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Per Capita Land Use through Time and Space: A New Database for (Pre)Historic Land-Use Reconstructions

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Abstract: Anthropogenic land cover change (ALCC) models, commonly used for climate modeling, tend to utilize relatively simplistic models of human interaction with the environment. They have historically relied on unsophisticated assumptions about the temporal and spatial variability of the area needed to support one person: per capita land use (PCLU). To help refine ALCC models, we used a range of data sources to build a new database that attempts to bring together PCLU data with significant time depth and a global perspective. This new database can provide new nuance for our understanding of the variability in land use among and between time periods and regions, data that will have wide applicability for continued research into past human land use and present land-use change, and can hopefully help improve existing ALCC models. An example is provided, showing the potential impact of new PCLU data on land-use mapping in the Middle East at 6000 BP.

Keywords: land use; land cover; ALCC; PCLU

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1. Introduction

Humans have been modifying their environments for millennia, becoming, over time, the driving force in changes to the global environment [1–4]. However, contention remains around when human land-use changes started and their impact on the environment through time [4–6]. Among the many impacts of past human land use are changes in vegetation type and cover, with the latter being an important driver of climate change [7]. While we can track land-use changes in the present in a variety of powerful ways [8,9], modelling how humans impacted land cover in the past through changes in land use is more difficult. However, understanding (pre)historic land use and land cover change is crucial for understanding climate change in the present [4].

Historical models of anthropogenic land cover change (ALCC models) are commonly used in climate modeling [3,10–12] and are generally constructed based on published estimates of past population combined with estimates of land-use requirements per person, or per capita land use (PCLU) [11]. While there are ALCC models covering the last several

thousand years [1–3], these models have been constrained by uncertainties in population data and by the limited availability of per capita land-use (PCLU) values applicable to different time periods, regions, subsistence strategies, and societies. This paper presents a new global database of PCLU values, spanning several millennia and multiple subsistence strategies, intended to improve the available data for ALCC models while providing an important resource for further research questions on human–environment interactions. This database builds on a wide range of data sources and helps to provide significantly greater nuance to our understanding of the variation of human land use through time and space.

ALCC Models and PCLU

ALCC models rely on PCLU estimates to reconstruct land-use change through time. They do this by multiplying population estimates by the area supposedly needed to support each person in the population, i.e., a PCLU value. Researchers working on ALCC models acknowledge that PCLU is highly variable [11], and for most parts of the world, it is difficult to reconstruct per capita land use with sufficient resolution earlier than 1960. Therefore, ALCC models have generally relied on relatively simplistic estimates [13]. Until the latest version, for instance, the most widely used ALCC model, the History Database of the Global Environment (HYDE), applied a single hindcast PCLU value for agriculture and a single value for pastoralism before 1960 [2]. The diverse range of competing ALCC models is, at least in part, likely due to the restricted variability in how PCLU values are applied. Thus, to improve accuracy, ALCC models need better models of past human land use. One approach would be improving the quality of PCLU data both regionally and temporally. More data about how and why land use varies across time and space would allow for their more nuanced application in ALCC models and in general land-cover/land-use research.

Furthermore, current ALCC models, such as HYDE and KK10 [1–3], rely heavily on data at the national boundary level. This is convenient for tracking modern land-use and land-cover change and for incorporating existing national-level population data sets, but is problematic for modeling land use backwards in time. For instance, land-use data in the HYDE model often show national boundaries persisting through time, well before the earliest existence of those boundaries (Figure 1). But getting rid of the effects of modern national boundaries is difficult, given that much of the data are at this resolution. One possible alternative approach might involve connecting per capita land use to climatic zones [14] rather than national boundaries by using either modern climate classification [14–16] or, potentially, models of past climate classifications [17,18], if PCLU values can be reliably linked to climate classes. This will allow for more accurately distributed per capita land-use values in the past and will release the data from the constraints of modern borders (Figure 2).

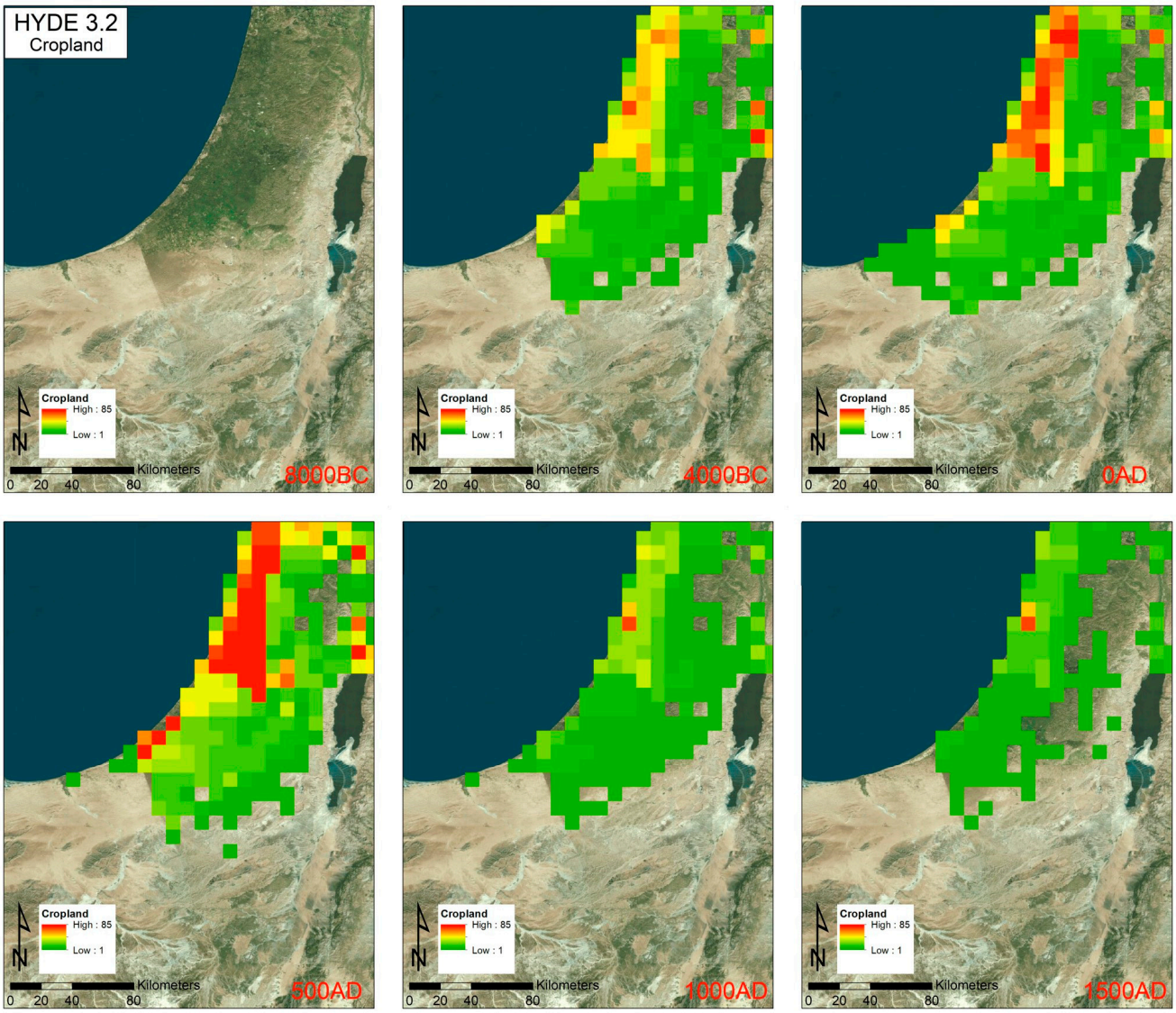


Figure 1. Sample of cropland estimates (in km^2 per grid cell) from HYDE 3.2 [1] from 8000 BCE to 1500 AD. The border between Israel and Egypt has a real land cover difference in the present along the modern-day border, as visible in the satellite basemap, but this difference incorrectly persists backwards in time through at least 4000 BCE in the HYDE model. Microsoft product screen shot(s) reprinted with permission from Microsoft Corporation, Redmond, WA, USA.

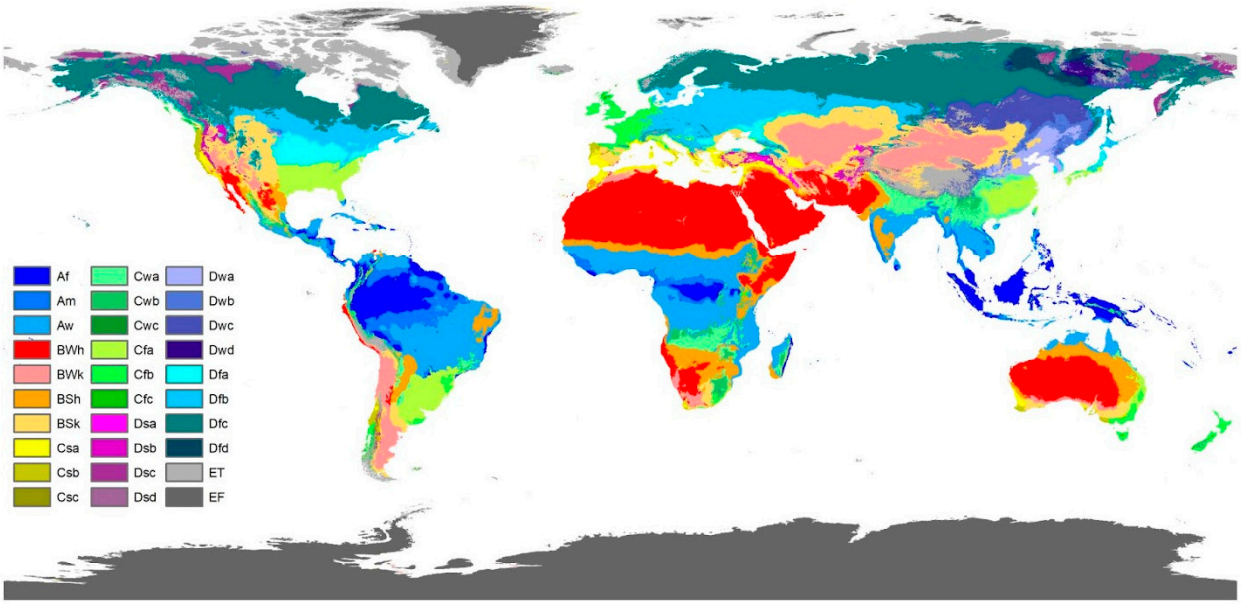


Figure 2. Köppen–Geiger global climate classification data visualization from [14]. Classes (and visualization) following Beck et al. (2018) [14]: Table 2. The purpose here is to show the variability and distribution of climate classes; see [14] for specific definitions.

2. Materials and Methods

2.1. Data Sources

The database presented here (see SI below) incorporates information from a wide variety of sources. It is a comprehensive, but not exhaustive, database built from legacy data obtained from literature searches and published databases. As a starting point, we incorporate PCLU values gathered by Goldewijk et al. [11], drawn from a range of modern and historic PCLU values from a limited number of countries. Their approach assumed that since historic land-use data are extremely limited, they would build a few representative samples of PCLU values for different regions and interpolate those values to neighboring countries that could be assumed to have similar land-use trajectories through time.

The best source of modern PCLU data, and the source for a significant amount of the PCLU data used by Goldewijk et al. [11] and others, are derived from data published by the Food and Agriculture Organization (FAO) of the United Nations [19,20], which maintains a global database that includes data on land-use area and population size from 1960 to the present. FAO land-use data are gathered from a variety of sources, including questionnaires filled out by each individual country and submitted to the FAO annually, estimates calculated by the FAO, data reported by other intergovernmental agencies, and data reported by official national publications and websites. Though limited to the last 64 years, this database is an excellent global baseline for per capita land-use values tied to national boundaries, as commonly used in ALCC models. Sampled data for cropland hectares per capita and pasture land hectares per capita from FAO data for 1960, 1970, 1980, 1990, 2000, and 2010 are included as a separate table in the database for all available countries. However, the spatial resolution of FAO data is poor, being homogenized to national boundaries, and the quality of data reporting may vary by region and through time [21,22]. The primary goal of the current database was to collect PCLU values from before 1960. However, we have also included values from 1960 to the present, supplementing FAO data wherever possible to provide more detailed information for specific subnational regions or societies.

The database presented here, therefore, moves forward from these existing sources by providing additional PCLU values from a variety of ethnographic, archaeological, and historical sources. Many PCLU values are transcribed or calculated from data collected by early-to-mid-20th century ethnographers, development specialists, and geographers,

e.g., [23–28]. Allan [27], for instance, synthesized population and land-use area values for a diverse range of peoples and subsistence practices drawn from earlier ethnographies to compare strategies among different environments and examine the variability of African food production. Additional data come from projects that calculate land-use values backward in time, based on archaeological and climatic data, for specific regions of the world. The PAGES Rhine LUCIFS project, for instance, focused on the reconstruction and quantification of concrete PCLU values for various prehistoric time slices (early Neolithic, Iron Ages) in the Rhineland [29–32].

One major limitation is a general lack of published data on per capita land use for hunting/gathering/foraging societies. Only a few values were found in older sources [27,33–36], representing data for just a few countries. Instead, the bulk of the hunter/gatherer/fishing/forager (HGFF) values [see 13] in the database come from Binford's *Constructing Frames of Reference* [37]. As part of a wider study of variability in hunter-gatherer subsistence strategies, Binford presents a database of 339 hunter-gatherer groups, with ethnographic and environmental variables for each one of them. These data incorporate the earlier ethnographic data published by Murdock [38] and include total population, an estimate of the total area occupied by each group, and a calculated value for density (in persons per 100-square-kilometer unit). These data have been converted to hectares per person and included in the database.

2.2. Data Structure

The PCLU database presented here includes data categories for: continent, country, subregion, time period, land-use categories, PCLU value, data source, comments, and cited in. Although subregions are included where possible, most data are only specified to the "country" level. This is not an ideal spatial resolution for these data, and in fact, the variable size of countries makes it somewhat problematic. In many cases, sources identify a more specific subregion, and these can be included in the database, but it is harder to standardize these subregional categories. In some cases, sources identify a particular ethnic group or population that is being recorded, and this is included in the comments section where applicable. However, the primary reason that "country" is used as the organizing spatial category is also because this aligns with the primary ALCC models (HYDE 3.2 and KK10) and will allow this data to be most easily incorporated into those models.

Subsistence strategies are recorded, where available, using the global land-use classification system developed by the LandCover6k project [13,39,40]. This classification system, designed in consultation with global climate modelers, historians, archaeologists, and geographers, provides a scale-independent [41], nested series of land-use categories. At the top level, LU1, land use is divided into general categories meant to enable the broad-scale analyses. The applicable values for this database are "hunting/gathering/fishing/foraging", "agriculture", and "pastoralism". Each of these categories can be further subdivided into more fine-grained divisions, LU2 and LU3, that provide more detailed information about land use. For agriculture, for instance, LU2 categories include "herbaceous ground crops", "swidden/shifting", "wet cultivation", and "agroforestry/arboriculture" (see [13] for a complete description).

PCLU values are recorded in hectares per capita (ha/cap), the standardized unit for this type of data in ALCC models. In many sources, PCLU is either not directly reported (for instance, "population" might be reported separately from "area under cultivation") or reported in different units [42]. In such cases, a PCLU value has been calculated to standardize the data according to the database.

2.3. Distribution of Values

The spatial and temporal distribution of PCLU values in the database is not random and reflects a few important biases. Although it includes ~1850 separate PCLU values covering nearly all of the 206 modern states, the three major land-use categories, and a temporal range of ~8000 years, there is significant redundancy, and the entries are heavily

skewed toward the present and some particular regions. This is summarized below in Tables 1 and 2 and discussed in the results below.

Table 1. Distribution of PCLU database values by region and LU1 category.

Continent	# of Agriculture Values	# Pastoralism Values	# of HGFF Values	Total
North America	186	17	223	426
Latin America	91	58	20	169
Europe (including former USSR)	203	95	9	280
Asia	244	42	24	310
North Africa and Middle East	311	29	0	340
Sub-Saharan Africa	152	41	21	214
Oceania	17	11	60	88
Total	**1204**	**293**	**357**	**1854**

Table 2. PCLU counts, by date, in the database.

	8000–4000 BCE	4000–2000 BCE	2000–1 BCE	0–1000 CE	1000–1800 CE	1800–1900 CE	1900–1950 CE	1950-Present
Count	53	42	73	50	85	307	274	835

3. Results

The database provides several important take-home messages about PCLU values that can inform ALCC models, presented below.

3.1. Variation among Subsistence Strategies

One of the significant things the database highlights is variation in PCLU values for different subsistence strategies based on the LC6k categories. There are some expected patterns here that reflect significant differences between agriculture, pastoralism, and HGFF. At the broadest level, we can see those differences in a density plot of the PCLU values for these three categories (Figure 3) and in spatial distributions as mean values per country (Figure 4). Agriculture and pastoralism have relatively similar ranges, but the PCLU values for agriculture mostly cluster below 1 ha/cap, while higher pastoralism values above 1 ha/cap are much more common.

As should be expected, HGFF requires significantly more land per person. Similarly, because HGFF economies are broadly influenced by the local biomass, biodiversity, and natural resources in a given landscape, the area required per person can vary much more than for food production strategies. Land-use requirements are heavily dependent on resource availability and so tend to vary with latitude and other climatic factors such as temperature and precipitation. Additionally, although it was long assumed that hunting and gathering peoples were passively dependent on naturally occurring resource availability, it is increasingly clear that many foraging groups, across a deep span of time, have been capable of both long-term modification and management of ecosystems [43–45] and of adapting foraging practices [46] in order to increase resource availability and decrease land-use requirements per person. Thus, PCLU values for HGFF can span a dramatic range, from as little as 10 ha/cap, overlapping with the high ranges of agriculture and pastoralism, to well over 10,000 ha/cap.

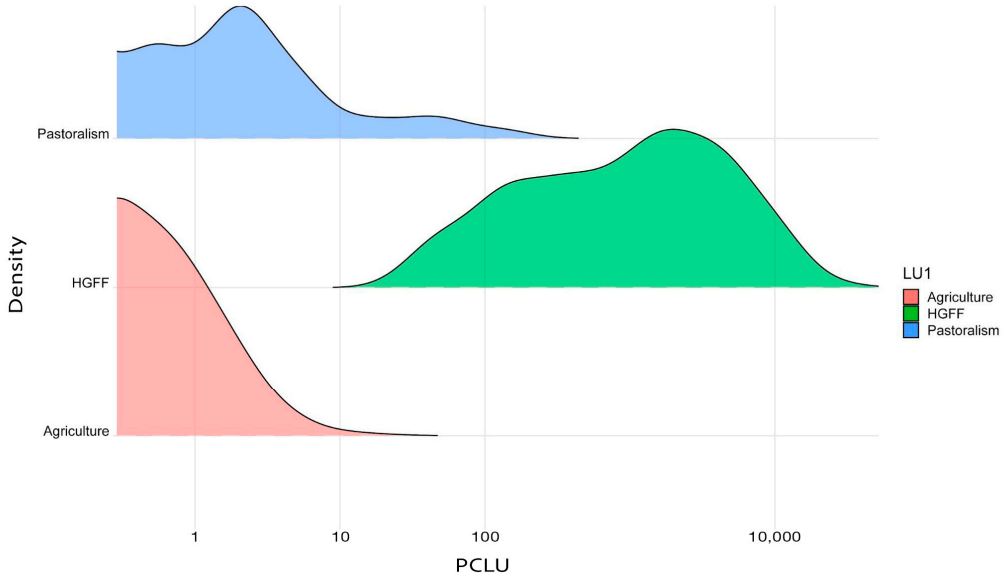


Figure 3. Density plot for all pastoralism, hunter/gatherer/fishing/foraging (HGFF), and agriculture per capita land-use (PCLU) values.

3.2. Variation among LU2 Categories

The PCLU database includes further land-use classification refinements following the LC6k system [13]. As mentioned above, Land Use 2 (LU2) and Land Use 3 (LU3) refinements allow for finer-grained distinctions to be made among HGFF, pastoral, and agricultural groups, though LU2 and LU3 values are not available for all entries in the database. Similar to the LU1 distribution, LU2 PCLU distribution follows relatively expected patterns, especially when only considering values from before 1960. Among agricultural groups, wet cultivation, such as paddy rice farming, has the smallest per capita land use, and swidden/shifting the largest. Among the pastoral groups, anchored pastoralism has the smallest PCLU values, overlapping significantly with swidden/shifting cultivation, and mobile pastoralism the largest (Figure 5, n.b. land-use type definitions follow [13]).

3.3. Geographic Distribution

A major goal of this database was to build a comprehensive collection of PCLU values that spans the entire globe at the national level and includes the maximum possible time depth. The inclusion of FAO data ensures there is at least one entry for almost every nation (Figure 6-top), providing blanket global coverage of recent land-use values. However, FAO data are already available and easily accessed (http://www.fao.org/faostat/en/, accessed on 14 June 2024). What archaeologists and ALCC modelers are most interested in is the availability of values before the start of FAO data (1960), which already tracks declines in per capita land use that accompanied the last half-century of global population growth and declining availability of new land to convert to agriculture or pasture [2,47]. While there are ~1800 PCLU values in the database from sources other than the FAO, many of these, too, are recent values. Figure 6 (middle) shows a plot of the PCLU values in the database that predate 1960. While there are nearly 900 PCLU values from before 1960, and these are spread over the last 10,000 years (Table 2), the geographic spread of this data is less complete. There are many countries, representing a significant proportion of the globe, with no coverage before 1960. This includes much of the Sahara, the Arabian Peninsula, Eastern Europe, and Central America.

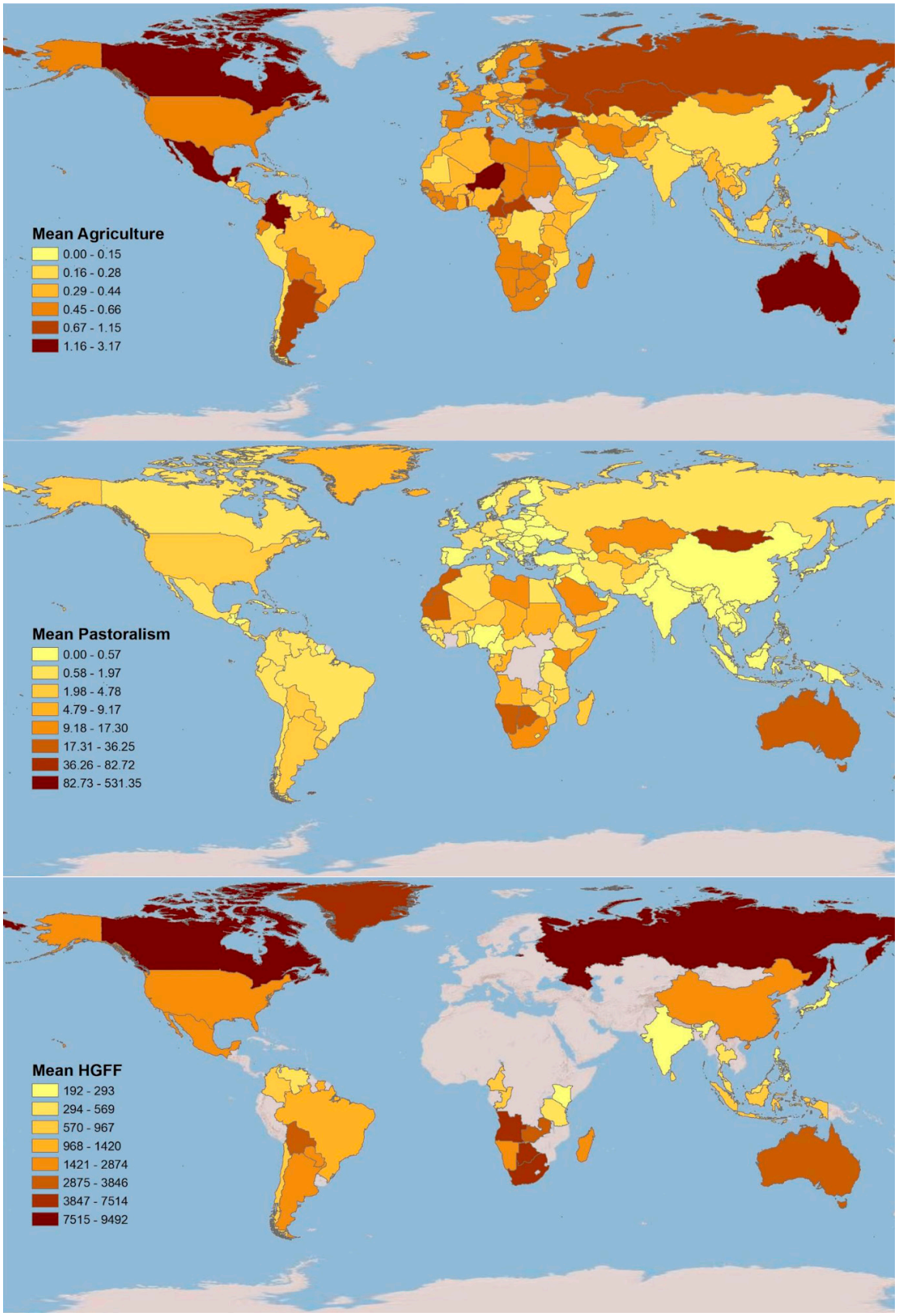


Figure 4. Comparison of mean PCLU per country (all dates): agriculture (**top**), pastoralism (**middle**), HGFF (**bottom**).

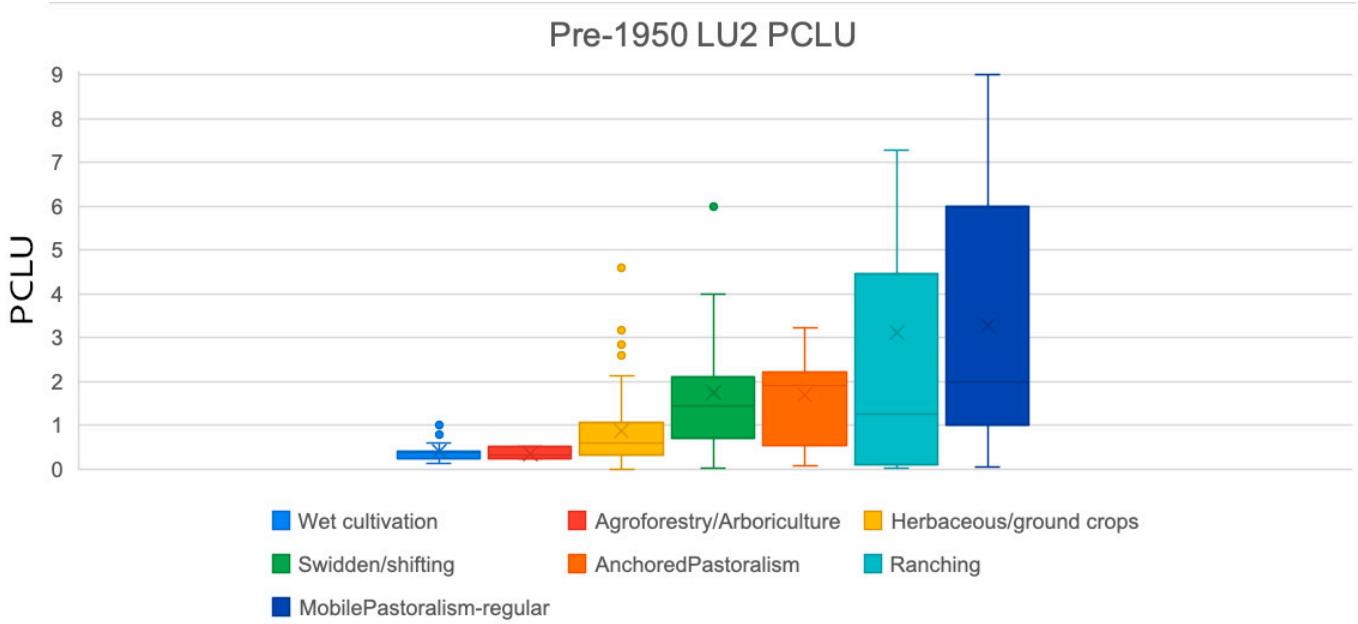


Figure 5. Comparison of second-level land-use (LU2) PCLU distributions for all pre-1960 entries.

3.4. Environmental Distribution

Understanding the long history of land-use change is critical for tracking changing biomes and even the earth system. Archaeological and paleoecological data have established that, for the entire Holocene, humans have been modifying the landscape and increasingly affecting the environment while increasing the carrying capacity of the land through changes in technology, the manipulation of ecosystems, the modification of domestic plants, and a wide range of productive practices [48,49]. While some of these cultural practices, such as irrigation canals in arid environments, worked to partially transcend natural limitations, in many contexts of the past, environmental conditions might be foreseen to limit the number of people that could be supported by a given unit of land. We should expect a strong, though not deterministic, relationship between environmental conditions and per capita land-use requirements regardless of time period and subsistence strategy. To a significant extent, this is true in the database.

For this analysis, we used high-resolution Köppen–Geiger climate maps [14] to compare with PCLU data. The Köppen–Geiger [K–G] classification system divides the world into five main classes, based primarily on vegetation, and 30 subtypes, based on precipitation and temperature [15]. This classification system has been widely used for climate and climate change research. There are, though, significant problems comparing the PCLU database to K–G classification. First is the issue of resolution. While Beck et al. [14] have published K–G maps at 1 km × 1 km resolution, the PCLU data are primarily divided by national boundaries representing, in many cases, huge areas of land containing many different K–G classes. Large countries, such as China, the United States, and Argentina, may contain as many as 25 different K–G classes as the dominant environmental condition in at least one 1 km^2 cell (Figure 6-bottom). However, for a basic comparison, we compared the PCLU database values to the most common K–G value for each country. This is a gross simplification of the climate for each country, though in the majority of cases, the most common K–G class does represent over 50% of the area in each country. Additionally, the K–G data represent a modern snapshot of environmental conditions (1980–2016) and may not match the conditions present when each entry in the database was recorded, especially for records in the distant past. The results of this analysis show, as expected, that PCLU values do vary based on dominant K–G class per country. Temperate regions have smaller and narrower ranges of PCLU values (Figure 7).

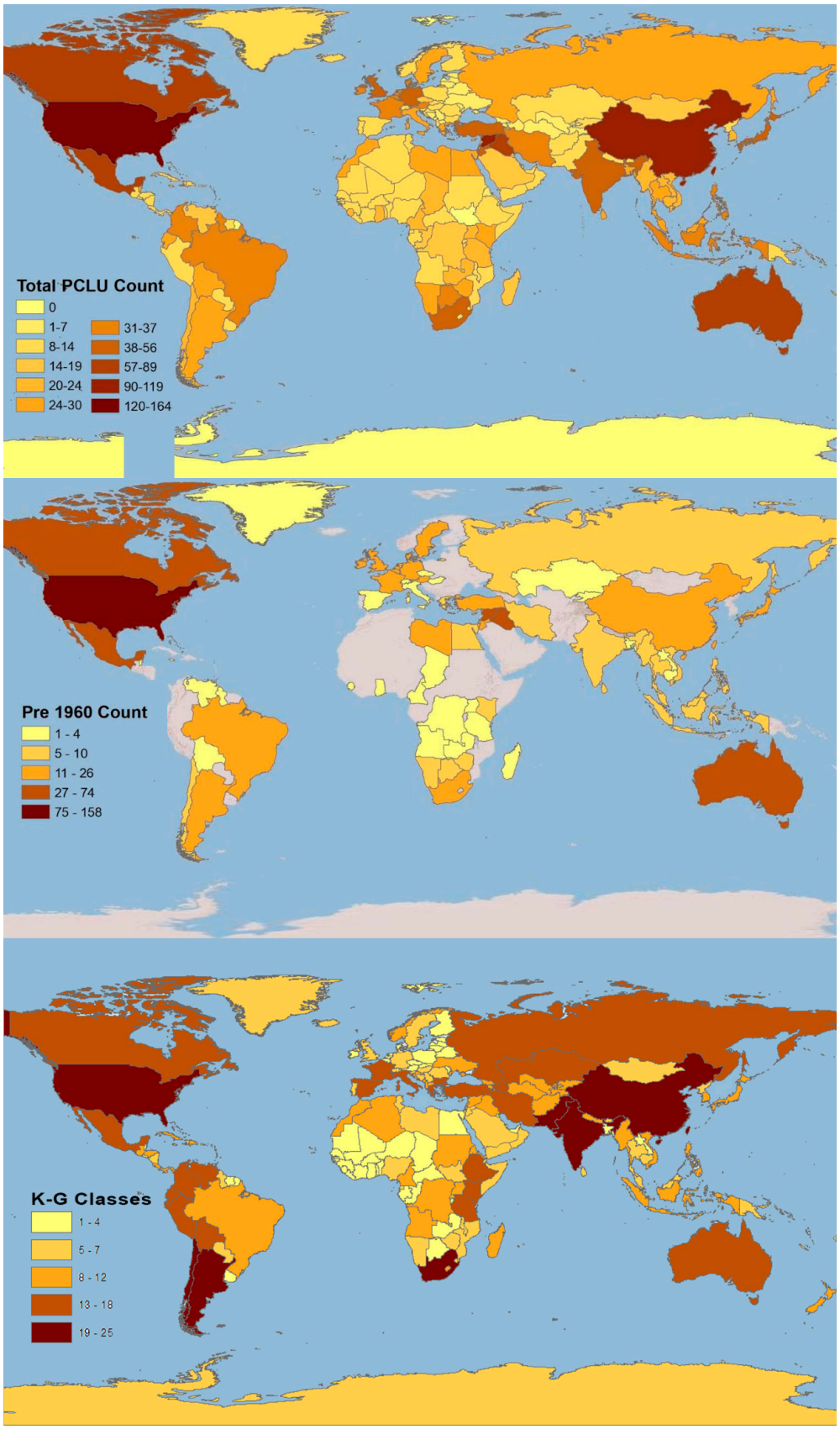


Figure 6. Comparison of total PCLU values per country (**top**), total PCLU values before 1960 per country (**middle**), and the total number of Köppen–Geiger classes per country (**bottom**).

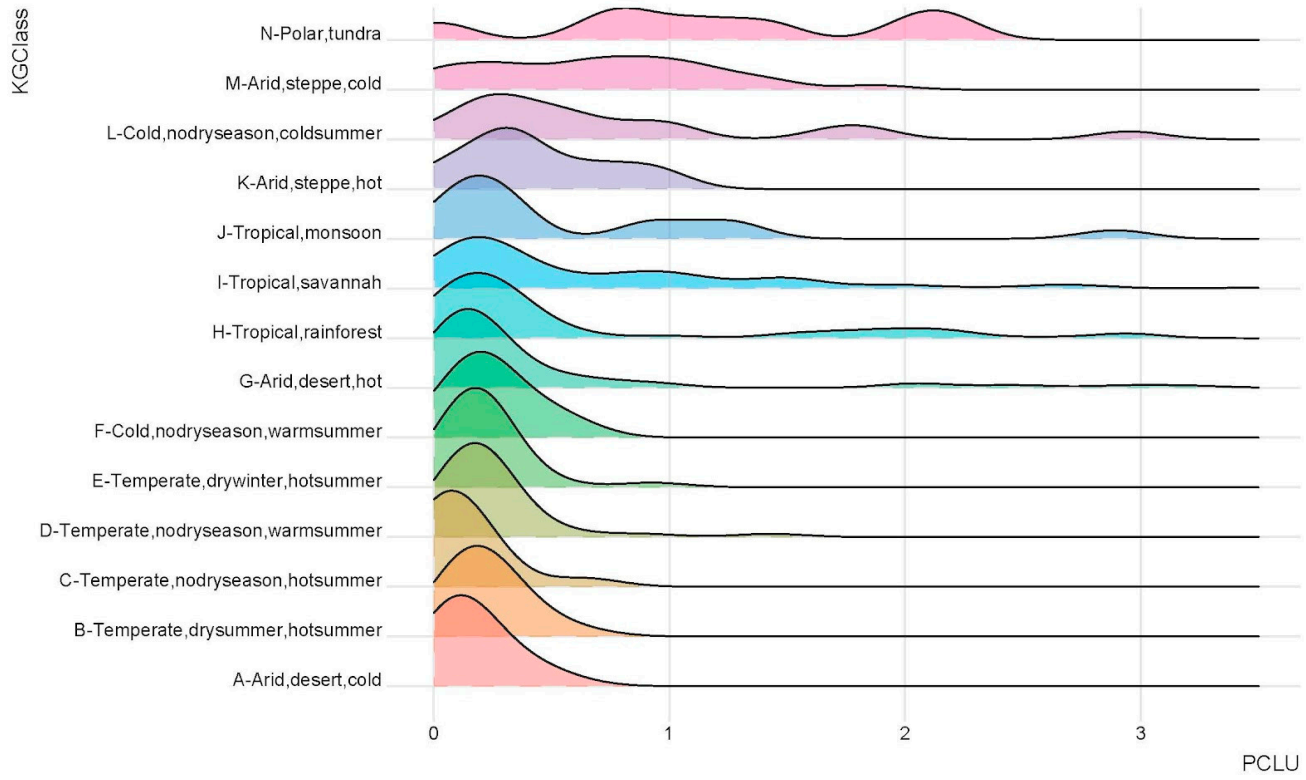


Figure 7. Density plot for PCLU values based on Köppen–Geiger class.

3.5. Subnational Regions

It is clear from the above that for at least some regions, national boundaries are far too broad to be described by a single PCLU value. For these regions, it would be better to have finer-grained subnational boundaries. Where possible, these sorts of additional georeferencing data have been included in the database. However, the availability of this sort of finer-grained detail is limited. The HGFF data published by Binford [37] includes enough information to visualize smaller spatial units for PCLU values for some countries, such as the US and Australia (Figure 8). But in most cases, there are limited subnational data.

3.6. Temporal Variation

Tracking PCLU change through time is particularly difficult because of the dearth of historic PCLU data [11,50]. In only a few regions do we have some reasonable continuity of PCLU values into the past. However, by aggregating the global data, we can see obvious trends in PCLU values through time. Figure 9 shows the box plot for all PCLU values divided into arbitrary time periods based loosely on the density of data in the database.

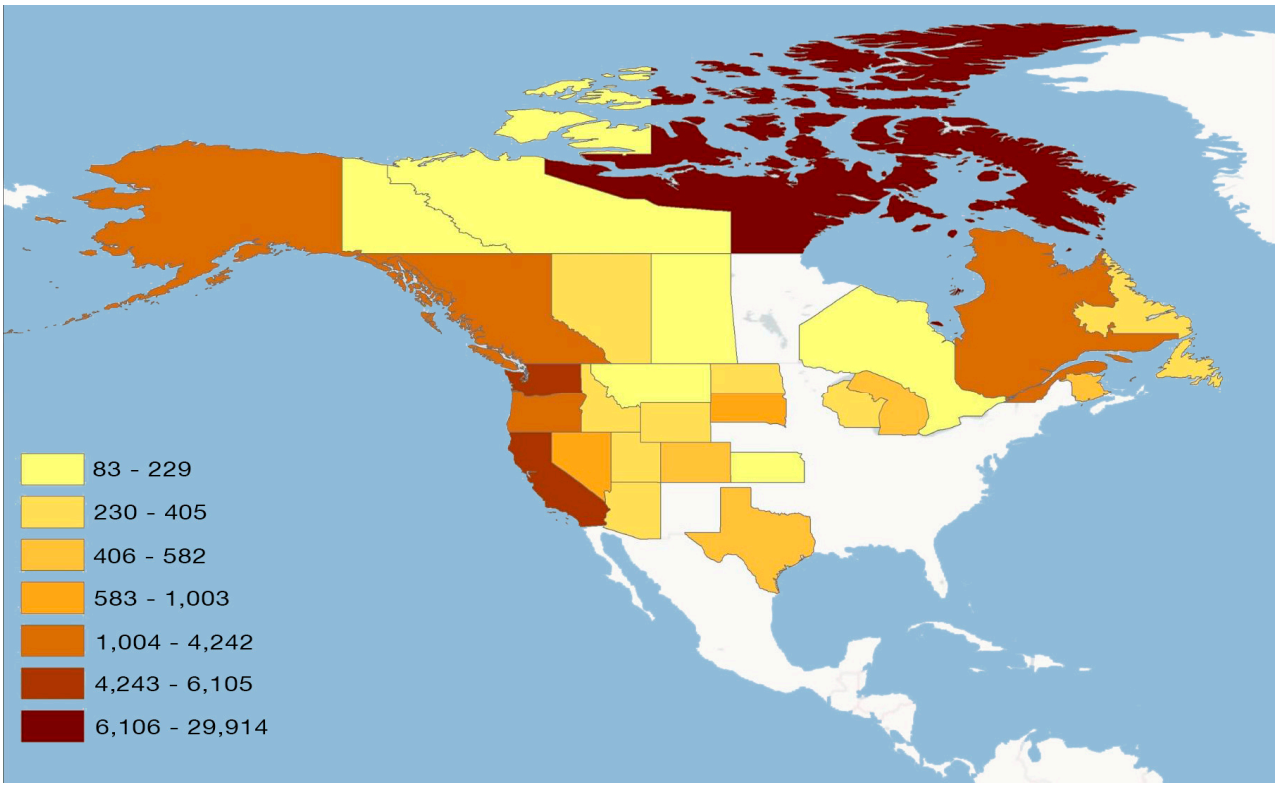


Figure 8. Mean HGFF PCLU value per modern US state and Canadian province.

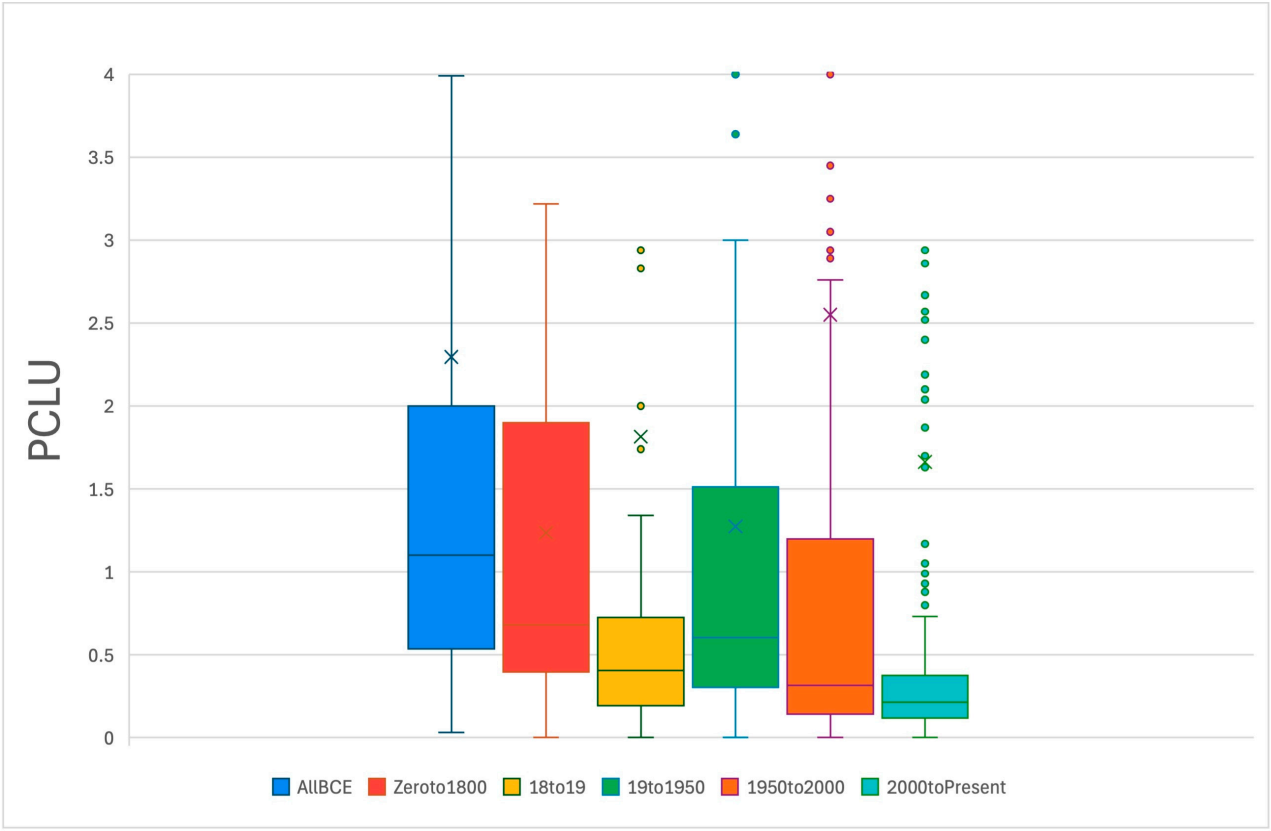


Figure 9. Plot of time ranges in PCLU database.

Changing land use through time can be difficult to model accurately. We know that, on average, per capita land use declines through time. But these changes can suffer significantly from problems of equifinality. Land use can be affected not only by changing environmental conditions but also by changing social structures and subsistence technologies. The anthropogenic modification of species and soils through time has had a dramatic effect on productivity and thus land-use requirements. This is especially marked for *Zea mays*, for instance, with domestication characterized by decreasing profligacy but the massively increasing size of individual ears [51]. Similarly, chinampas, created by the Aztecs and still in use in some parts of Mexico, require the careful creation of rich, organic soils from excavated canals built up into floating gardens and have one of the highest levels of productivity of any technological intervention [52].

The strength of the current database lies in its broad range of subsistence types, time periods covered, and global range, rather than the total number of data points over a significant time span for any one country. In only a few examples does the database include many entries that cover a significant time span for the same country. In the US, for example, the database includes 200+ entries, and these entries span from 600 CE to the present. However, the vast majority of those dates are from 1800 CE onwards and represent a broad variety of environmental conditions rather than a linear sample of a single area through time. For a few countries, such as China, the database contains more temporally expansive entries. The database contains ca. 80 entries for the modern state boundaries of China. While the specific entries may be similarly spread across a range of environmental conditions, they do provide a more evenly distributed range of dates, from 1 CE to the present, allowing a more complete temporal visualization of PCLU through time (Figure 10).

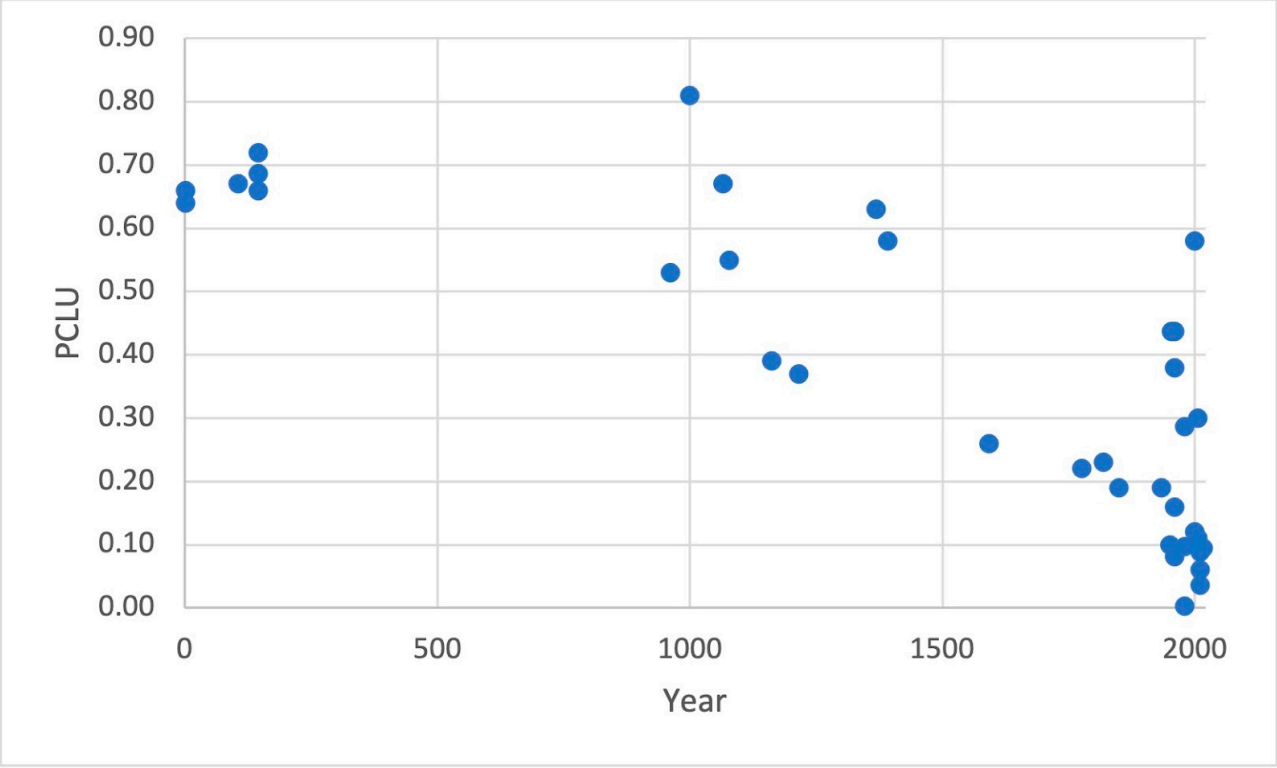


Figure 10. PCLU database values vs. time for China. Each dot represents one PCLU entry in the database.

While Goldewijk et al. [11] focused on specific individual countries for which there were historic PCLU values that could be used to construct temporal regional PCLU trajectories, one goal of our database was to build a more comprehensive aggregation of values

from any country or time period. This means that rather than building PCLU trajectories for a specific country that can be interpolated to other neighboring regions, our database can potentially combine all historic values from across a region to include a greater range of such values. For instance, aggregating values from all northern European countries gives a greater breadth of temporal values, spanning 6000 years (Figure 11 n.b., this figure only includes agriculture and pastoralism PCLU values).

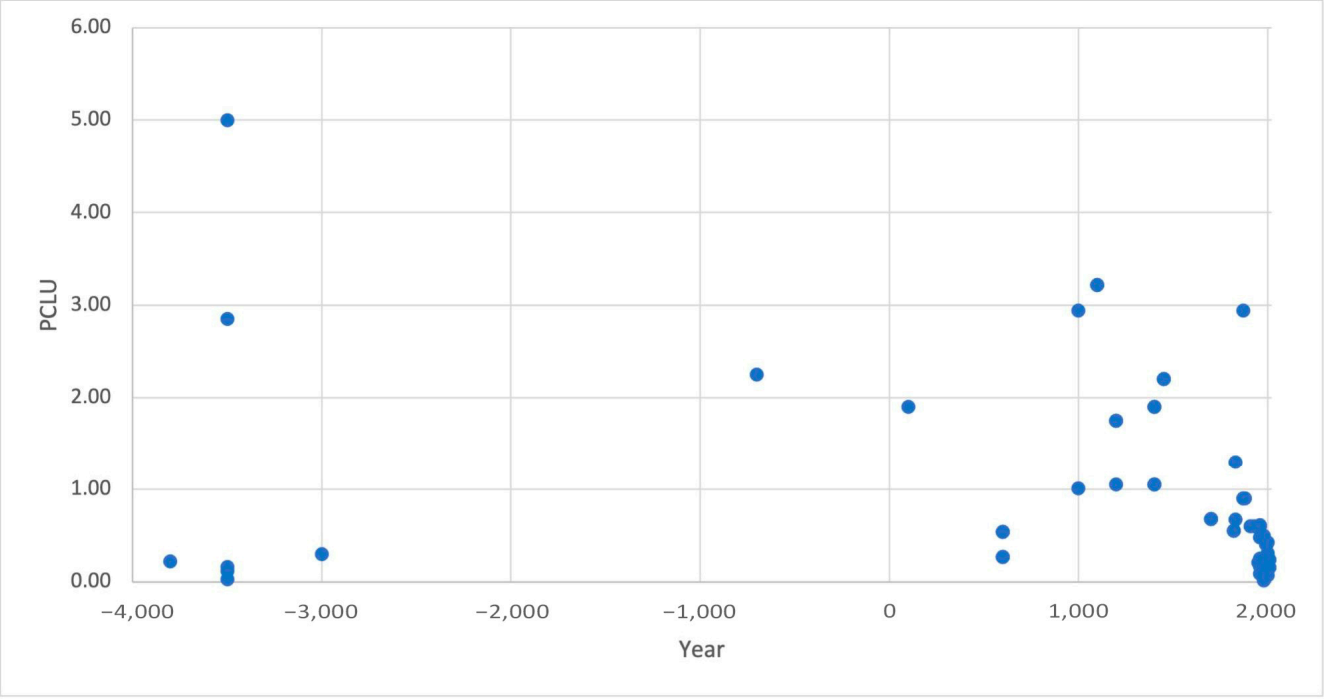


Figure 11. PCLU database values vs. time for all of Northern Europe. Each dot represents a PCLU value in the database.

One crucial assumption made both here and in HYDE is that the best PCLU estimate for countries and areas for which no data exists is calculated by finding adjacent areas with the most similar ecological and environmental features. While this is undoubtedly the easiest way to fill in blank spots based primarily on proximity, a more nuanced approach might compare the particular features of individual subsistence practices to find the best estimate of local land-use requirements at a particular time and place. In this case, the careful application of global ethnographic data might play an extremely important role. Comptour et al. [53], for instance, suggest that Congo Basin yam hills/raised beds could be used as an analogue for raised fields in pre-Columbian Latin America. Such a time-consuming approach is beyond the scope of this paper but could make an important contribution to the development of more nuanced PCLU models.

4. Discussion

4.1. Population and Land Use

The relationship between land use and population is complex. As noted, small populations practicing extensive forms of land use such as HGFF may use large areas of land at a low intensity, while large, aggregated populations may use the same amount of land but at a higher intensity. While each group uses the same area, the potential consequences for land cover and other human impacts are significantly different. Land "use" (as measured simply by area without reference to production strategy, land-use intensity, or management) is thus of limited utility and should be seen as a starting point rather than the goal of analysis.

Land-use intensification refers to strategies that aim to increase productivity while holding land constant, a process associated with a range of factors, including but not limited to population growth [54,55]. The intensification of agricultural production allowed the development of population aggregates such as towns and cities, and it has been documented as a response to other factors, such as commercial opportunities and even inequality and resource aggregation, meaning that it is only roughly correlated with population increase.

Even if it is not the sole causal factor, on a global scale, over the course of the Holocene, population increases have been associated with decreasing land use per capita. This can be visible within HGFF societies (e.g., the increasing use of low-ranked prey species with demographic pressure [56–58]) as shifts between major subsistence practices (e.g., the shift from HGFF to food production [59,60]) and within food-producing societies (e.g., as changes in technology increase food production efficiency [61]). The continued existence of low-intensity forms of land use provides evidence, however, that this general trend is by no means universal. Further, even societies with high land-use intensity often combine more and less intensive forms of production (for example, irrigated rice farming with extensive grazing and the collecting of wild plants [54]), making the use of a single per capita land-use value problematic even for a small region.

Given these difficulties, ALCC modelers have adopted different strategies, either using a single PCLU value for all time periods [1] or assuming a steady process of historical land-use intensification [3], resulting in a reduction of PCLU over time. Neither solution is ideal, and the use of more focused PCLU values appropriate to specific times and places, while presenting limitations, may allow ALCC models to better capture the impacts of historical land-use variability. An important part of this goal for model improvement is to better incorporate land-use shifts beyond those from HGFF to food production. As critical as farming was (and is) as a driver of land-cover change, other forms of subsistence also modified vegetation and carbon cycles [62,63], and aggregating the impacts of these forms of land use is a desideratum for future research.

4.2. Increased Nuance within LU1 Categories

ALCC models and the PCLU estimates they currently utilize are primarily designed to capture the most dramatic shifts that affect land cover, i.e., shifts from HGFF to agriculture and the concomitant deforestation that accompanies this change in many (but not all) places. This focus sets aside the effect of many other changes affecting land use, including changes in agriculture technology such as the development of plowing [61,64–66], the management of soils to increase crop productivity [67–69], changes in wild resource management in HGFF societies [46,57], and shifts in surplus production [70–73], etc. Our current database helps capture some of that variation by providing additional ways to track differences among major subsistence strategy classes (LU1), including more nuanced land-use classification (LU2) and a greater range of time depth.

4.3. Potential Applications

The limited variability of the PCLU data utilized in ALCC models has been previously highlighted [11,13] and is one of the key motivating factors for the construction of the current database. This new database brings together a large number of values for the entire globe across a deep range of time, with the potential to provide more nuance to present ALCC models. In fact, improved PCLU data are already helping to refine such models [1,11]. However, as described above, there is a limit to the availability of global PCLU data before 1960. While Klein Goldewijk et al. [11] have introduced a significant improvement in the latest version, with the addition of some 456 PCLU values comprised of historical agriculture and pastoralism estimates, our new database builds on that to produce a much larger dataset for global modeling, with 1854 values across agriculture, pastoralism, and hunting/gathering/fishing/foraging. However, it currently remains

unclear if this expanded dataset is sufficient to significantly affect ALCC models such as HYDE.

One way this data could be used would be as a resource from which to construct regional lookup tables (LUTs) for key time slices. Such tables would provide increased variation in ALCC models. This could be done by taking the best data available, either incorporating direct data for each country, subsistence strategy, and time period, where available, by applying appropriate regional data where necessary, or by making informed decisions about how to apply values from other regions and time periods based on environmental and subsistence strategy similarities as needed. As an example, we constructed a LUT for the Middle East at 6 kya based on the land-use data published as part of the LandCover6k project [13]

There are six land-use categories coded for the Middle East at 6k in the published example, and these are shown in Table 3. These include agriculture with and without irrigation, extensive/minimal, hunting/gathering/fishing/foraging (HGFF) with low-level food production, and mobile-regular pastoralism. A single PCLU value has been assigned for each land-use type for this region and time period based on what is available from the PCLU database and our own assessment of which values are appropriate to apply based on date, location, and context.

Table 3. PCLU lookup table (LUT) for the Middle East at 6 kya.

LC6k Land-Use Category	Mean/Single PCLU	Range
Agriculture, herbaceous ground crops, rainfed	0.5	0.21–0.79
Agriculture, herbaceous ground crops, with water modification	0.48	0.28–0.53
Extensive, minimal	0	0
HGFF, low-level food production	4248	588–13,333
No evidence, underwater	0	0
Pastoralism, mobile-regular	1.5	0.5–3

For rainfed agriculture, the database contains 32 entries for historical reconstructions of PCLU from 6000 kya to 1000 kya. The closest match in the database in time and space is from Wilkinson [74,75], with estimates for rainfed agriculture at various levels of annual rainfall in northern Mesopotamia. These values have been averaged, and their range has been included. However, even more nuances could be included by combining historic rainfall estimates with these data to plot different PCLU areas based on regional variation in rainfall. For irrigation, a mean value is derived from the combination of Akkermans [76] and Wilkinson [74], who provide values for irrigated agriculture in the region for 8000 kya and 4100 kya, respectively. There is no PCLU for areas that were underwater or had minimal human presence. Finally, although there is no PCLU value for HGFF in the Middle East in the past or present, a mean was calculated for the range of entries that come from broadly similar environmental conditions. This includes arid parts of sub-Saharan Africa; arid areas in the Americas, such as Arizona; and areas in Oceania, such as western Australia.

4.4. Impacts on HYDE

The LUT example provided here can be plugged into the population data that underlies HYDE 3.2 to see how a more nuanced approach to PCLU values impacts this test region. Although HYDE allocates national population data to a finer-resolution grid, here a simplified version is presented using just the national-level data and the "baseline" estimate (rather than the upper or lower estimates) [1]. Table 4 presents the total land-use area estimates for just two land-use categories—rainfed agricultural land and irrigated

agricultural land—as calculated in HYDE 3.2 and with the PCLU substituted from the LUT presented above. Figure 12 presents this data as a map of the region, comparing land-use estimates for these two types. The ratio of rainfed to irrigated agriculture for the LUT estimates is based on the ratio of these two types of agriculture, calculated from the LC6k estimate for the Middle East for 6k [13].

Table 4. Total land area, in km^2, for rainfed and irrigated agriculture, using modern national boundaries, for HYDE and with the proposed 6k PCLU lookup table.

Country	HYDE 3.2 Rainfed Agriculture	HYDE 3.2 Irrigated Agricultural Area	Irrigated Agricultural Area Using LUT	Rainfed Agricultural Area Using LUT
Jordan	2267.859	0	245.09	0
Saudi Arabia	0	0	0	0
Iraq	13,129.88	749.3536	606	858.11
Yemen	0	0	0	301.63
Oman	0	0	0	0
United Arab Emirates	0	0	0	0
Qatar	0	0	0	0
Bahrain	0	0	0	0
Kuwait	0	0	0	0
Syrian Arab Republic	14,090.65	99.83208	935.52	574.19
TOTAL (km^2)	29,488.38	849.18	1786.61	1733.93

The population data are constant between these two examples; only PCLU values and the relative percentage of each land-use type per country have changed. But the impact on total land use is relatively large and not unidirectional. At 6k, for the Middle East, HYDE 3.2 relies on a single large value for rainfed agriculture [11], 4 ha/c, derived from Butzer [77]. However, more recent estimates for rainfed agriculture are much lower than this, as noted above, so the total area estimates where rainfed agriculture was most significant in modern-day Iraq and Syria are an order of magnitude larger in HYDE 3.2. Although a common concern is that HYDE underestimates land use in earlier periods [78], this shows the potential ways that it may also overestimate land use in some regions. Additionally, the distribution of land is spread more widely across the region based on these models.

4.5. Alternate Approaches

Building lookup tables, such as Table 3, provides a good starting point for ways to use the expanded PCLU database presented here to improve past land-use models at various time slices. However, a different approach may still be needed to get at some of the crucial variables in human land use that are not adequately captured by the limited historic PCLU data (such as surplus production, etc.). Instead of relying solely on a combination of estimates of per capita land-use and population models, one alternative approach would incorporate direct evidence for historic land-use and land-cover change. The LandCover6k project is attempting to build such a global database [13,39,40], combining global pollen data for land cover with archaeological data for land use for six key time slices chosen in consultation with climate modelers [79]. This database is being constructed at a resolution that is significantly higher, with a global grid of 8 km × 8 km cells. Global datasets like this can significantly improve models of pre-industrial anthropogenic land-cover change and provide a more realistic building block for earth system model (ESM) simulations [80]. However, such approaches are time consuming, harnessing decades of global archaeological data that are rarely published with this sort of synthesis in mind. So, in the meantime,

improved PCLU data, providing a better model of how land use has varied across time and space, may provide a useful tool for modelers.

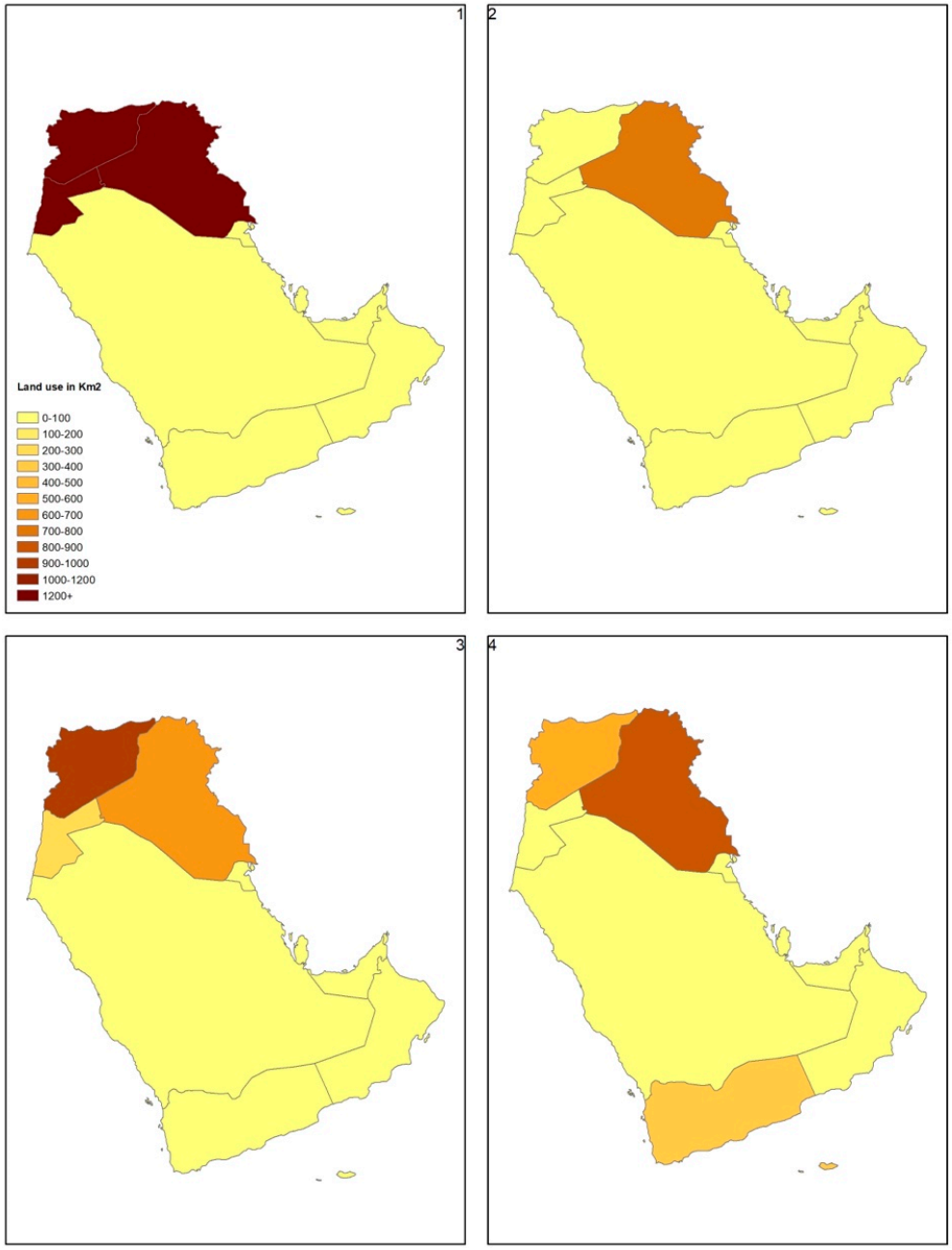


Figure 12. (**1**) HYDE 3.2 baseline total land rainfed agricultural land at 6k; (**2**) HYDE 3.2 baseline total irrigated agricultural land at 6k; (**3**) Total rainfed agriculture land area using HYDE 3.2 baseline population data and PCLU from lookup table above; (**4**) Total irrigated agriculture land area using HYDE 3.2 baseline population data and PCLU estimates above.

5. Conclusions

Understanding the role of humans in land-cover change over the last ten thousand years is a critical part of modeling climate change into the future. Since we know that current ALCC models lack nuance in important details, such as the variability of per capita land use through space and time and across subsistence practices, it is critical that we improve these models with all available resources. The database presented here is an important step towards building finer-grained models of past human impacts. The incorporation

of significant additional sources of PCLU data can only help improve the quality of land-use models, as evidenced by the example provided from the Middle East. Beyond its applicability to climate models, this database should also be of interest to archaeologists looking at how land use, subsistence strategies, technologies, and populations have co-varied and interacted in different ways.

Supplementary Materials: The database and an accompanying bibliography are both available here: https://doi.org/10.6084/m9.figshare.25631802.

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