 2011). These estimates are ultimately derived from estimates of past population sizes (e.g., (McEvedy and Jones 1978) and make assumptions about how human populations use land for agriculture. Although such studies should be applauded for their ambitious scale, they have a number of features that make them less-than-ideal for our purposes. First, in order to test certain theories it is desirable to separate out *achieved* production and population from *potential* production and population (i.e., the population that could theoretically be supported but is not, for whatever reason). A number of interesting hypotheses about human social and political evolution invoke "population pressure" as a key variable in causing changes in human societies (i.e., how close actual population is to potential population, and the stresses induced when there is competition for land and resources). For example, demographic-structural theory (Turchin and Nefedov 2009), argues that state instability and societal collapse is a result of the pressures on resources from population growth, which, in turn, leads to population decline. Boserupian models of agricultural change, mentioned above, see agricultural innovations themselves as resulting from population pressure. Second, this approach does not make full use of the historical and archaeological information about past agricultural systems that could potentially inform estimates of productivity. Finally, the data on past population are fairly rough estimates, and are typically made at the coarse-grain level of a province or whole country (Boyle et al. 2011). There is always some degree of uncertainty associated with these estimates, and unless handled with care, such an approach can indicate a false level of precision, given the data that are being used as inputs.

Estimating Carrying Capacities from the Ground Up

In order to understand the impact of agriculture and increasing productivity on human societies, we need a "bottom-up" approach that estimates productivity or potential productivity independently of population size. Of key theoretical interest is using this information to estimate the *carrying capacity* of a given region. For our purposes, we define carrying capacity as the maximum human population size that can be supported in a given unit of space. It is a function of the physical and biological characteristics of the region being examined and is also dependent on the types of agricultural technology and techniques possessed by the population that affect the productivity of the crops grown in that region. Carrying capacity is something that can be calculated (at least theoretically) across agricultural systems and, therefore, facilitates comparisons between different time periods and regions. Furthermore, it is an important variable because it enables us to compare the actual population to the size of the population that could possibly inhabit such a region, including cases where there is a substantial mismatch between these two estimates. This can provide a measure of the population pressure a society experiences. Mismatches could also reflect cases where a surplus is produced in order to guard against shortfalls in some years or where a substantial proportion of productivity is diverted to elite members of society (Ladefoged, Lee, and Graves 2008). In the former case, we would expect actual population and a measure of carrying capacity that took into account annual fluctuations to converge over longer time periods, whereas this would not be the case in the latter example. The measure of carrying capacity can include technological or other cultural features that affect crop productivity. Therefore, over suitably long time periods and geographic scales, this estimate of carrying capacity will also provide a measure of *relative* agricultural productivity. In other words, in the absence of direct assessments of actual productivity, this measure is still likely to be informative about which regions and time periods were more productive than others. Such a measure is also extremely useful for testing many hypotheses about socio-cultural evolution.

Previous work has attempted to calculate carrying capacity for hunter-gatherers (Binford 2001), which is a somewhat more straightforward task than for agriculturalists. This is because foragers' sources of food are determined primarily by external climatic conditions and other characteristics of the physical environment, such as "unearned" sources of water, including rivers, which enable plant growth in otherwise arid environments (Birdsell 1953).[1] Although such

[1] It is important to point out that there is a great deal of variation between hunter-gatherer societies in terms of the technologies they have developed and the subsistence strategies they employ. For example, societies that exploit highly concentrated fish stocks or

climatic and environmental considerations are obviously important for agriculturalists, calculating agricultural carrying capacity has a number of added complications (Figure 1). One such factor is the characteristics of crops (i.e., how they respond to external factors such as temperature, water availability, and soils). Hunter-gatherer population densities tend to be highest in tropical regions with high temperatures and greater amounts of rainfall, i.e. where net primary production is high (Birdsell 1953; Binford 2001; Currie and Mace 2012). On the other hand, large agricultural populations can be supported by grain crops derived from wild grasses. Cereal productivity, and, therefore, agricultural population density, tends to be greatest when annual patterns of rainfall create seasonal climates that allow grains to dry properly (Bellwood 1997), which is generally (but not always) at higher latitudes. For example, in island Southeast Asia, rice productivity is highest in regions such as Java, where monsoon conditions create a more distinct dry season (Bellwood 1997). Humans are also niche constructors *par excellence* (Kendal, Tehrani, and Odling-Smee 2011), and agriculture is probably one of the most dramatic representations of our ability to substantially modify our environment and, thus, reduce or ameliorate the impact of external environmental factors. Artificial selection (either intentional or unintentional) has also been a key process in improving crops and increasing yields over time, so having information about historic cultivars and varieties is of great importance. In addition to these crop characteristics, another important determinant of agricultural productivity is the level of agricultural technology and the specific agricultural practices that enhance productivity, which have varied dramatically in time and space. We return to this issue below.

The fundamental idea behind this approach to estimating carrying capacity is to construct a function that predicts crop productivity based on a variety of theoretically informed inputs, the parameters of which will then be estimated and empirically validated. This estimate in terms of energy can then be converted into a population estimate based on an understanding of the energy requirements of human populations (Food Agriculture Organization of the United Nations 2004; Figure 1). In both cases, calibration and validation will require historical information about past crop productivities, ideally with as broad a geographic and temporal distribution as possible. Figure 2 shows examples of changing productivities of two cereal crops (rye and wheat) in two regions in Europe (various places in England, and East Flanders, Belgium). In both cases, productivity has increased, but to what degree these changes are due to changes in climate, technology, or genetics needs to be assessed.

vegetation can live at very high population densities relative to big-game hunters (Johnson & Earle 2000, Binford 2001).

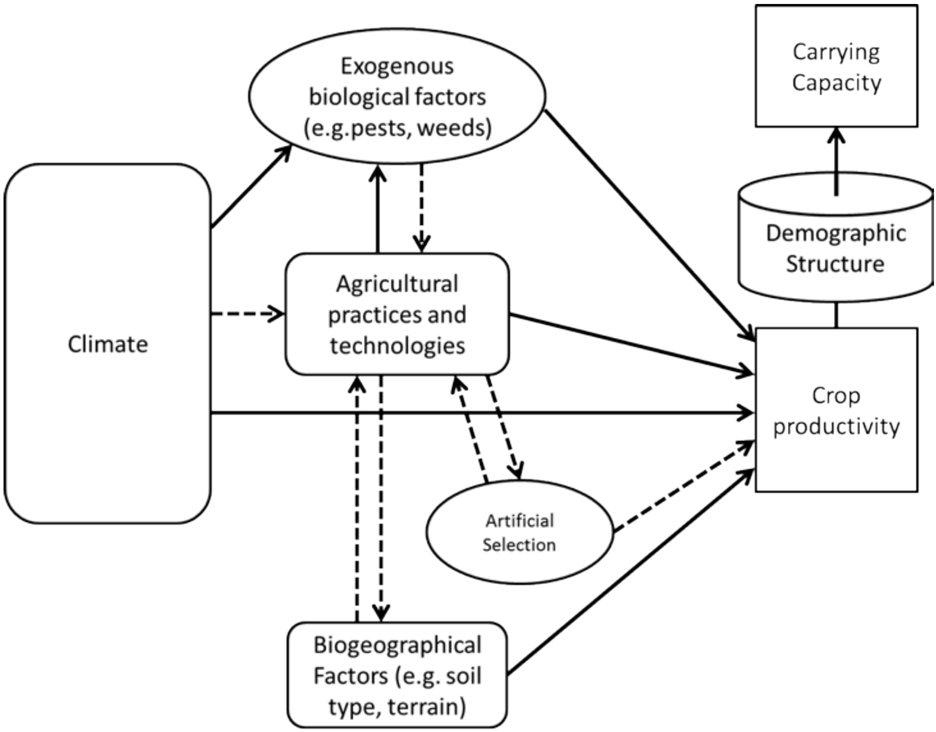

Figure 1. Schematic representation of the factors discussed in this paper that determine crop productivity and, ultimately, carrying capacity. Rectangular boxes indicate the outputs we want to assess, which are the productivity (yield/unit area) of a particular crop species and the carrying capacity of a given region. Going from crop productivities to carrying capacity can involve making certain assumptions about the demographic structure of a population. Rounded rectangular boxes represent factors that we can directly estimate and incorporate into models of crop productivity, whereas ovals represent factors that are incorporated more indirectly. For example, pests and weeds may be assumed to be constant problems that are only ameliorated if certain agricultural practices (e.g., weeding) are in place; artificial selection can be incorporated through estimating or inferring improvements in yields over time. Solid arrows represent the direct effect of some factors on others at a given point in time (e.g., certain agricultural practices improve crop yields). Dotted lines represent the effects of some factors on others over time (e.g., climate affects what agricultural practices are developed).

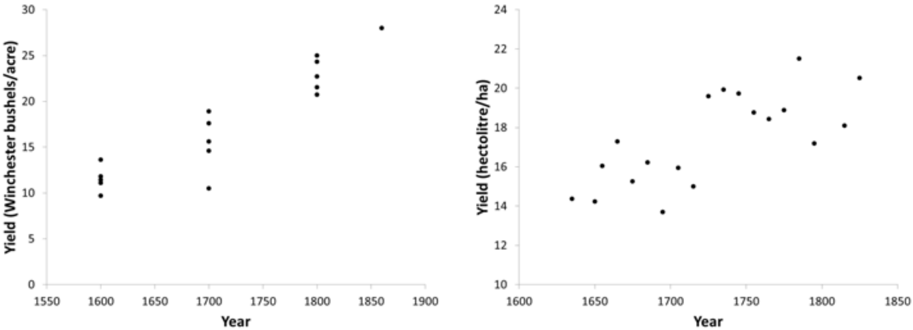

Figure 2. Historical estimates of yields from two different crops in two different regions of Europe. The right-hand side shows yields of rye (hectoliters per hectare) in the East Flanders Region of Belgium (Dejongh 1999), while the left-hand side shows yields of wheat (Winchester bushels per acre) in various regions of England (Clark 1991). Both regions show an increase in yields over the time period covered, which could be due to a number of factors including climate change, genetic improvements due to artificial selection, or improved agricultural techniques and technology.

Obviously, estimating potential agricultural productivity on a global scale and over long time periods is not an easy task. In order to make this task manageable, it will be important to employ a number of simplifying assumptions and strategies. One such simplification will be to focus on a single crop for any given region. Because we are interested in assessing the amount of energy produced, a reasonable starting point is to focus on the major carbohydrate source grown. For example, (Nicholas 1989) based estimates of potential pre-Hispanic productivity in the valley of Oaxaca using only information on a single crop, maize. Previous experience with calculating carrying capacity in Europe suggests that reasonably accurate estimates can be obtained just by using a single crop such as wheat or rye (as appropriate; Turchin 2005; Scheidel 2001). The focal crop will, of course, vary from region to region due to different histories of domestication and the spread of different crops (e.g., wheat or rye in Europe, rice in China, maize in Mesoamerica, etc.). In some cases, when different crops seriously affect the estimate, it may be advisable to estimate carrying capacities based on more than one crop. In some places, ecological conditions may vary over a relatively small distance, such that one crop does well where another one does poorly. For example, Pacific islands are characterized by wet conditions on the windward sides, where taro (*Colocasia esculenta*) does best, and drier conditions on the leeward side, which favors sweet potato (*Ipomoea batatas;* Kirch 1994).

The Need for a Systematic, Comparative Approach

Agricultural productivity (and the factors that determine it) varies in space and, importantly, in time. In recent years, a large amount of work has been conducted on historical climate change and the effects of climate on crop productivity (see section 4). This work needs supplementing with information about historical crop yields and the cultural and technological factors that affect agricultural productivity. Unfortunately, such data are not readily available in the kind of systematic manner on a global scale that would aid these endeavors due to the general turn away from broad-scale theorizing and comparative perspectives in disciplines such as anthropology, archaeology, and history. Here, we demonstrate how initiative that we have developed, Seshat: The Global History Databank [2], can provide a framework for collecting the necessary information to model agricultural productivity in the past and, more generally, to test comparative hypotheses about cultural evolution and human history.

Most historians and archaeologists studying agricultural systems or other aspects of human societies tend to be experts in particular time periods and/or tightly defined regions. Although there are some who argue that there are broad-scale patterns and general processes shaping human history, their claims tend to rely on illustrative examples and are not systematically tested in the manner that is common in the natural sciences (Diamond 2010). However, in order to test competing ideas properly, a more rigorous way of adjudicating between alternative hypotheses is required. A barrier to such an endeavor is the lack of data of suitable quantity and quality in the kind of systematic format that is required. It is for these reasons that the Seshat project aims to work directly with historians and other relevant experts to construct a large-scale database that collates the most up-to-date knowledge and understanding of past human societies in a systematic manner. Importantly, the information is coded into well-defined variables suitable for statistical analyses so that different hypotheses can be rigorously tested. Although the Seshat approach can be applied to any aspect of human societies, in this paper, we focus in on the variables of relevance to agriculture.

As a sampling strategy, we have selected 30 regions of roughly 10,000 square kilometers from around the world that are delimited by natural geographic features, such valleys, plains, mountains, coasts, or islands. Examples of these Natural Geographic Areas, or NGAs, include Latium (in present-day Italy), Upper Egypt, Hawaii, and the Kansai region of Japan (see Figure 3, and Turchin et al. this volume). We have employed a stratified sampling strategy such that the NGAs are broadly distributed geographically and exhibit substantial variation in the polities

[2] Further background and details about the methodology employed by Seshat can be found in the accompanying article in the same issue of this journal by Turchin et al. (2015)

that inhabited these NGAs in terms of the degree and timing of the appearance of the first large-scale, complex societies. For information related to agricultural systems for each NGA, we are gathering data on variables that relate to the NGA itself and the forms of agriculture practiced there, going back as far as possible in the Holocene (see below). In related projects, we are capturing information about all the polities that occupied the NGA during this time. This will allow us to match different sources of information about different aspects of human societies and enable us to test a range of different hypotheses about human social and cultural evolution.

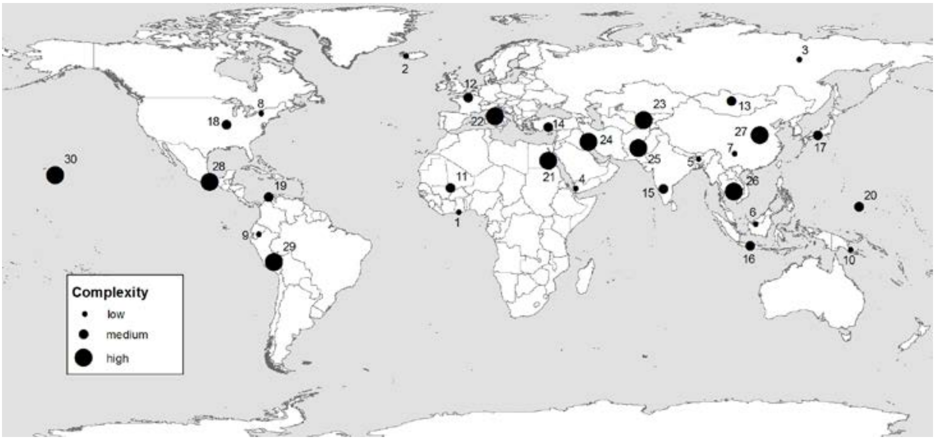

Figure 3. Sample of 30 Natural Geographic Areas (NGAs) that form the focus of our initial efforts at collecting historical and archaeological information about past societies and their agricultural systems. The specific NGAs were chosen in a stratified manner such that societies are sampled from different world regions and across a wide range of socio-political complexity (large circles: high complexity; medium circles: medium complexity; small circles: low complexity; see Turchin et al. 2015 for further details). NGAs are labelled by number as follows:1) Ghanaian Coast, 2) Iceland, 3) Lena River Valley, 4) Yemeni Coastal Plain, 5) Garo Hills, 6) Kapuasi Basin, 7) Southern Hills, 8) Finger Lakes, 9) Lowland Andes, 10) Highland New Guinea, 11) Niger Inland Delta, 12) Paris Basin, 13) Orkhon Valley, 14) **Konya Plain**, 15) Deccan, 16) Central Java, 17) Kansai, 18) Cahokia, 19) North Colombia, 20) Chuuk, 21) **Upper Egypt**, 22) Latium, 23) Sogdiana, 24) Susiana, 25) **Kachi Plain**, 26) Cambodian Basin, 27) Middle Yellow River Valley, 28) Valley of Oaxaca, 29) Cuzco, 30) Big Island Hawaii. NGAs used as case studies in the text are highlighted in bold.

Capturing Information on Past Agricultural Systems

What information do we need to capture about past societies in order to estimate the productivity of agricultural systems? Over the last two years, members of our research team have been developing a codebook to describe the variables relating to agricultural productivity (see supplementary file). Typically, variables in the codebook relate to the presence or absence of certain features (e.g., metal tools), naming of specific features that were present (e.g., the main crop species and varieties), or a quantitative measure of certain features (e.g., the duration of fallow periods). The development of this codebook has been an iterative process, and has improved through discussing these issues with experts on agriculture in past societies. For each NGA, we examine the variables of interest during the time since agriculture was first practiced until the present day. Research assistants ("coders") work with expert historians and archaeologists to identify the most relevant literature, attempt to code the variables in the codebook from these sources, and, where possible, indicate the time at which features appear or change. These codings are then ultimately checked for accuracy by experts in the appropriate region and/or time period. Currently, the variables we are coding relate to Land Use, Features of Cultivation, Technology & Practices, Conventions & Techniques, Post-Harvest practices, Food Storage and Preservation, Social Scale of Food Production, Agricultural Intensity, and Major Carbohydrate Sources. We describe each of the categories below and illustrate the kinds of variables we are capturing within them.

Land use variables relate to the areas of the NGA that were either used for agriculture (e.g., the percentage of land that was actually used for cultivation) or that could potentially be cultivated (i.e., the land in the NGA that was suitable for agriculture regardless of whether it was actually used or not). To give a couple of modern examples, according to the CIA World Factbook (CIA 2014), around 25% of the total area of the United Kingdom is given over to crop production, whereas Japan, with its much more mountainous terrain, devotes only 12% of its land to producing crops. The amount of land that could potentially be cultivated is of theoretical interest in estimating carrying capacity because, holding all other things constant, the more land that can be used for agriculture, the greater the carrying capacity. The area actually used for agriculture at any point is likely to be much more closely related to actual population size at that time, e.g., a small population that has recently moved into a new territory will initially only make use of a fraction of the amount of the land that could potentially be used. Both the actual land used and potentially cultivable land are dynamic variables that can change over time due to such factors as new technologies and practices or climate change.

The **Features of Cultivation** are described in terms of the size and duration of use of fields and gardens used in agriculture and the length of time over which they are left fallow. For example, ethnographic evidence from the Bine-speaking groups, who live in the wetland areas of lowland southwest Papua New Guinea, reveals that the size of a typical swidden field is around 10,000 square meters (from the scale drawing of the fields provided) and a typical field is used for 2 years before being left fallow for 5-10 years (Eden 1993). In contrast, under the three-field system of permanent agriculture that was widespread in Europe from the Middle Ages, a field would be used for growing crops for two years and then left fallow for one year (White 1964). These variables have a large effect on calculating the amount of land that is producing crops in any given year and, therefore, the overall productivity of the system. For example, a system which has a fallow period of one year will be twice as productive in the long run as a system that has a fallow period of three years.

Technology & Practices relate to the tools used in agriculture (e.g. Are tools generally made from stone, wood, or metal?, What particular tools were used?), and the methods used in preparing the soil for agriculture. Improvements in agricultural technology and techniques of soil preparation such as weeding, hoeing, or ploughing fields help to improve growing conditions and, thus, lead to increased yields. Certain technologies such as improved cutting tools and the use of the horse in ploughing reduced the labor costs to agriculturalists (van Gijn, Whittaker, and Anderson 2014).

In cultivating crops, different **Conventions & Techniques** are used that improve yields. This includes the order and combinations in which crops are grown. *Crop Rotation* helps to maximize productivity and reduce fallow by growing different crops in a particular sequence. Often, this involves at least one crop that fixes nitrogen and other essential nutrients back into the soil. *Polyculture* refers to the practice of growing different crops within the same field. In the case of intercropping (where an additional crop is planted in the spaces available between the main crop), it can help to maximize the use of space. Polyculture can also improve productivity through the fact the features of the crops complement each other in important ways. A classic example is the combination of corn-beans-squash developed in the Americas (Mt.Pleasant and Burt 2010): Maize provides structure for beans to grow, beans fix nitrogen, and squash prevents weeds and acts a natural mulch. Another technique is *multicropping,* which involves growing two or more crops in the same field during a single year, but with the important feature that there is substantial temporal separation in the planting times of different crops (which thus distinguishes it from polyculture). This could take the form of double-cropping (a second crop is planted after the first has been harvested) or relay cropping (the second crop is started amidst the first established crop before it has been harvested). This set of variables also includes the application of *fertilizers* to crops to increase the nutrients available to them. This can occur either incidentally from domestic animal waste deposited in fields or more deliberate, active application by humans using either domestic animal waste or other materials such as marl (pulverized limestone added to reduce soil acidity) (Mathew 1993). Another technique is *mulching* which involves using stones or other items to cover the soil to prevent moisture loss through evaporation, which can be very beneficial in arid conditions (Stevenson et al. 2006).

Another important set of variables under this category relate to the application of water to fields, which can dramatically improve productivity because crops are no longer dependent on rainwater to receive sufficient moisture. This can occur through natural means when crops are grown in fields where flood waters are receding (e.g., early agriculture along the Nile) or in fields that are still water-logged or swamp-like (e.g., some forms of rice, and swamp taro cultivation). "True" *irrigation*, however, involves a more deliberate application of water to fields or gardens. Often, this involves the construction of features to divert, store, and control the flow of water so that crops receive the right amount of water at the right time. Some crops, such as rice, are more productive in permanently submerged fields, but others would drown under such conditions. Irrigation can also involve small-scale water control, such as the kind of pot irrigation practiced in Oaxaca, Mexico, where wells are dug every few meters and individual plants are watered by hand (small ridges are often also dug around the plant to keep the water contained)(Kirkby 1973). Irrigation has sometimes led to dramatic transformation of the environment, such as the terraced landscape created by the Ifugao in the northern Philippines (Conklin 1980), or on the island of Bali (Lansing 1991).

Other forms of *landscape improvement* that don't involve diverting water to crops can also be important ways of increasing productivity. This can relate to such features as drainage ditches (whose function is opposite to that of irrigation systems in that it is designed to take water away from crops) or walls (in cases where they serve a function such as retaining soil rather than just marking boundaries or ownership). For example, at Kohala on the Big Island of Hawaii during the late prehistory of that region, walls were constructed as part of dry-field system that helped protect crops from damage by winds and reduced evapotranspiration, thus increasing yields (Ladefoged, Graves, and McCoy 2003).

Another group of variables focuses on **Post-Harvest practices, Food Storage and Preservation**, and relates to what is done after crops have been grown and harvested to improve the final product, enabling it to be used for longer periods of time. *Threshing* involves the separation of the edible grain or seed from the husk and straw that surrounds it. Before mechanization, it was carried out laboriously by hand or through the use of domestic animals. *Winnowing* is a process that follows threshing and involves using moving air (or throwing grain into the air and letting it fall back down to earth) in order to separate the lighter chaff from the heavier grain. Both these techniques can be carried out in ways that reduce labor inputs and reduce waste. Other important post-harvest agricultural processes are *food preservation techniques* (e.g., pickling, drying, grinding to make flour) and *storage*, both of which allow surplus production to be stored for longer periods than would otherwise be possible. This can be extremely important in alleviating falls in production or famine in years when agriculture is compromised for whatever reason. Because food storage can be a public good, we are interested not only in the evidence of where or what containers in which food is stored but also the scale at which food storage occurred (i.e., was it primarily a household affair, or was it conducted at the level of the village or an even wider sociopolitical unit?).

We have also developed a collection of variables designed to capture the **Social Scale of Food Production** to get an idea about the degree and scale of cooperation in the domain of agricultural production. For example, is the preparation of fields and harvesting of crops conducted by individual households, or are there more collective practices involving kin or descent groups, or a whole village? Here we can also capture whether dependent forms of labor were employed in agriculture, such as waged labor, slavery, or *corvée*, which are socially and economically important. It is an important theoretical issue whether cooperation in particular domains, such as agriculture, is limited to that domain (under-pinned by specific institutions) or whether it reflects more generalized, society-wide cooperative tendencies.

We are also attempting to capture **Agricultural Intensity**, which is a measure of the extent to which societies depend on growing crops to meet their subsistence needs. This is likely to be particularly important at earlier periods of history when societies were transitioning to food production. However, it also provides important information about those societies for whom animal husbandry is of prime importance (e.g., "pastoralists") and those traditional societies that still gain a substantial amount of their subsistence from aquatic (i.e., fishing) or terrestrial wild animals (i.e., hunting). For some societies, trade with other societies may be a further important dietary source. These cases may be informative for understanding sources of bias, or discrepancies in estimates of population derived from an assumption of the productivity of a region based solely on crop yields.

Finally, for each society, we want to capture what the **major carbohydrate sources** were, i.e., what were the crops that people grew that provided the bulk of their diet? Because much of the historical or archaeological literature does not provide quantitative estimates of such things as the *proportion of food production resulting from a particular crop*, or the *importance to the diet of a crop,* we have found it useful here to ask coders to estimate these variables on a scale of 0–10, where these values translate to percentages (i.e., 1=10%, 6=60%, etc.). Where multiple crops are identified, the total values estimated should not total more than 10 (100%). These estimates provide us with information about which crops are most suitable, and in approximately what proportions, to include for modelling agricultural productivity. Many large-scale complex societies tend to be reliant on a relatively small number of main crops as sources of carbohydrates, whereas smaller-scale swidden agriculturalists cultivate a wider variety of crops.

Case Studies

In this section, we present three case studies describing the agricultural systems of past societies in three of our NGAs. This will make clearer the kinds of features we are interested in and the challenges associated with extracting information on these features from the historical and archaeological records. The regions we have selected for this purpose are the Kachi Plain, the Konya Plain, and Egypt. In the first two, we examine the very earliest phases of crop production, when agricultural activity was on quite a small scale, and our information is based primarily on archaeological information. The Egyptian case is from a later time period, when agricultural technologies and capabilities had advanced quite substantially, and the sources are mainly historical. Comparing these case studies brings out a number of important insights.

The Konya Plain.[3] The Konya Plain is located in central Anatolia (in modern-day Turkey). For this case study we are focusing on the site of Çatalhöyük during the earliest periods of agricultural development, around 7600–6000 BCE (the period known as the Pre-Pottery Neolithic B, or PPNB). Çatalhöyük covers around 13 ha and probably had a population that numbered in the thousands (Cessford 2005). This type of 'mega-village' is a settlement type that began emerging in this region during the PPNB. Closely packed mud brick buildings were superimposed, one on top of another, and there is no evidence of public buildings or plaza-type public spaces. This suggests that the society that inhabited this site was reasonably egalitarian and lacked full-time occupational specialists, even though these settlements were comparable in size to many early cities. It should be noted that in the Near East a greater research focus has been on the origins of agriculture, rather than the details of early farming systems. However, there is still a lot of useful information we can discern from the archaeological record during these earliest phases.

Çatalhöyük is surrounded by heavy clay soils that formed under marsh-like conditions due to the alluvial fan created by the Çarsamba River. Early farmers are generally thought to have been drawn to such alluvial regions, where crops could grow well due to the water and nutrients supplied by such a system (Sherratt

[3] This section on the Konya Plain is adapted from information presented in a number of previous articles: Bogaard et al. 2005, 2009, 2013, 2014; Russell and Bogaard 2010. Those sources contain more information about the archaeological basis of the inferences drawn in this section, citations of the relevant literature cited and potential sources of disagreement than is possible within the constraints of the current article.

1980). More recent research indicates the presence of certain weeds associated with dry-farming and herding, suggesting that these forms of subsistence were also important to these early agricultural communities. The presence of dry-farming can also be inferred due to the lack of multi-cell cereal husk phytoliths, which would tend to be found if cereals are grown in moist wetland soils (Roberts and Rosen 2009). Geomorphological studies indicate that the local landscape at Çatalhöyük was made up of both wet and dry habitats, both of which could potentially have been exploited by early agriculturalists. How important 'dryland' conditions were in the Konya plain is an active area of inquiry.

The diet at Çatalhöyük was based on domestic cereals (i.e., hulled wheats including einkorn and emmer; free-threshing wheat; barley), pulses (lentil, pea, bitter vetch), sheep, and goats. However, early farming communities at Çatalhöyük continued to exploit wild resources as an important part of the diet. Large animals such as aurochsen (cattle), deer, horses, and wild boar were hunted, and fruits, nuts, and oil-rich seeds were collected and stored. In common with other Anatolian sites, hulled cereals (which provide greater protection to the seed) tended to replace the naked forms at Çatalhöyük (e.g. hulled barley started emerging alongside the naked form from the end of the Neolithic). Whilst these kinds of changes in crop characteristics are in evidence, the range of crops grown appears to have stayed fairly constant. The presence of both cereals and pulses makes it plausible that some form of productivity-enhancing crop rotation was practiced. Although it is almost impossible to find direct archaeological evidence of crop rotation, such techniques are practiced by traditional dryland-farmers in the Near East. Getting enough water to crops is likely to have been an import challenge for farmers in the lands around Çatalhöyük. Different sites would have experienced different levels of flooding and silt deposition, and this could vary from year-to-year. In order to make enough water available to crops, particularly in dryland conditions, it is feasible that early farmers practiced small-scale flood irrigation or watering.

In recent years, evidence of the importance of domesticated sheep (and other caprines) has come to light (Russell and Martin 2005). Herding emerged during the PPNB at a time when crop cultivation had already been established, and this practice could have had important positive effects on crop productivity. Grazing of unripe crops by caprines helps prevent cereal stems collapsing under their own weight ('lodging'), which can be a danger in highly fertile plots; it also results in shorter, denser crop plants less prone to this problem ('tillering'). Grazing has an additional benefit in that it helps convert stubble into manure which is deposited by the animals on arable land. Although direct archaeological evidence is lacking, the more deliberate application of manure to land by people is also suggested by the evidence of the use of dung for other purposes such as fuel, and indications that livestock were kept quite close to the settlement.

Investigations of burned houses provide evidence of food storage at Çatalhöyük. In such houses, the location of the remains of plants and animals are likely to be the places where they would have been most common in day-to-day life. We see an increase in built storage features during the PPNB in line with an increasing reliance on agriculture. The location of these storage features changes from the Middle PPNB to the Late PPNB. Initially they were found in transitional porch- or anteroom-like spaces, but then in the later periods they are found in the inner recesses of compartmentalized houses. This can be taken as evidence as a move towards more 'private' forms of storage. In addition to these built features, more perishable storage containers are indicated by phytolith traces and plaster impressions. Furthermore, botanical clusters have sometimes been found that suggest that bundles of crops were stored in the rafters of houses. These features of household storage at Çatalhöyük in the PPNB indicate that households were economically autonomous.

The Kachi Plain.[4] The Kachi plain (sometimes spelled "Kacchi") is an alluvial fan created by the Bolan River that is situated in modern-day Baluchistan, Pakistan (Petrie and Thomas 2012). The archaeological site of Mehrgarh, which lies at the northern end of the Kachi plain, has been key to understanding early agriculture in this region. The Kachi region is generally quite arid and agricultural activity is heavily affected by patterns of rainfall that lead to flooding of the alluvial fan. However, evidence from pollen analysis suggests that the region may have been considerably wetter in the Neolithic than it is today. The archaeological site is actually comprised of a number of distinct areas of occupation along the right bank of the Bolan River, covering an area of about 300 ha. The populations that occupied the site appear to have been sedentary, however, it seems that from time-to-time the location of settlements shifted to new areas within the site. Occupation of the site stretches from 7000 or 6000 BCE to 2000 BCE and is commonly divided into eight major phases (I–VIII) (Jarrige et al. 2013; Jarrige et al. 1995). The discussion here will focus on the agricultural practices during the 'Neolithic' occupation at the site, which runs to approximately 4300 BCE (Periods I, IIA, and IIB)(Jarrige et al. 2013). We will also touch upon when important changes occurred in the transition to the 'Chalcolithic' occupation: Periods III, IV and V (running from 4300-3200 BCE)(Petrie 2015).

Archaeological evidence provides us with information about the diet of the early farming communities at Mehrgarh. Naked six-row barley (*Hordeum vulgare*) was the predominant cereal crop at Period I, making up more than 90% of the

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[4] The information in this section on the Kachi Plain is adapted primarily from a book chapter by (Petrie 2015), A vital source of information on Mehrgarh are the publications of the French Archaeological Mission to Pakistan (1974 - 1986, and 1997 - 2000) directed by J.-F. and C. Jarrige. As with the Konya Plain section those publications should be consulted for full references and more detailed information.

identified crop remains. Domestic, hulled six-row and wild and domestic, hulled two-row barley were also present, whilst domestic strains of emmer and einkorn wheat have also been detected at very low levels. Animal remains from this early stage are mainly wild species, including bovines, deer, gazelle, goat, and sheep, but there is also evidence of domesticated goats. Period IIA sees a switch from hunting of these wild animals to the exploitation of domesticated cattle, and some sheep and goats. In contrast to sheep and goat, which appear to have been domesticated farther to the west, cattle domestication almost certainly happened locally. Period II sees the appearance of fired ceramic vessels, and also evidence of grain storage structures, which are relatively small and compartmented (Jarrige et al. 2013).

Settlement patterns help reveal information about the population dynamics of the region. A growth in population in Period IIA is indicated by an increase in the number and size of settlements, and the overall size of the settled area. These new settlements tended to be situated on alluvial fans, which suggests that groups were targeting these specific ecological niches in preference to other potential areas (Petrie and Thomas 2012). The agricultural area and therefore the carrying capacity were somewhat limited, so overall population size would have remained relatively small. However, in Mehrgarh Period III, there was a further increase in the number of settlements, which reveals how the sedentary population of western South Asia was increasing dramatically at this time (Possehl 1999; Petrie et al. 2010).

The system of farming in this region can be characterized as the cultivation of crops in small, permanent fields or gardens located in the alluvial plains, with periodic flooding providing the necessary nutrients to the crops (Petrie and Thomas 2012). Initially, this is likely to have been a passive process in which crops were planted in the naturally occurring flood plains. However, during Period III (i.e. 4300–3500BCE) deliberate field systems appear be in place, and there is direct evidence of manipulating water flow through channels in order to actively irrigate the land in other parts of Baluchistan. It is possible that this method may have been practiced from as early as 6000 BC (Petrie et al. 2010). The use of stone, bone, and wood tools is in evidence in early periods, but metal tools, in the form of copper, only appear in the Chalcolithic period. Tilling the soil does not appear to have occurred in early phases, with no evidence of tools for tillage such as digging sticks, hand hoeing, or use of the light plough (though evidence for such practices may not be preserved in the archaeological record (McIntosh 2008)). Cattle-driven ploughing technologies were probably absent during the Neolithic and Chalcolithic, as we only have robust evidence of the use of the plough from the Harappan period (c.3300–1900 BCE) as attested by Miller's (Miller 2003) analysis of cattle bone pathologies, and the discovery of a terra-cotta model light plough (ard) at the Banawali site in the state of Haryana, India (McIntosh 2008; Wright 2009). Apart from irrigation, there is little evidence of agricultural practices designed to increase productivity, such as crop rotation, fallowing, multi-cropping, and mulching (although again these are difficult to detect and identify archaeologically). Although wheat and barley were both grown, there is no compelling reason to suggest they were grown together, and there was no obvious combination of crops that would enhance productivity by being grown together (i.e., the practice of polyculture was probably absent). There is no direct evidence of the deliberate use of cattle dung in manuring at Mehrgarh, but research at Indus Civilization sites elsewhere has shown that dung was probably used as fuel (Lancelotti and Madella 2012).

Egypt. The history of Egyptian civilization is intimately linked with the Nile River, which flows through north-eastern Africa. In this section, we concentrate on the historical evidence from the period of Pharaonic rule between the Old and New Kingdoms[5] (~2900–1070 BCE), although comparisons are also drawn with earlier or later periods to illustrate important changes. Far from a uniform landscape, the Nile Valley was, in Pharaonic times, an aggregation of several micro-regions, each one with its own physical and irrigation particularities. For instance, the valley was narrower in most of Upper Egypt and, consequently, agricultural land was scarcer, whereas Middle and Lower Egypt included about 80 percent of potential agricultural areas. However, population density was lower in Middle and Lower Egypt, and alternative uses of soil are well-attested (e.g., extensive cattle raising, fishing and fowling). In fact, the abundance of agricultural soil in Middle and Lower Egypt is often invoked as an explanation as to why pharaohs founded domains regularly in these regions since the very beginnings of Egyptian civilization (Butzer 1976; Moreno García 2007; Bunbury 2010).

Our knowledge of the organization and management of the landscape during this period is somewhat incomplete. It is important to note that most of the available historical sources were produced by institutions like temples, crown domains, and landholdings of the elite, whereas peasant tenures are still poorly understood. That is why crops highly demanded by the state and its tax system (cereals, flax, and, later, wine and oil) enjoy an overwhelming importance in the written record, whereas other agricultural produce, including more perishable products (pulses, horticulture), appear more difficult to detect. Such an unbalanced picture has had heavy consequences for the knowledge of crop rotation, agricultural tools and irrigation techniques (Moreno García 2006, 2014). Nonetheless, cereals and extensive agriculture, as well as the use of ploughs and draught animals (oxen, donkeys), were characteristic of the institutional sphere. This is probably not representative of the agricultural practices and production techniques prevailing in the domestic sphere, where intensive horticulture and cerealiculture, the use of the hoe (instead of the more expensive plough), and pig-

[5] For information pertinent to calculation of the carrying capacity of the Egyptian socioecological system in later periods see (Korotayev and Khaltourina 2006)

and goat-rearing were probably the norm. Having these limits in mind, it appears that since the late Neolithic, two main crops were cultivated in Egypt: barley (*Hordeum vulgare*) and emmer (*Triticum turgidum dicoccon*). Later on, sometime around the sixteenth century BCE, an important shift occurred. Emmer became the main crop, dates (*Phoenix dactylifera*) became more common (as attested in the written record), and olive plantations and vineyards created by the crown became widespread, including in the oases of the Western Desert (Eyre 1994). These innovations were concomitant with the intensification of international exchanges (cereals were traded between Egypt, the Levant, and the Hittite Empire) and with new irrigation technologies (the *shaduf*) mainly used in small plots devoted to horticulture. Literary texts suddenly evoke peri-urban areas and villas belonging to the elite, where gardens, wells, and horticulture played an important role. Archaeology confirms this picture of gardens planted with vines, date palms, and fruit trees as common in urban and peri-urban villas. As for administrative sources, New Kingdom texts evoke fleets sent by temples, the royal palace, and dignitaries to collect dates, flowers, fruits, wine, and other goods, while texts from around 1100–700 BCE confirm that horticulture was common in small plots around wells and that, in some cases, purchase strategies focused on such coveted pieces of land. Finally, extensive cerealiculture expanded in New Kingdom times, especially in areas with low population density, such as northernmost Middle Egypt and the Eastern Delta. Historical sources such as the *Wilbour Papyrus* and *Ostracon Gardiner 86* describe in detail the agricultural activities, yields, and taxes collected from the institutional domains founded in those areas (Moreno García 2006, 2014).

Institutional sources also reveal information about the practice of fallowing and crop rotation in the Egyptian agricultural system. Extensive institutional fields planted with cereals prevailed in land called *qayt* ("high"), where the annual flood of the Nile did not always reach and yields were lower than in *kheru* ("low") and *mau(t)* ("new") fields. In fact, from an administrative point of view, "high" fields were supposed to produce five sacks per year, but some quotations in the *Wilbour Papyrus* suggest that the expected standard yield was actually 10 sacks (the same standard as "new" fields) but only once in two years. This document also suggests that, in some cases, fields were left fallow, but contemporary letters reveal that land planted one year with cereals was cultivated with "plants" or "fresh plants" the following year. These could refer to alternative crops, such as pulses or plants that would be used for fodder, but unfortunately, the Egyptian terms are rather imprecise. In any case, some kind of crop rotation and/or fallow system was probably necessary in order to restore the fertility of the soils rarely reached by the seasonal Nile flood. Crop rotation was common in Greco-Roman times and later, but the choice of the crops to be planted (flax, cereals) also obeyed profit considerations, as the letters written by Heqanakhte, a well-off potentate living around 1950 BCE, demonstrate (Moreno García 2006, 2014; Allen 2002).

Finally, crop processing is well-attested in the institutional sphere. Cutting cereals low on the straw leaves cereal stubble in the fields for livestock to graze and also leaves a long length of straw attached, a harvesting method well-known in the Old Kingdom. However, the practice of reaping high on the straw seems to have prevailed in New Kingdom times, and Pliny reported that, in Egypt, wheat was cut twice. According to the iconography and the textual evidence, trampling by animals was the method usually employed for threshing; beating with a stick might have been the prevalent method when small quantities were processed, but it has been hardly represented at all in Egyptian art. Thus, threshing floors appear conspicuously in the administrative record, usually linked to institutional domains and to the delivery of taxes in cereal (Murray 2000; Moreno García 2006, 2014).

Comparisons of Case Studies. Although the regions and time periods covered in the above examples are somewhat limited (at least with respect to the scope of our overall project), nonetheless, a number of insights can be drawn from comparing these case studies. First, there are both similarities and differences between the agricultural systems described above. Among the similarities, all of the case studies are drawn from regions where periodic flooding by rivers has created conditions that allow for productive agriculture in places that were otherwise somewhat arid. In Egypt, this natural process has been supplemented by extensive irrigation systems that actively control the flow of water to crops. In the Kachi and Konya examples, we lack direct evidence of active irrigation during the earlier time periods considered, although there remains the possibility that such techniques were practiced (albeit on a smaller scale than in the Egypt example). The Kachi and Konya examples show a number of similarities, which is not surprising, given that they are relatively small-scale and represent the some of the earliest agricultural societies in their respective regions. Although all cases ultimately share historical links with the origins of agriculture in the Near East, certain features, such as the native domestication of cattle in Kachi, the potential importance of dry farming in Konya, and the elaboration of agricultural systems in Egypt, illustrate how these systems developed differently in each region. The case studies also reveal important differences in the sources of information that we have to understand past agricultural systems.

Both archaeological and historical sources have their strengths and weaknesses. The textual sources from Egypt provide rich information, but are somewhat biased towards the institutional sphere and have less to say about what the majority of the population were doing. Archaeology, which is our only source of information in the Kachi and Konya examples, can reveal the material remains of what most people in societies were doing. On the other hand, it can be difficult to discern features of interest, such as direct evidence of crop rotation or fallowing, with archaeological data alone. We return to the limitations of studying past societies in the discussion. As we move forward and continue to collect more information on agricultural systems in the past, including those that derive from other independent centers of plant domestication (e.g., the New World, East Asia), this kind of systematic comparative perspective will provide further insights into the patterns and processes of agricultural development and human socio-cultural evolution.

Coding Past Agricultural systems: Challenges and Opportunities

Our knowledge about the past is fragmentary for a number of reasons, and there are many challenges facing our approach. Many of these are by no means unique to the study of agricultural systems, and relate to the nature of the historical and archaeological records. Firstly, we must deal only with the limited material remains of past societies (including their writings), or the marks they left on the world around them. Features of behavior and practice are not preserved directly but instead have to be inferred from what does remain. Secondly, some regions and time periods are better-studied than others, and this reflects a number of factors, including ecological conditions, that make some regions easier to excavate than others, the personal interests or theoretical persuasions of researchers, and broader social and historical factors that shape which countries and institutions have the money to conduct such research. In other words, there are certain biases in our records of the past of which we need to be aware when attempting to draw broader inferences. One potential source of error comes from the fact that although our units of analysis are the NGAs and the societies that have inhabited them in the past, we often only have information from a small number of archaeological sites or a limited set of historical records. For example, our inferences about the early stages of agriculture in the Kachi Plain, discussed above, are extrapolated from the single site of Mehrgarh. A potential risk here is that this site may not be representative of what was going on in the wider NGA. On a practical point, there is not much that can be done here except to recognize that we must work with whatever information we have, be aware of the potential limitations and sources of error, and be ready and willing to update our understanding as and when new information is discovered. Our general strategy is to make as clear as possible the assumptions involved in defining and coding these variables, and in how they will get incorporated into further inferences about the productivity of past agricultural systems.

One way to make sure we are using the best available data and are aware of its limitations is by engaging fully with academic historians and archaeologists who are experts on our focal regions and time periods. Such experts enter into the process in a number of ways. Firstly, they help us navigate what is known already, identifying the most relevant literature, aiding in the design of the codebooks, and advising on what information is or is not feasible to obtain. Secondly, they verify that the information being collected is based on the most up-to-date knowledge and scholarship. Finally, as we move forward and begin analyzing these data statistically, experts will also be able to provide important background information and context that can help in the interpretation of the results. It should be noted that researchers can sometimes come to different conclusions about how historical and archaeological records should be interpreted. In other words, there is often conflicting evidence, or a lack of consensus about what the data are telling us. We try to avoid imposing any kind of typological scheme or monolithic theoretical perspective on the data, and the coding framework allows us to indicate where there are disagreements.

Another practical step we have taken in dealing with how to interpret the information that is present in the archaeological and historical records is to try and make the coding process as objective as possible. This is done by focusing on presence/absence-type features, which are often much easier to code with certainty, and almost by definition are more consistent across different situations than quantitative estimates or judgments. We have found it often helps to break things down into component parts that can be more readily coded in a presence/absence manner, particularly for societies known only archaeologically. For example, rather than simply asking whether irrigation was practiced or not, we can ask if certain features related to irrigation systems (e.g., dams, channels etc.) were present or not. In our experience, certain features, such as the presence or absence of metal tools or food storage facilities have proven relatively straight-forward to code. Other variables have proven more challenging because, due to their annual or cyclical nature, many agricultural practices can be quite hard to discern archaeologically. A solution to this is to have very specific criteria about justifying the presence of such techniques. For example, for crop rotation, a sensible justification could be that within a particular site, a spectrum of crops were grown that is compatible with the rotation of crops. The point here is not that these justifications are without error, or cannot be challenged, but rather, that the reason given should be made clear.

Attempting to code data systematically across different regions highlights that, for many variables of interest, there will be many cases in which not much, if anything, is known. Because this project is primarily interested in the broad patterns and processes of human history, the issue of missing data or scholarly disagreement perhaps matters less than if we are trying to find the particular details of a given time or place. In other words, as long as we have information on enough variables and enough regions then major trends should still be discernible. On a practical level, we are able to incorporate such sources of uncertainty into any statistical analyses that we perform, and we can explore whether making different assumptions about the data affects our overall results and conclusions. Although sometimes frustrating from an analytical perspective, highlighting where there are gaps in our understanding also serves a useful purpose in the wider sense in that it highlights those areas where future research efforts can be productively targeted.

Toward an Empirically Informed Model of Carrying Capacity in Past Human Societies

Having outlined out the general factors that will be important in assessing potential productivity in past societies, in this section, we sketch out how we are combining earth system science approaches with historical and geographical information to create a model of carrying capacity in past societies. Our general approach is to take estimates of productivity based on the output of simulations of modern crop growth and then modify these estimates based on the kind of historical information discussed above.

A variety of process-based models have been developed to simulate crop growth and productivity using detailed physical and biological processes. The details of the inputs required by these models can vary greatly depending on the question being addressed and the scale at which a simulation is being applied (which can range from a global level to the level of individual fields). For this project, we are making use of the LPJmL global crop model of (Bondeau et al. 2007), which simulates the productivity of a limited number of broad crop functional types (temperate cereal, rice, tropical root, etc.) through an explicit model of crop growth and development based on the features of such plants, their eco-physiology, and the management techniques applied to them. The model uses inputs relating to climate and weather in order to assess productivity under a variety of scenarios.

One of the advantages of LPJmL for our purposes is that it is constructed at a suitable level of abstraction, with a limited number of inputs, which is suitable for projecting back into the past. A downside of simulations is that they are often time-consuming to run and require specialist expertise to develop. To overcome this constraint, emulators have been developed that are computationally fast, statistical representations of process-based models.[6] In previous work, (Oyebamiji et al. 2015) developed an emulator of the LPJmL model. It generates a spatial map of maize, rice, cereal, or oil crop yields (in terms of kg per ha) at approximately 50 km resolution. The crop emulator allows for variable management levels, allowing us to capture the effects of developing agricultural technologies. The emulation framework takes a matter of minutes to derive a global map of crop yield for a

[6] A process-based computer simulation attempts to model the actual process of crop growth, with a greater or lesser degree of detail and realism depending on the simulation. An emulator is a statistical model of a simulation, which describes the statistical relationships between the inputs to the simulation (e.g. climate, soil type etc.) and the output (crop yield).

specified climate input and crop management level. This speed compares to several days of computing that would be required if we were using its underlying simulators. We are, therefore, using this emulator approach for reasons of tractability, flexibility, and to facilitate the analysis of modelling uncertainties.

To date, LPJmL has been used primarily to simulate current and future conditions. However, the emulation approach allows us to take the modelled associations between climate and crop productivity and project these back into the past using information about past climate. For this project, we have developed a crop-modelling framework that uses emulation of a crop simulator (LPJmL) and a paleoclimate simulator (PLASIM-ENTS intermediate complexity climate model; Holden et al. 2015). This paleoclimate emulator generates spatially and seasonally resolved fields of temperature, precipitation, and cloud cover as functions of the Earth's orbital configuration. The climate data is then passed to an emulator of the LPJmL crop model. As with the original (Oyebamiji et al. 2015) emulator, the outputs of this crop emulator are spatial maps of crop yields, but this time, those maps are derived from the estimated climate at defined periods in the past. To make the outputs more relevant to past societies, the suite of crops being considered will be extended beyond the maize, rice, cereal, or oil crops of the original emulator to take into account additional important classes of crops, such as tropical cereals (e.g., sorghum) and tropical roots (e.g., cassava). The simulator and the emulator also estimate productivity under rain-fed and irrigated conditions, which can help inform our historical estimates of productivity based on knowledge about the presence of irrigation techniques in the past.

With these estimates of productivity in hand, we can set about adjusting them based on the historical data on past agricultural systems described above. The basic idea is that within a Geographical Information System framework, we can take the initial coverage maps supplied as output from the emulator and apply a formula that shifts the estimated yields up or down depending on the particular crops, agricultural techniques and practices, and other relevant factors at different points in time and in different regions. The values used in these formulas will be based on estimates and information from the literature. As a first step in adjusting the emulator output, our data can tell us when agriculture began being practiced in different regions and which crops are most important to assess for different regions. Adjustments will have to be made based on the human-induced biological improvements that crop varieties have undergone. For example, (Kirkby 1973) was able to estimate the improvement in maize yields that occurred over time in Oaxaca, Mexico, based on the increase in the length of ears of corn evident in the archaeological record. Furthermore, information about variables, such as the size of fields and whether land is farmed permanently or more sporadically (e.g., in swidden systems), will affect the amount of land that could be devoted to food production and, therefore, the carrying capacity under that system. The effects of other variables can also be assessed with reference to the literature about the degree to which techniques such as fertilizing, mulching, or crop rotation affect crop productivities.

This process can be conducted at several scales. Firstly, because the historical data relate directly to particular NGAs, we can make adjustments at this level to estimate productivity and carrying capacity at the NGA level. However, because our NGAs are well-sampled geographically, we can use this information in conjunction with other sources to make reasonable extrapolations out from these points to assess potential productivity on regional and global scales.

Conclusion

The importance of agriculture to studies of the human past demands that we make greater efforts to collect information about past agricultural systems (and other aspect of past societies) in a systematic and standardized manner. We can use this information to explicitly model the productivity and potential of those systems on a global scale. This is clearly a large undertaking, and there are a number of challenges and limitations facing the approach as we have outlined in this paper. The approach we are taking derives from a desire to test hypotheses about the human past in the same kind of quantitative, systematic, and rigorous manner that characterizes the natural sciences. Our aim is to accomplish this in a way that makes full use of the vast knowledge and understanding built up by scholars in the social sciences and humanities and provides a way of sharing and collating this knowledge to provide further understanding and new lines of enquiry. In other words, we are seeking to establish new interdisciplinary and mutually beneficial collaborations between researchers in the humanities and the sciences. This enhanced method of working holds the promise of bridging the gaps between the 'two cultures' of academic inquiry. This process of estimating past productivities and carrying capacities will necessarily involve painting with broad brush strokes and making a number of theoretically informed assumptions. However, the benefit of such an approach lies in making explicit the steps in the process and assessing the effects of different modelling assumptions on our estimates of carrying capacity. The task is an ambitious one, yet promises to provide important insights into fundamental aspects of past societies, and will enable us to more rigorously test key hypotheses about human socio-cultural evolution.

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