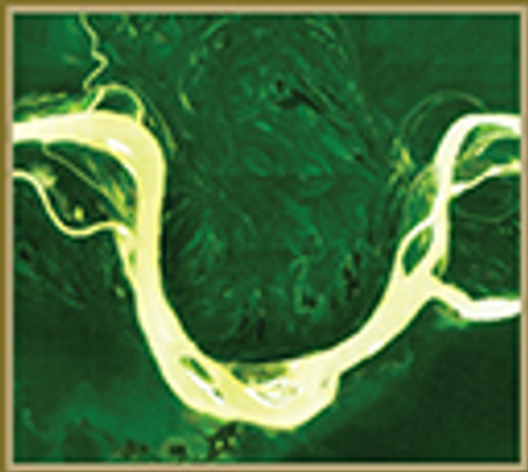
# Climates, Landscapes, and Civilizations



Liviu Giosan, Dorian Q. Fuller, Kathleen Nicoll,
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*Editors*

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**Liviu Giosan**
**Dorian Q. Fuller**
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**Cover Image:** (top left) The Sun is the principal natural driver of Earth's climate (http://commons.wikimedia.org). The water cycle translates climate signals into diverse landscapes ranging from (top right) highly productive floodplains (http://commons.wikimedia.org) to (bottom left) completely inhospitable deserts (http://commons.wikimedia.org). In the process of becoming a geological-scale force, humans have conquered even the most hazardous landscapes and devised strategies for survival and rapid recovery. (bottom left) Reconstructed pre-Columbian house structures built in El Baga National Park, Cayo Coco, Cuba. Photograph credit: Jago Cooper.



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# CONTENTS

# PREFACE

The current volume brings together papers presented at the AGU Chapman Conference "Climates, Past Landscapes, and Civilizations," held in March 2011 in Santa Fe, New Mexico. We wish to thank all participants and organizers of the conference and are grateful to all contributing authors, reviewers, and editorial staff who have helped to produce this book. The meeting was attended by more than 100 scientists, scholars, and journalists across the fields of Earth sciences, anthropology, and archaeology, with the overarching goal of enhancing the cross-disciplinary dialogue on the history of complex interrelationships between humans and their environment. Discussions, thematic group sessions, and answers to individual questionnaires revealed differences among disciplines on the design, methodology, and interpretation of research but also pointed out a strong collective interest to develop collaborative pathways toward bridging any perceived disciplinary divides.

Research on the history of interactions between humans and the environment is intrinsically interesting to diverse audiences and engaging for the wider public. The fate of past cultures also presents us with completed intricate experiments that provide a wealth of data for exploring models of the resilience and sustainability of coupled socioenvironmental systems. At a time when climate change, overpopulation, and scarcity of resources are increasingly affecting our ways of life, the lessons of the past provide multiple reference frames that are valuable for informing our future decisions and action plans. Despite this wide interest and investigational potential, collaboration across disciplines is uncommon, and adequate funding to explicitly support this style of interdisciplinary research remains scarce. The two broad fields of inquiry, Earth sciences and archaeology, have distinct customs and rhythms of publishing and discussion of new ideas, and hypotheses are mostly generated within nonoverlapping professional societies. Consequently, Earth scientists and archaeologists, experts in these fields analyzing the same phenomena at various temporal and spatial scales, rarely overlap effectively in planning and performing their research. Information outside each of these disciplines is used at a level below its potential, and in the process, the complexity of phenomena is diluted. Solutions to bridging this divide are not simple, but they are not beyond reach and may include a wider presentation of existing interdisciplinary research to multiple stakeholders and funding agencies and cross-disciplinary working groups within professional societies and dedicated meetings. Further progress may require integration and standardization of databases and establishing new organizations dedicated to interdisciplinary research on coupled socioenvironmental systematics. Both the differences and convergence of opportunities discussed during the Chapman meeting are reflected in the current volume and in other conference papers published outside this volume.

The early anthropogenic hypothesis provided a larger context for presentations at the meeting. The centerpiece of this hypothesis, developed by paleoclimatologist Bill Ruddiman in a series of papers since 2003, proposes that humans began to exert an influence over the global climate thousands of years ago through greenhouse gas emissions linked to the expansion of agriculture (see the introduction to this volume by Ruddiman and references therein). While archaeologists have always been concerned with the interactions between past cultures and their environment, the global scope and fingerprint of these interactions suggested by the early anthropogenic hypothesis introduces a new level of complexity in Earth sciences and provides a path for future interdisciplinary research. In the introduction to the present volume, Ruddiman argues for an increased role of archaeology and anthropology in validating competing models of land use. Novel use of historical information on social organization and resources and regional and global assessments of the scale and spatial distribution of past societies, as well as better criteria for discriminating between anthropogenic and natural landscapes, are just a few elements that are critical for advancing this goal. Along similar lines, Cadzow argues in his chapter for research on the primary drivers of long-term environmental impacts such as hunter-gatherers and agriculturists rather than focusing only on major sites or civilizations. The impact of these "unsung" societies, although more diffuse, may have left a more profound (and not necessarily harmful) fingerprint on landscapes and ecosystems.

The overlap of human agency and natural climate change on landscapes and ecosystems is often confounding and, in many cases, difficult to disentangle. The extinction of

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Pleistocene megafauna and the termination of the Clovis lithic technology/culture during the Younger Dryas is one example of such complex phenomena that has elicited an active debate recently. In this volume, Boslough and colleagues present new data and argue against a recent hypothesis that proposed that a large impact or airburst caused simultaneous climate cooling, extinction events, and cultural changes at the Younger Dryas around 12.9 ka. When climate changes can be detected and isolated from anthropogenic overprints, high-resolution records can reveal new relevant aspects for the socioenvironmental systems at fine scales. Along this line, Berkelhammer et al. present a high-resolution speleothem record of the monsoon regime from northeast India and document for the first time the 4.2 ka climate event on the Indian subcontinent against which the reorganization of the Indus Valley civilization can be assessed. Aharon and colleagues provide a high-resolution climate reconstruction from a speleothem from DeSoto Caverns in Alabama and address the role of instability rather than singular climate events on the fate of Mississippian chiefdoms in the southeast United States.

Sea level changes represent a cumulative and more gradual aspect of global climate variability, often with profound local effects on culture. Landscape formation in coastal settings is tightly constrained by sea level variability, leading to the progressive development of habitability niches. This is discussed by Amorosi and Morelli in their chapter on the fate of Neolithic Cardium Pottery Culture in the Mediterranean and by Rollet in his analysis of the advent of large-scale irrigated rice agriculture in the Fuzhou Basin of China.

Regional complexity requires synoptic reconstructions of climate changes and associated landscape responses for in-depth examination of their links to cultural events. High-resolution geospatial imaging, areal expansion of paleoenvironmental databases, their integration with archeological metainformation, and scenario-based modeling of coupled socioenvironmental systems are increasingly applied to advance these research directions. Maemoku et al. couples high-resolution terrain models with estimates of river flow and chronologies of eolian landforms to provide constraints on the interpretation of the Ghaggar-Hakra Valley as the lost, legendary Sarasvati River of the Indian Vedas. A common mechanism for regional climate change in the west Asia and Indian monsoon domain is proposed by Staubwasser, after analyzing the common pacing of reconstructed Indus River outflow and water column stratification in the Red Sea over the last 5000 years. Focusing also on South Asia, Lemmen and Khan model the transition to agriculture in the Indus Valley region, taking into account the biophysical forcing factors as well as sociotechnological innovation, migration, population, and subsistence changes. A modeling approach is taken by Berking and colleagues, who use downscaling of atmospheric general circulation model results to investigate the rise and fall of the city of Naga along the middle Nile during the first millennium before the Common Era.

The cause-effect relationships between climate and human history are often nonintuitive, and multidisciplinary approaches are required to reconstruct them. An unexpected relationship between climate and the Siberian Scythians is revealed by Panyushkina, who posits that a decrease in habitation in the Altai Mountains during warmer climate intervals may have increased mobility and possibly resulted in the development of transhumant pastoralism. In contrast, the civilizing value of prehistoric climatic stress leading to acculturation, social complexity, and relocation is discussed by Nicoll, who analyzes the effect of droughts on the Neolithic culture at Nabta Playa, west of the Nile Valley, and the rise of the Pharaonic culture in Egypt. Force and McFadgen discuss the role of active tectonics in landscape development over long time scales by providing diverse environments and also through creative destruction events that accelerate the development of cultural complexity.

A wide array of archaeobotanical, geoarchaeological, and philological data is synthesized by Riehl et al. to analyze the multiple drivers controlling the transformation of agricultural systems in northern Mesopotamia. A combination of environmental reconstructions, archaeological methods, and evidence from historical documents is also employed by Thurston and Plunkett, who reconstruct the “invisible” history of human activity under continuous pasture cover in Northern Ireland. In a review of resilience to storms in Caribbean island communities, Cooper highlights the importance of examining cultural life cycles from a long-term perspective that brings forward the capacity for rapid recovery rather than strategies for robust resistance to disasters. Development of novel proxies, monitoring, and dynamical reconstructions are advocated in several papers in this volume. Adding to the increasing body of literature that recognizes sedimentary materials as important components of the archaeological record, Baade discusses irrigation-linked anthropogenic soils in two contexts where their identification contributes to our understanding of regional cultural developments: the high Himalaya and coastal Peru. Draut et al. address the role of detailed monitoring of sand transport and vegetation in analyzing the effects of climate variability on landscape dynamics and cultures in arid regions with eolian elements. Gatti and Oppenheimer address extreme events such as the Youngest Toba eruption, using a modeling method to better constrain the distribution of ash from the eruption while noting that the environmental effects remain largely unquantified due to the low resolution of the proxy data.

Covering the range from collapse to transformation, cultural responses to climate and landscape change may include abandonment, redistributions, and reorganizations of settlement types and patterns, recalibration of food procurement strategies, trade network development, migration and colonization, and technological transitions. Continuing discussions on this topic started at the conference, and in accord with many points raised in other papers in this volume, Aimers argues for developing and using dynamic models of cultural development in his analysis of the cultural transformations of the lowland Maya in the ninth century A.D. The author underscores the need for close collaboration between Earth scientists and archaeologists to understand the broad spectrum of cultural responses. Research design should approach this complexity with an open mind that moves beyond deterministic assumptions about civilization collapse and instead focuses on understanding the resilience strategies involved in past cultural transformation.

One key issue that emerged at the conference as a particularly important focus going forward is the need for developing increasingly precise chronologies for both paleoenvironmental and archaeological data. This is important at both the "site scale" of the archaeology as well as at the regional scale. Furthermore, it is essential that archaeologists, geologists, and environmental scientists working within the same region collaborate in data collection, assessment, and synthesis. This will help temper disciplinary biases and provide opportunities for new observations and theoretical developments based upon a better understanding of the complexities of human-environment interactions.

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# Bridging a Disciplinary Gap

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This paper examines a perceived divide between two groups referred to as "archeologists" and "physical climate scientists." The former group encompasses field scientists in related disciplines such as geoarcheology, archeobotany, and those aspects of sedimentology and paleoecology that focus on the Holocene. Also included are human geographers who study written historical records of civilizations spanning the last 2 millennia. The latter group covers those working in fields such as atmospheric sciences, paleoclimatology, paleoceanography, hydrology, ice core and marine geochemistry, numerical (general circulation) modeling, and carbon-cycle modeling. Few scientists on the two sides of this barrier have successfully bridged this gap, even though the potential benefits of doing so are considerable. This paper makes the case that climate scientists, trying to understand the middle and late Holocene, need to consider how the spread of agriculture transformed past landscapes and potentially altered regional and larger-scale climate. It also points to ways in which archeologists can benefit from placing regional studies in the kind of "big picture" view common in climate studies.

## 1. INTRODUCTION

Several AGU members organized and held a March 2011 Chapman conference with the title "Climate, Past Landscapes, and Civilizations." Their intention was to bring together people in different disciplines to bridge disciplinary barriers related to these three topics. From my perspective, the conference was a successful step toward an important goal that deserves much more attention in the future.

The first two parts of this chapter focus on examples in which physical climate scientists have at times shown a surprising lack of awareness of ways in which our own species has altered the face of the planet, even in relatively recent centuries. The last section suggests ways that archeologists could help to bridge these disciplinary barriers and provides examples of progress in that direction during the last few years.

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## 2. FORGOTTEN MILL PONDS

In the 1950s, two highly respected hydrologists, Gordon Wolman and Luna Leopold, investigated a region of second- and third-order streams in the mid-Atlantic Piedmont of the United States. Acting under the assumption that these streams were natural in origin, they formulated the underlying physical laws that appeared to govern their behavior [*Wolman and Leopold*, 1957; *Leopold and Wolman*, 1960]. This research played a prominent role in the development of the science of fluvial geomorphology.

Half a century later, *Walter and Merritts* [2008] reexamined the same region and found a strong human overprint on the landscape (Figure 1). Logging of the piedmont had begun with the earliest European settlement in the late 1600s, accelerated in the 1700s, and continued into the middle or late 1800s. Small water-powered sawmills were built along these streams at average intervals of a few kilometers to process cut timber. Mills also provided waterpower for grain grinding, textile production, paper production, and iron forges. Each mill had an upstream millpond dammed by earthen structures to divert water for power. The piedmont region was well suited to mills because of its gentle stream

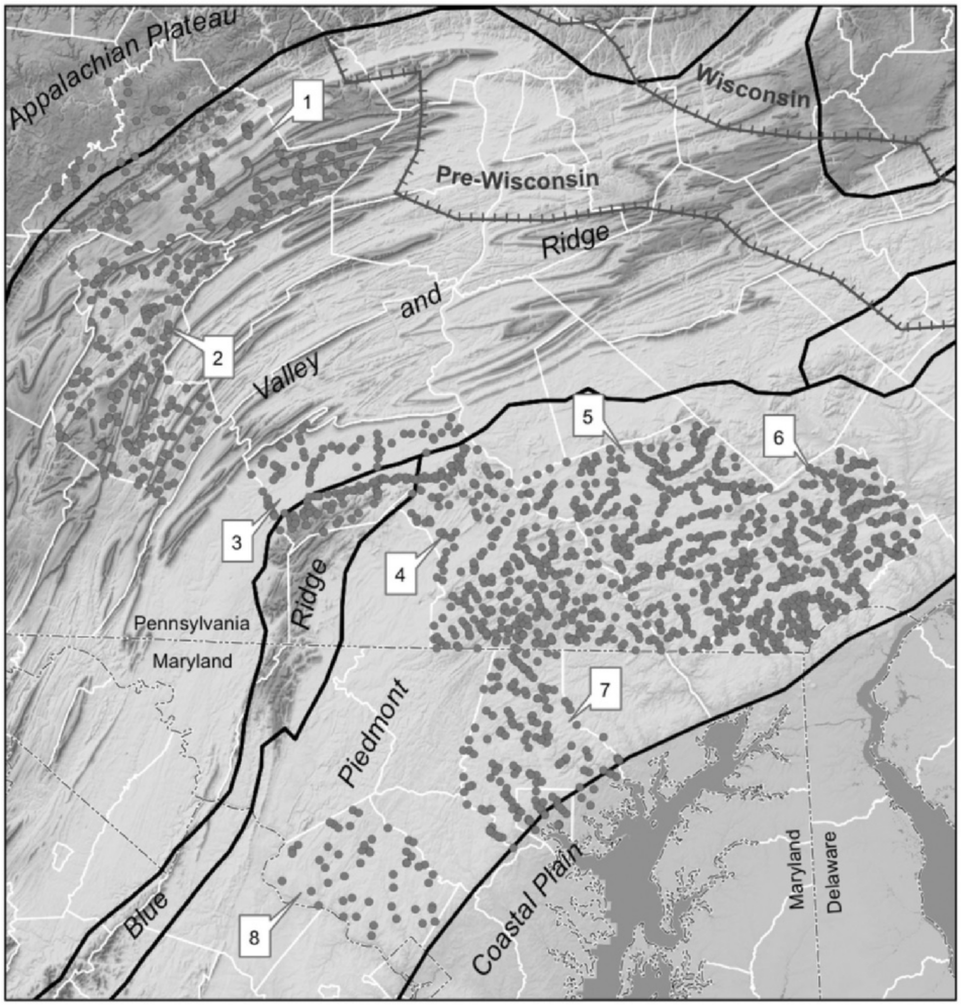


**Figure 1.** Location of mid-1800s mill dams in eight mid-Atlantic counties based on historic atlases: in Pennsylvania, 1, Centre County; 2, Huntingdon County; 3, Cumberland County; 4, York County; 5, Lancaster County; 6, Chester County; and in Maryland, 7, Baltimore County; and 8, Montgomery County. From *Walter and Merritts* [2008] and *Merritts et al.* [2011].

gradients and location near navigable tidal water not far downstream.

Based on LIDAR (Light Detection And Ranging) surveys that showed flat-lying areas ("valley flats"), historical records, and field examinations, Walter and Merrits found evidence for at least 8000 mills and millponds along prominent creeks and streams in the Pennsylvania piedmont, and *Merritts et al.* [2011] also found numerous others across the Mid-Atlantic (Figure 1). Peak mill use occurred between 1780 and 1860, with more than 65,000 water-powered mills in the eastern United States by that time.

By the middle 1800s, more than a century of timbering (and agriculture) had transformed the mid-Atlantic piedmont into a largely humanized landscape. After the more accessible lowland forests were cut, later clearance removed forests from steeper and more remote hillsides, where erosion destabilized the soil and sent fine sediment into the streams and millponds. But as steam power gradually replaced waterpower, most of the mills were no longer needed. And with no more forest to cut, the wooden and steel structures in the sawmills were recycled to new locations farther west or south or to higher terrain where timbering was still underway. With the sawmills gone, the millponds filled in with eroded sediment, and with new forest taking over, the Piedmont began to revert to what looked like a natural state.

A century later, when Wolman and Leopold studied the region, they interpreted the landscape as natural, analyzing the meandering patterns of piedmont streams flowing mostly in single channels across the "valley flats" they thought were floodplains. But Walter and Merritts showed that these "floodplains" are actually the remnants of millponds that had filled with sediment, in some cases breaching the mill dams. The stream channels were meandering across these millpond deposits.

Based on historical accounts and on sediment deposits in a few undammed regions that survive today, Walter and Merritts concluded that the natural streams that had previously existed in the piedmont were small branching channels flowing through forested wetland (sedge) meadows separated by islands stabilized by alder trees and shrubs. Woody debris that jammed the stream channels helped produce these complex branching flows. Little fine sediment had accumulated in those natural pre-clearance channels, although they were rich in organic matter.

These remarkable papers serve as a stark warning to anyone studying the more distant past, including the effects of early Americans on the landscape prior to European arrival, as well as the long history of land use in Eurasia. If hydrologists in the 1950's had entirely "forgotten" the history from just one or two centuries earlier, what might have been "forgotten" about things that happened several millennia ago?

## 3. FORGOTTEN (OR OVERLOOKED) PREINDUSTRIAL RECORDS OF LAND USE

From direct personal experience, I offer here a second example of how scientists trained in physically based areas have been unaware of fundamental knowledge in disciplines that have traced the imprint of humans on Earth's surface prior to the industrial era. Assessing the magnitude of this past human imprint has implications that extend into other disciplines, including early emissions of greenhouse gases ($CO_2$ and $CH_4$) and their potential role in keeping late Holocene climate warmer than it would otherwise have been [*Ruddiman*, 2003].

Several attempts have been made to quantify the history of land clearance [*Houghton*, 1999; *DeFries et al.*, 1999; *Ramankutty and Foley*, 1999; *Goldewijk*, 2001; *Joos et al.*, 2004; *Pongratz et al.*, 2008; *Strassmann et al.*, 2008]. Most of these studies were based on estimates that per capita cultivation has amounted to just a few tenths of a hectare to one hectare [*Seiler and Crutzen*, 1980; *Goldewijk*, 2001; *Ramankutty et al.*, 2002]. Several of these reconstructions made the key simplifying assumption that the same small per capita clearance numbers applied back into the pre-industrial Holocene.

This critical assumption tied those land use reconstructions more or less linearly to estimates of the past population of the planet (Figure 2). In the year 1500, global population was 450–500 million, or less than 7% of the modern value, but by 1850, it had risen to 900 million (~13% of modern), and now we number 7 billion people. As a result, these land use reconstructions inevitably placed most global forest clearance within the population explosion of the industrial era, with very little clearance prior to about 1700.

This assumption of roughly constant per capita clearance and land use sounds reasonable at first. More than once I have heard it justified by a simple challenge: "Why would (early) farmers have farmed any more land than necessary to feed their families?" The clear implication is that per capita land use has had no reason to vary for thousands of years.

But this constant land use assumption is demonstrably wrong. It is refuted by field-based studies in archeology, anthropology, and related disciplines, as well as by historical evidence summarized below [*Buck*, 1937; *Rackham*, 1980; *Chao*, 1986; *Ellis and Wang*, 1997; *Mather and Needle*, 2000; *Williams*, 2003; *Bradshaw*, 2004]. This evidence shows that early farmers used far more land per capita than those in recent centuries.

*Ruddiman* [2003, 2007] noted a striking historical example of the failure of the constant per capita assumption: a survey of England ordered in 1086 by William the Conqueror. The

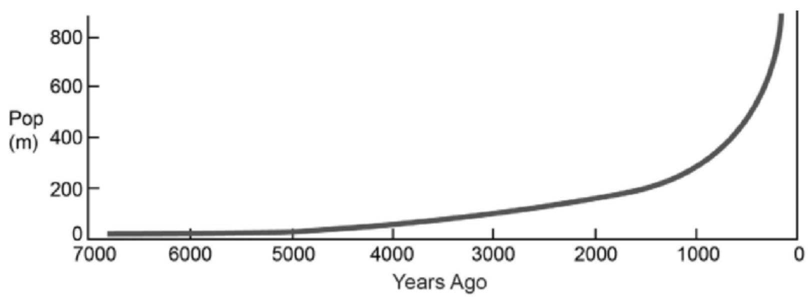


**Figure 2.** Estimated pre-industrial global population for the middle and late Holocene. Based on *McEvedy and Jones* [1978] and *Denevan* [1992]. Trend is truncated at 800 million people living at the end of the pre-industrial era (the early 1800s).

results, recorded in the 1089 Domesday Book, counted a population of 1.5 million people and found that 85% of the arable land in Britain and parts of Wales and Scotland had been cleared (Figure 3). Because this survey was done almost 1000 years ago, its accuracy might be thought questionable. But Oliver Rackham, an exacting and meticulous botanist/paleobotanist, tested it using a range of innovative methods [*Rackham*, 1980]. Among other things, he considered well-dated archeological remains of homes and villages, place names that constrain the founding of villages to particular eras, and the degree of match between wooded areas recorded in the Domesday survey and modern woodlands (generally a very close match). Rackham concluded that forest clearance in 1089 was at least as high as the 85% value recorded in the Domesday Book and quite possibly a little higher.

This Domesday example completely contradicts the proposed one-for-one link between population and clearance (Figure 3). Today, roughly 60 million people live in Britain, Wales, and Scotland, with ~80–85% of the arable land cleared. Based on an assumed one-to-one relationship between population and clearance, the 1.5 million people alive in 1089 should have cleared about 2% of the arable land. Yet the Domesday survey showed ~85% clearance, at least as much as today.

Other records of early forest clearance in other parts of Europe (France, Denmark, Sweden, Greece and Ireland) were summarized by *Mather and Needle* [2000], *Williams* [2003], *Bradshaw* [2004] and previous studies cited in those papers. Most of the records are from the years 1000 to 1800, but a few went back to the start of the European historical era near 2000 years ago. These historical data again revealed surprisingly extensive early clearance long before the last few centuries. They found that forest clearance does not track population in a one-for-one way but instead follows a sigmoidal trend [*Mather and Needle*, 2000; *Kaplan et al.*, 2009]. Clearance accelerates quickly at low population densities and is nearly complete by the time population densities reach an intermediate level of 100 people per km$^2$ (Figure 4). Additional population increases have little or no effect, because most of the forests have already been cut.

Historical data from China also confirm that per capita land use was much larger one or two millennia ago and had decreased by the centuries just before the industrial era. Working in pre-WWII Nanjing, *Buck* [1937] compiled land use trends during the last 2000 years across the entire agricultural area of east central China based on central dynastic administrative records (later updated and refined by *Chao*, 1986). The survey covered both dry land crops like millet, soybeans and wheat in the north, and irrigated rice in the south. The trend shows a decrease in per capita cultivated area from 0.6–0.7 hectares per person nearly 2000 years ago to 0.15–0.2 hectares by the early 1800s (Figure 5). *Ellis and Wang* [1997] found a similar decrease in per capita cultivation during the last 1000 years in a county-sized region of rice irrigation near the Yangtze River.

This range of evidence from Europe and China reveals a pervasive trend toward smaller per capita land use through time, but why did this happen? The most likely answer

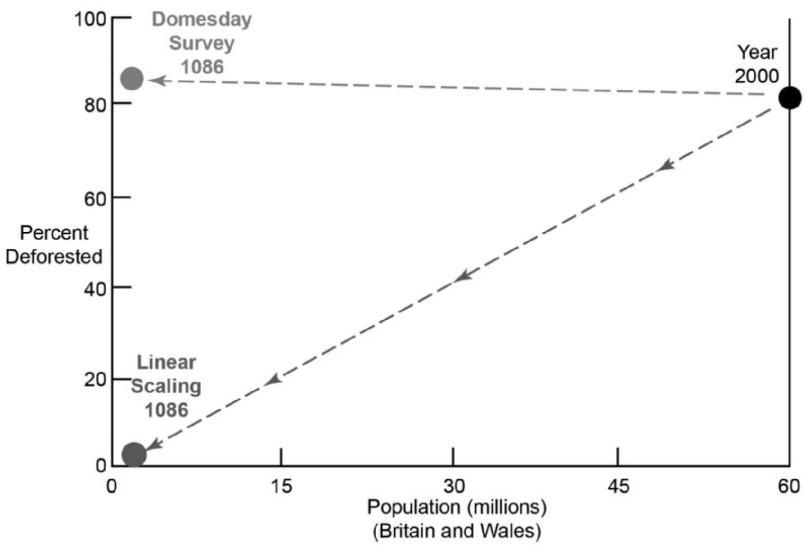


**Figure 3.** The assumption of constant per capita land use projects 2–3% forest clearance in Britain and Wales for the year 1089, but the Domesday survey shows 85% clearance at that time.

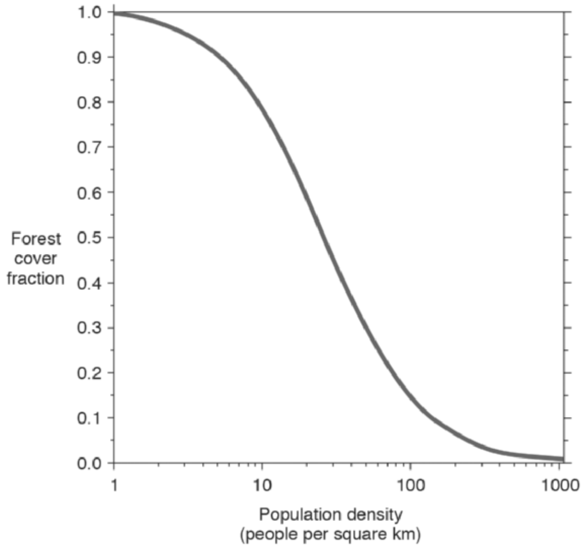


**Figure 4.** Sigmoidal trend of forest clearance versus population density based on historical data in Europe [*Mather*, 1992; *Kaplan et al.*, 2009].

comes from economist Ester Boserup. Decades ago, *Boserup* [1965, 1981] proposed that a gradual shift in the style of agriculture occurred over many millennia because of population growth, innovation and the adaptation of new farming skills (Table 1).

During the earliest "long-fallow" phase, farmers shifted constantly from plot to plot. They either cut down trees or girdled them to stop the flow of sap in the outer bark layers. Then they set fire to the dead debris during dry seasons and used dibble sticks to plant seeds in the ash-enriched soil. After a few years of growing crops, the soil fertility dropped

**Table 1.** The Boserup Sequence of Changing Population and Land Use[a]

| | Changes Through Time (Long Fallow to Short Fallow to Annual Cropping to Double Cropping) | |
|---|---|---|
| | Earlier | Later |
| Population density | low | high |
| Labor required per acre | low | high |
| Productivity per acre | low | high |
| Per capita area farmed | high | low |

[a]Based on *Boserup* [1965, 1981].

and farmers moved to new plots and repeated the sequence. Plots were reoccupied (if at all) after lying fallow for several decades, long enough to allow significant recovery of soil fertility.

This long-fallow phase of early agriculture used large amounts of land because of the cleared plots that were abandoned and left lying fallow. Each year's actively farmed plot may have occupied no more than one hectare per person, but the constant shifting from old to new areas left behind a large footprint of cleared forest long after each plot was abandoned (Figure 6). Because abandoned plots take a few decades to develop even semi-mature trees, only a small fraction of total reforestation (and carbon sequestration) would have occurred several decades after abandonment. These changes in above-ground carbon in vegetation were accompanied by similar changes in shallow soil carbon, with initial loss after clearance, and slow recovery later. This sequence of footprints left behind in effect boosts the cumulative area cleared per family to many hectares per person.

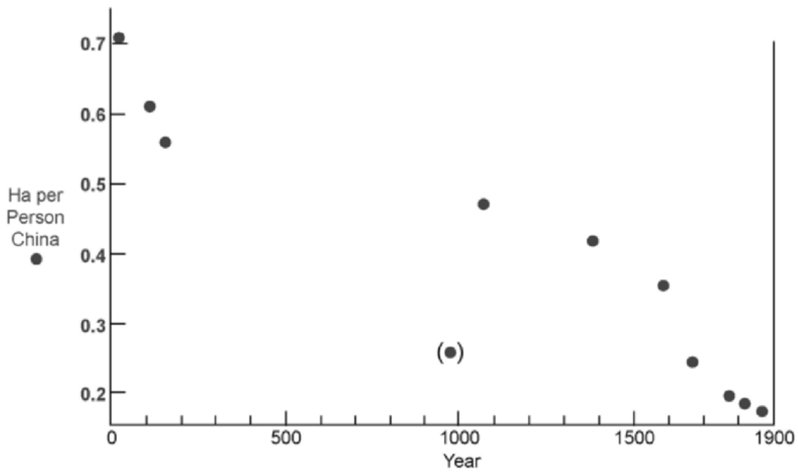


**Figure 5.** Per capita cultivation in China based on historical data [*Buck*, 1937; *Chao*, 1986].

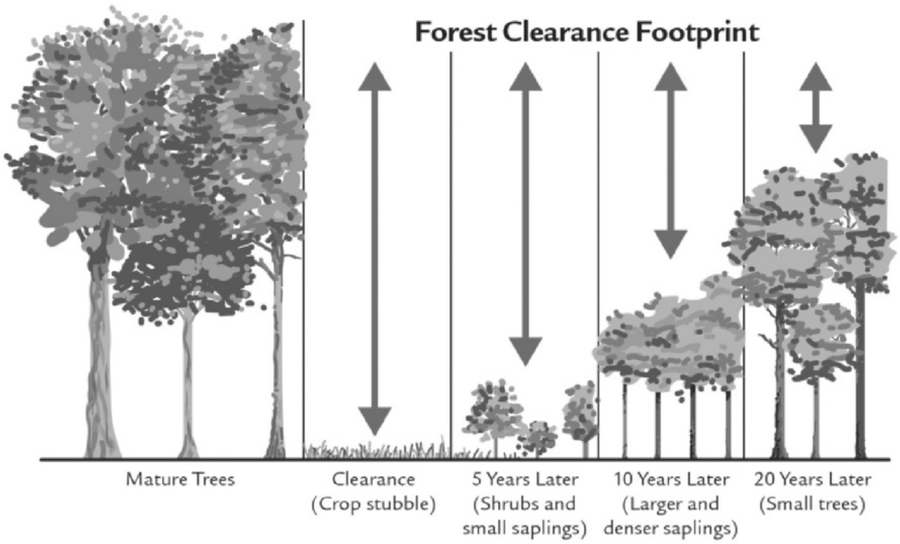


**Figure 6.** Cleared forest regrows slowly, leaving a "footprint" of abandoned land.

Over many millennia, the more reliable nutrition provided by agriculture led to population growth. As this happened, claims on the locally available land began to increase, as farmers began to be hemmed in by neighbors. As farming families became constrained to smaller holdings, they were forced to produce more food from their land.

This shift to smaller plots was possible because new farming methods were being adopted that gradual shortened the fallow period from several decades to just a few years and also lengthened the interval during which each plot could be actively cultivated before its nutrients were depleted. Eventually, plots could be cultivated every year or even twice a year. Key to these innovations was a new attention to enriching soil quality, at first by mixing in grass and other available vegetable debris, and later by spreading animal and human manure. With these new techniques, farmers used less land but still kept food productivity high.

This "Boserupian" view of the effects of population growth on land use is widely known to scientists in the fields of archeology, human geography and anthropology, and it is often used as a standard of reference against which to assess supporting or contradictory evidence [e.g. *Grigg*, 1979; *Netting*, 1993; *Turner and Shajaat*, 1996]. Yet Boserup's insights, and the published evidence for extensive early clearance, was either unknown to, or ignored by, most numerical land use modelers.

Boserup's view of past land use has recently gained renewed attention. *Ruddiman and Ellis* [2009] used various sources to estimate the average decrease in per capita land use during the middle and late Holocene. They inferred that per capita land use fell by a factor of about ten from ~4 hectares per person 7000 years ago to less than 0.4 hectares just before the industrial era. In a parallel effort, *Kaplan et al.* [2009] used the historical evidence from Europe noted earlier and found that the population density needed to cause a given fraction of forest clearance had increased through time (in effect, the sigmoidal curve plotted in Figure 4 moved from left to right through time). This trend indicates that farmers gradually cleared smaller amounts of forested land per capita as time passed, again consistent with the Boserup synthesis.

*Kaplan et al.* [2011] used the historical evidence from Europe to estimate global clearance during the last several millennia, with adjustments for higher primary productivity levels and longer growing seasons in the tropics. They estimated gradually decreasing per capita land use in all regions, with a marked acceleration during the last 3000 years. Their simulated clearance shows much of China, India, Mesopotamia and Europe largely cleared of forest and other vegetation already cleared by 2000 years ago (Figure 7a). The clearance simulated by Kaplan's method matches the regions where *Lewthwaite and Sharratt* [1980] mapped organized cultures and well-developed agriculture at that time (Figure 7b). Reconstructions of anthropogenic alteration of natural vegetation biomes by *Ellis* [2011] also show major human overprints in these regions long before the industrial era. In contrast, a simulation based on one of the models that assumes small and nearly constant per capita clearance (in this case the HYDE model of *Goldewijk* [2001]) shows very little deforestation by 2000 years ago, even in heavily populated areas that hosted highly advanced cultures (Figure 7c).

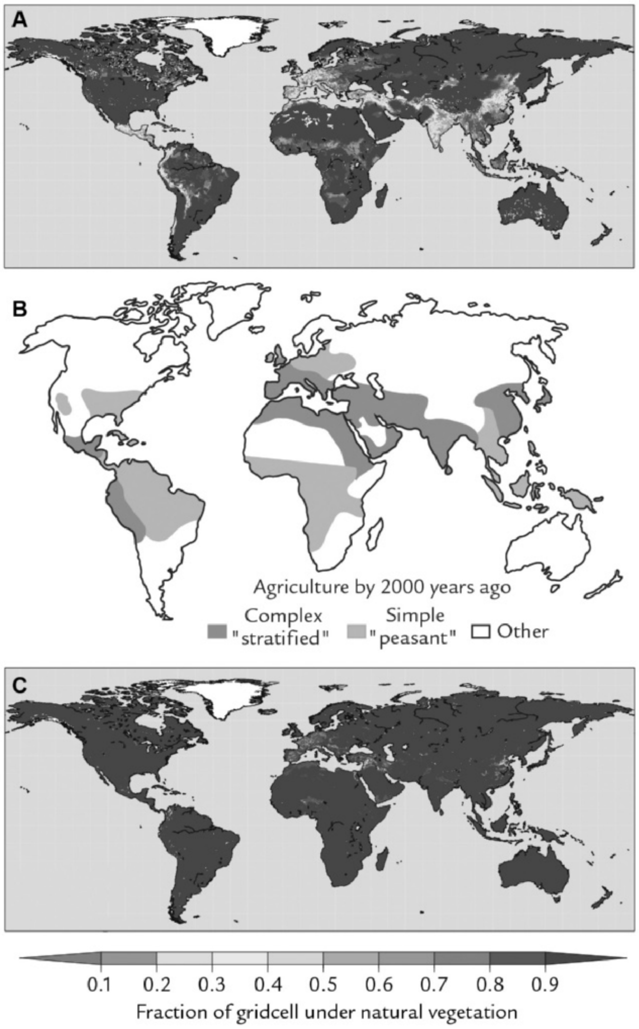


**Figure 7.** (a and c) Two simulations of vegetation clearance 2000 years ago from *Kaplan et al.* [2011] compared to (b) map of agriculture based on archeological information (from *Roberts* [1998] adapted from *Lewthwaite and Sherratt* [1980]).

In another recent effort, *Fuller et al.* [2011] synthesized archeological evidence on the spread of irrigated rice agriculture beginning near 5000 years ago. They found that by 1000 years ago irrigated rice was being grown in every region in Asia where it is grown today. By assuming that the subsequent infilling of irrigation farming in each area followed the log of population growth (based on the modern spatial relationship), they reconstructed an exponential increase in the area of irrigated rice after 5000 years ago. They estimated that the area of irrigated rice had reached 35% of the modern level by 1000 years ago, even though the population was only 5–6% of modern. Once again, this evidence suggests that early land use was far higher than the population levels would imply. *Fuller et al.* [2011] also estimated an exponential growth of $CH_4$ emissions that closely resembles and accounts for most of the $CH_4$ trend measured in ice cores for the interval 5000 to 1000 years ago.

In summary, a wide range of historical and archeological data shows that early land use was much higher on a per capita basis than during recent centuries. These results invalidate previous land use simulations that were based on assuming a small, roughly constant amount of clearance. Future simulations will need to incorporate this evidence for changing land use values.

Earlier, I mentioned the simple but deceptive challenge: “Why would (early) farmers have farmed any more land than was necessary to feed their families?” One response to this reasonable question is an equally simple counter-challenge: "Could farmers really have been so dim-witted that they learned nothing new about their basic livelihood during the last 7000 yrs, not a single new skill that enabled them to get more food from each acre of land they farmed?"

Ester Boserup’s synthesis provides a more thoughtful response to this question by placing land use in the perspective of what people had to do to survive in a world where population was growing rapidly. With neighbors gradually crowding in, most farmers could no longer rotate freely from wooded plot to wooded plot when they chose. Slowly, they were forced to produce more food from the shrinking plots of land available, and eventually from small and constant land holdings. As populations grew, farmers no longer had any choice.

Historical evidence further suggests a surprising reversal in deforestation trends during the industrial era. *Mather* [1992] found evidence that Britain, France, Sweden, and Switzerland had begun *reforesting* by 1850 and continued to do so through the entire industrial era (Table 2). Mather called this reversal from the ongoing deforestation of previous millennia the “forest transition”. Reforestation has also occurred in western Russia since 1920, because of population losses during and since the two world wars, mortality caused by forced relocations of ethnic populations, and a

**Table 2.** Time of the Start of Industrial Era Reforestation (the “Forest Transition”)

| Country | Start of Reforestation |
|---|---|
| England/Wales | 1750 |
| Sweden | 1800–1830 |
| France | 1825 |
| Switzerland | 1850 |
| Hungary | 1925 |
| Eastern United States, Canada | 1900 |
| Russia | 1920 |
| China | 1980s |

recent population decline. Net reforestation has also been occurring in China since the 1980's, in large part because of directives from the central government.. Even eastern North America, which had been rapidly deforested as recently as the 1700s and 1800s, was already reforesting by the late 1800s or early 1900s, as *Walter and Merritts* [2008] noted. In many regions, reforestation occurred after 1850 because mechanization of farm equipment made larger-scale, more cost-effective agriculture possible on fertile prairie and steppe soils by enabling farmers to plow out deep-rooted vegetation typical of semi-arid regions.

In summary, early attempts by land use modelers to reconstruct the pre-industrial history of forest clearance and land use for agriculture greatly underestimated the extent of early clearance. These modelers had "forgotten" (or never knew about) key work decades ago that told a very different story.

## 4. ARCHEOLOGICAL CONTRIBUTIONS TO INTERDISCIPLINARY EFFORTS

Because I am a marine geologist/paleoclimatologist, it may be thought presumptuous for me to comment on whether or not similar barriers to interdisciplinary communication exist within archeology and related fields. Nevertheless, I have enough recent personal experience, confirmed by informal discussions with a few archeological colleagues, to point out at least one area where room for improvement seems to exist (and has now begun to occur).

A decade ago, I became interested in the "big picture" aspects of archeology: the large-scale story of how agriculture developed in different regions and gradually spread across the continents. Not long afterward, I also became interested in how the agricultural practices used to obtain food from the land changed through time. Taken together, I see these advances as one of the most fascinating "stories" our species has to tell, and arguably the most important. Without these advances, the modern world we know would not have come into existence.

My early investigations of past land use were unsystematic, but gradually I reached the point where I felt I was seeing the field more or less whole. So I offer the following comments on archeology from this decidedly non-expert outside perspective.

Despite all the admirable work done in this field, my impression is that archeology and its closely related disciplines are to some extent "balkanized." By this, I mean the field often lacks a "big picture" view, especially the kind that comes from integrating discrete point-source information into larger-scale regional maps. I realize that most of the actual work of archeology is the product of long "dirty boots" field seasons spent intensively examining a particular site of a certain age in a specific region. The first results of this kind of labor are inevitably specific to that one site in that one region, although often the published results are usually compared to nearby sites to see how well they fit into larger regional-scale interpretations.

What I have not found in my reading is much evidence of efforts to integrate this hard-won site-specific information into a larger story at subcontinental to continental scales. Books like *"First Farmers"* by *Bellwood* [2005] very capably summarize general trends in words, but few such summaries have tried to take advantage of the larger-scale trends that can now be revealed by mapping the enormous number of well-dated archeological sites available in most regions.

One admirable exception (and a good example of what I mean) was the effort by *Zohary and Hopf* [1993] who used archeobotanical information from hundreds of well-dated archeological sites in southwest Asia and Europe to map the first arrival of the fertile-crescent package of crops between 10,000 and 5,500 years ago. *Turney and Brown* [2007] later displayed this information in an informative way by showing sites color-keyed to different ages. The book *The Holocene* by *Roberts* [1998] also added several regional-scale maps from primary sources.

But otherwise, at least to my knowledge, these efforts stood alone in attempting large-scale map integration of archeological and archeobotanical data. Much of what I learned about this larger picture came from reading two trade books, *Guns, Germs, and Steel* by *Diamond* [1999] and *1491*, by *Mann* [2006]. Although both were very informative, they had the relatively limited graphic treatments typical of trade books.

Recently, the situation has improved considerably. For example, *Li et al.* [2009] mapped archeologically dated sites in east central China between the interval from 8000 to 7000 years ago and the one from 5000 to 4000 years ago. In those 3000 years, the number of sites shows a 30-fold increase. Because these people were mainly agriculturalists, their presence in naturally forested regions implies the start of major forest clearance in China during this interval, along with increased $CO_2$ emissions.

Two independent but convergent efforts [*Gong et al.*, 2007; *Ruddiman et al.*, 2008] mapped the spread of rice paddy agriculture in China after irrigated rice was domesticated near 6500 years ago. As noted earlier, *Fuller et al.* [2011] has recently used archeobotanical criteria to refine and extend these efforts to all of southern Asia for the interval between 6500 and 1000 years ago. *Fuller et al.* [2011] also used archeological data to map the spread of livestock across Asia and Africa during the last 7000 years, although they did not attempt to estimate methane emissions. Previously, *Chen et al.* [2010] had mapped the spread of Zebu cattle across India.

As some of these examples show, synthesizing archeological data is important for an interdisciplinary reason. These data sets can be used to test the hypothesis that the spread of agriculture long before the industrial era was already having a major effect on greenhouse-gas emissions [*Ruddiman*, 2003, 2007]. Because several regions still lack archeological syntheses of crop data, future efforts are needed to fill in the largest time/space gaps in current coverage. Another important interdisciplinary effort in the future will be to develop models that can transform discrete point-source archeological data into integrated estimates of regional greenhouse-gas emissions.

## 5. CONCLUSIONS

As of 2011, scientific disciplines related to archeology and those covering various physically based sciences seem poised for a mutually beneficial and explosive growth in areas of overlapping interest. Artificial barriers that have constrained cross-disciplinary exchanges have begun to break down.

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# Arguments and Evidence Against a Younger Dryas Impact Event

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We present arguments and evidence against the hypothesis that a large impact or airburst caused a significant abrupt climate change, extinction event, and termination of the Clovis culture at 12.9 ka. It should be noted that there is not one *single* Younger Dryas (YD) impact hypothesis but several that conflict with one another regarding many significant details. Fragmentation and explosion mechanisms proposed for some of the versions do not conserve energy or momentum, no physics-based model has been presented to support the various concepts, and existing physical models contradict them. In addition, the a priori odds of the impact of a >4 km comet in the prescribed configuration on the Laurentide Ice Sheet during the specified time period are infinitesimal, about one in $10^{15}$. There are three broad classes of counterarguments. First, evidence for an impact is lacking. No impact craters of the appropriate size and age are known, and no unambiguously shocked material or other features diagnostic of impact have been found in YD sediments. Second, the climatological, paleontological, and archeological events that the YD impact proponents are attempting to explain are not unique, are arguably misinterpreted by the proponents, have large chronological uncertainties, are not necessarily coupled, and do not require an impact. Third, we believe that proponents have misinterpreted some of the evidence used to argue for an impact, and several independent researchers have been unable to reproduce reported results. This is compounded by the observation of contamination in a purported YD sample with modern carbon.

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