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Development and testing of scenarios for implementing Holocene LULC in Earth System Model Experiments

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Abstract: Anthropogenic changes in land use and land cover (LULC) during the pre-industrial Holocene could have affected regional and global climate. Current LULC scenarios are based on relatively simple assumptions and highly uncertain estimates of population changes through time. Archaeological and palaeoenvironmental reconstructions have the potential to refine these assumptions and estimates. The Past Global Changes (PAGES) LandCover6k initiative is working towards improved reconstructions of LULC globally. In this paper, we document the types of archaeological data that are being collated and how they will be used to improve LULC reconstructions. Given the large methodological uncertainties involved, we propose methods to evaluate the revised scenarios by using independent pollen-based reconstructions of land cover and of climate. A further test involves carbon-cycle simulations to determine whether the LULC reconstructions are consistent with constraints provided by ice-core records of CO_2 evolution and modern-day LULC. Finally, we outline a protocol for using the improved LULC reconstructions in palaeoclimate simulations within the framework of the Palaeoclimate Modelling Intercomparison Project in order to quantify the magnitude of anthropogenic impacts on climate through time and ultimately to improve the realism of Holocene climate simulations.

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1 Introduction and Motivation

Today, nearly 40% of the ice-free land surface is under anthropogenic use, and large parts of the remaining land area is influenced by human activities (Foley et al., 2005; Ellis and Ramankutty, 2008; Ellis et al., 2010; Ellis et al., 2013). Substantial transformations of natural ecosystems by humans began with the shift from hunting and gathering to cultivation during the Mesolithic and Neolithic periods (Mazoyer and Roudart, 2006; Zohary et al., 2012; Tauger, 2013; Maezumi et al. 2018), although there is controversy about the relative importance of climate changes and human impact on landscape development both during and since that time. Resolving the uncertainty about the extent and timing of land use is important because changes in land cover as a result of land use (LULC) have the potential to impact climate and the carbon cycle. Direct climate impacts occur through changes in the surface-energy budget resulting from modifications of surface albedo, evapotranspiration, and canopy structure (biophysical climate feedbacks, e.g. Pongratz et al., 2010; Myhre et al., 2013; Perugini et al., 2017). LULC affects the carbon cycle through modifications in vegetation and soil carbon storage (biogeochemical climate feedbacks, e.g. Pongratz et al., 2010; Mahowald et al., 2017) and turnover times, which changes the C sink/source capacity of the terrestrial biosphere. LULC changes have contributed substantially to the increase in atmospheric greenhouse gases during the industrial period (Le Quéré et al., 2018). It has been suggested that greenhouse gas emissions associated with Neolithic LULC changes were sufficiently large to offset climate cooling after the Mid-Holocene (the overdue-glaciation hypothesis: Ruddiman 2003). Although this has been challenged for several reasons, including inconsistency with the land carbon balance derived from ice-core and peat records (e.g. Joos et al., 2004; Kaplan et al., 2011; Singarayer et al., 2011; Mitchell et al., 2013; Stocker et al. 2017), a LULC impact on climate in more recent millennia appears more plausible.

Climate model simulations have shown that LULC changes have discernible impacts on climate, both in regions with large prescribed changes in LULC and in teleconnected regions with no major local human activity (Vavrus et al., 2008; Pongratz et al., 2010; He et al., 2014; Smith et al., 2016). At the global scale, the biogeophysical effects of LULC change during the Holocene have been estimated to cause a slight cooling (0.17 °C) that is offset by the biogeochemical warming (0.9 °C), giving a net global warming (0.73 °C) (He et al., 2014). However, in these simulations, biophysical and biogeochemical effects were of comparable magnitude in the most intensively altered landscapes of Europe, Asia, and North America (He et al., 2014). Using parallel simulations, with and without LULC changes, Smith et al. (2016) showed that detectable temperature changes due to LULC could have occurred as early as 7000 years ago (7ka BP) in summer and throughout the year by 3ka BP. All of these conclusions, however, are obviously contingent on the imposed LULC forcing, which is highly uncertain.

There have been several attempts to map LULC changes through time (e.g. Ramankutty and Foley, 1999; Pongratz et al., 2008; Kaplan et al., 2011; Klein Goldewijk et al. 2011; Klein Goldewijk et al. 2017a, b). All of these reconstructions assume that anthropogenic land use is a function of population density and the suitability of land for crops and/or pasture. They then use estimates of regional population trends through time in combination with assumptions about per-capita land use and spatial land use allocation schemes to estimate anthropogenic changes in LULC across time and space. However, differences in the underlying assumptions, which are generalized from limited and often site-specific data, have resulted in large differences in the final reconstructions (Gaillard et al., 2010; Kaplan et al., 2017). Hence, there are still very large uncertainties about the timing and magnitude of LULC changes, both at a global and at a regional scale (Figure 1).

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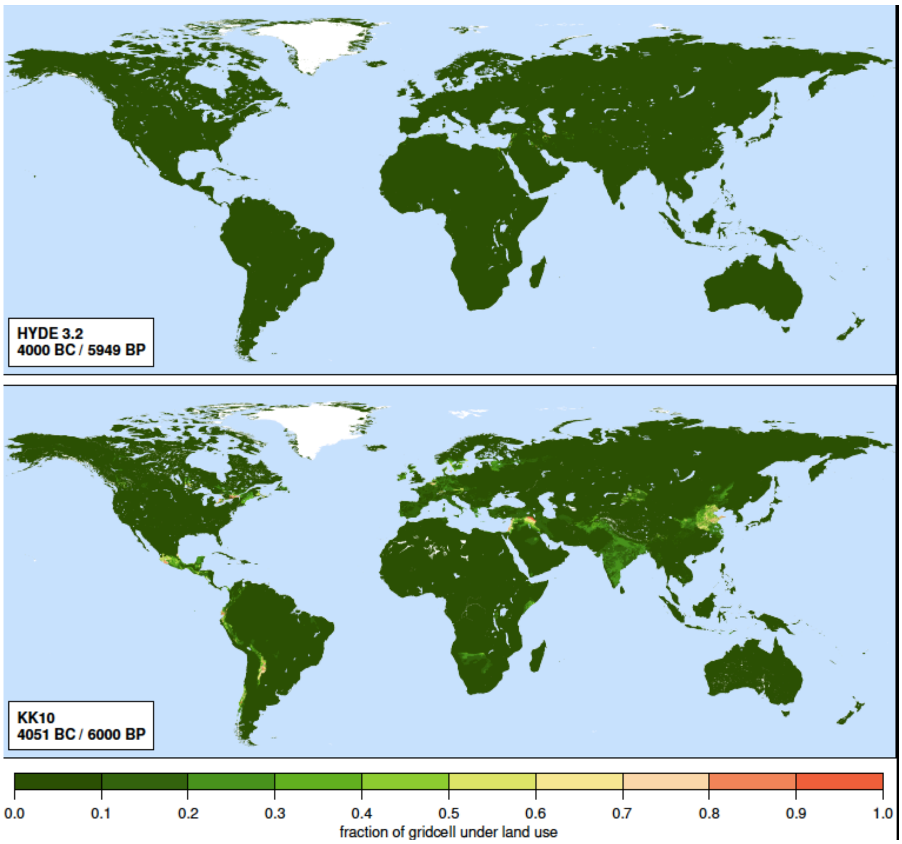

Figure 1: *Land use at ca 6000 years ago (6ka BP) from the two widely used global historical land-use scenarios HYDE 3.2 (top panel, Klein Goldewijk et al. 2017a) and KK10 (bottom panel, Kaplan et al. 2011), illustrating the large disagreement between LULC scenarios at a regional scale. In both scenarios, the land-sea mask and lake areas are for the present day.*

There is a wealth of archaeological, historical and palaeo-vegetation data that could be used to improve the relatively simple rules used to generate global LULC reconstructions. For example, settlement density and numbers of radiocarbon-dated artifacts can be used to infer population sizes and their temporal dynamics (Rick, 1987; Williams, 2012; Silva and Vander Linden, 2017). Carbonised and waterlogged plant remains and animal bones can be used to infer the nature of agriculture at a site, although their presence provides no quantitative information about the area under cultivation (Wright, 2003; Lyman 2008; Orton et al., 2016). Although the record of LULC is likely to be patchy and incomplete, because of preservation and sampling issues, systematic use of archaeological data is one important way to improve current LULC scenarios.

The goal of the Past Global Change (PAGES, http://www.pages-igbp.org/) LandCover6K working group (http://pastglobalchanges.org/ini/wg/landcover6k/intro) is to develop a rigorous and robust approach to provide data and data products that can be used to inform reconstructions of LULC (Gaillard et al., 2018). In this paper, we present a protocol to use archaeological data to improve global LULC reconstructions for the Holocene. Given the large uncertainties associated both with the primary data and in how these data are incorporated into LULC scenarios, we propose a series of tests to evaluate whether the revised scenarios are consistent with the changes implied by independent pollen-based reconstructions of land cover and whether they produce more realistic estimates of both carbon cycle and climate change. Finally, we present a protocol for implementing LULC in Earth System Model simulations to be carried out in the Coupled Model Intercomparison Project (CMIP: Eyring et al., 2016), specifically within the Palaeoclimate Modelling Intercomparison Project (PMIP: (Jungclaus et al., 2017; Otto-Bleisner et al., 2017; Kageyama et al., 2018). However, the data sets and protocol will also be useful for other CMIP projects, including the Land Use Model Intercomparison Project (LUMIP) and the Land Surface, Snow and Soil Moisture Model Intercomparison Project (LS3MIP) (Lawrence et al., 2016; van den Hurk et al., 2016).

2 LandCover6k Methodology

The primary source of information about human exploitation of the landscape comes from archaeological data. In general, these data are site specific and spatiotemporal coverage is often patchy, and the types and quality of evidence available vary between sites and regions. Generalising from site-specific data to landscape or regional scales therefore requires making assumptions about human behavior and cultural practices. Because of the inherent uncertainties, we advocate an iterative approach to incorporate archaeological data into LULC scenarios. Specifically (Figure 2), we propose testing the revised LULC scenarios to see whether the changes resulting from incorporating diverse archaeological inputs are plausible and consistent with other lines of evidence. As a first test, the revised LULC scenarios of the extent of cropland and grazing land through time will be compared for consistency with independent data on land-cover changes, for example pollen-based reconstructions of the extent of open land (see e.g. Trondman et al., 2015; Kaplan et al., 2017). Further testing the LULC scenarios would involve sensitivity tests using global climate models and global vegetation-carbon cycle models. While the computational cost of the climate simulations can be minimized using equilibrium time-slice simulations, the carbon cycle constraint relies on transient simulations, but may be derived from uncoupled, land-only simulations. Simulated climates at key times can be evaluated against reconstructions of climate variables (e.g. Bartlein et al., 2011). The parallel evolution of CO_2 and its isotopic composition ($\delta^{13}C$) can be used to derive the carbon balance of the terrestrial biosphere and the ocean separately (Elsig et al., 2009) and, in combination with estimates for other contributors to land carbon changes such as C sequestration by peat buildup, provides a strong constraint on the evolution of LULC through time. An under- or over-prediction of anthropogenic LULC-related CO_2 emissions during a specific interval results in consequences for the dynamics of the atmospheric greenhouse gas burden in subsequent times (Stocker et al., 2017). Thus, these tests can be used to identify issues in the original archaeological datasets and/or the way these data were incorporated into the LULC scenarios that require further refinement.

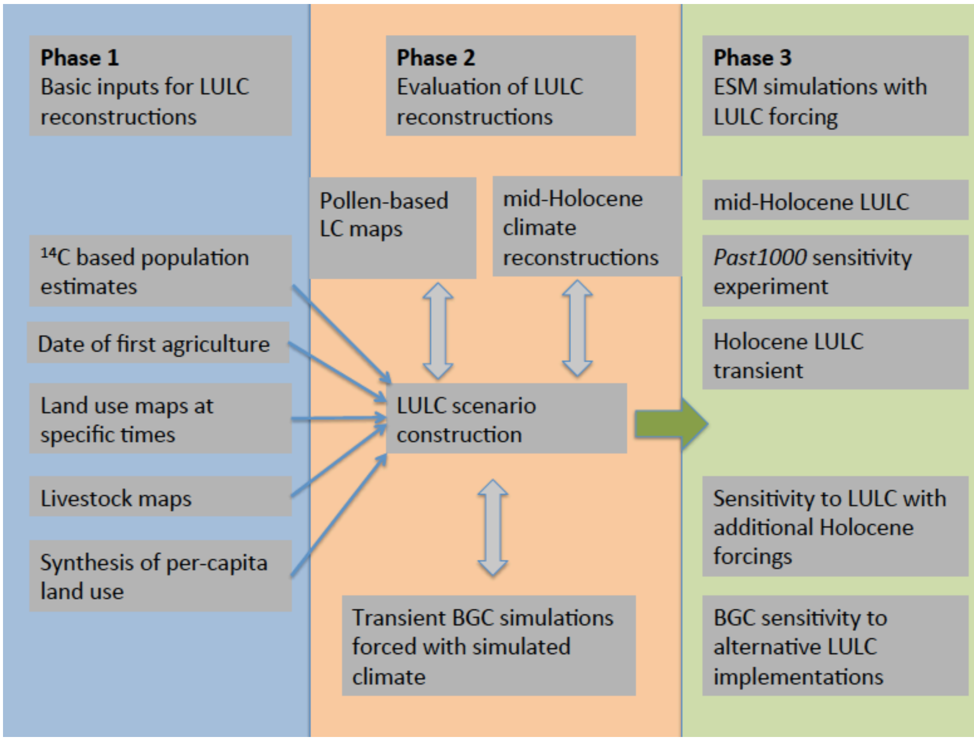

Figure 2: *Proposed scheme for developing robust LULC scenarios through iterative testing and refinement, as input to Earth System Model (ESM) simulations. The archaeological inputs developed in Phase 1 can be used independently or together to improve the LULC reconstructions; iterative testing of the LULC scenario reconstruction will ensure that these inputs are reliable before they are used of ESM simulations. The uppermost three LULC simulations capitalize on already planned baseline simulations without LULC; the lowermost two simulations are envisaged as new sensitivity experiments.*

3 Archaeological data inputs

LandCover6k is creating a number of products that will be used to improve the LULC scenarios (Figure 2). Here, we summarise the important features of these data products before showing how they will be incorporated within a scenario-development framework.

3.1 Population dynamics from ^{14}C data

Radiocarbon is the most routinely used absolute dating technique in archaeology, especially for the Holocene. Many thousands of radiocarbon dates are available from the archaeological literature. A number of regional and pan-regional initiatives are compiling these records (e.g. the Canadian Archaeological Radiocarbon Database: https://www.canadianarchaeology.ca/). Statistical approaches, such as summed probability distributions (SPDs), can then be used to infer past demographic fluctuations from these compilations (Figure 3). This method assumes that the more people there were, the more remains of their various activities they left behind, and that this is directly reflected in the number of samples excavated and dated (Rick, 1987: Robinson et al., 2019). There are biases that could affect the expected one-to-one relationship between number of people and number of radiocarbon dates, including lack of uniform sampling through time and space and

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increased taphonomic losses with increasing age, but these can be minimised through auditing the datasets. Assessment of the robustness of population reconstructions through time can be made statistically, by comparing a null hypothesis of demographic growth constructed from an exponential fit to the data with the actual record of number of dates through time (Shennan et al., 2013; Timpson et al., 2014). Mathematical simulations show that the method is relatively robust for large sample sizes (Williams, 2012). Radiocarbon dates have been successfully used in several regions to identify population fluctuations associated with the introduction of farming and subsequent changes in farming regimes (Shennan et al., 2013; Zahid et al., 2016; Oh et al., 2017; Freeman et al., 2018) as well as climatic oscillations (Whitehouse et al., 2014; Crema et al., 2016).

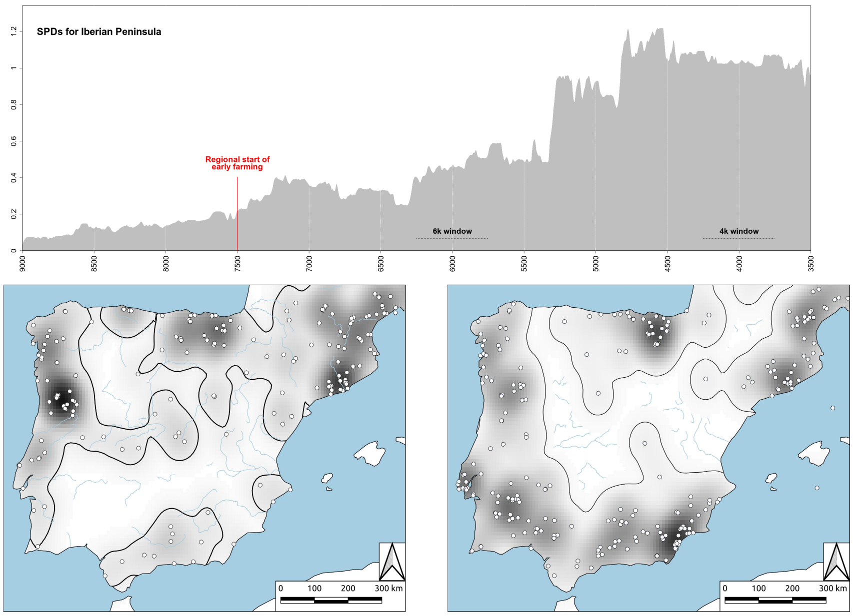

Figure 3: *Reconstruction of changes in population size in the Iberian Peninsula during the Holocene (9000 to 2000 BP, 9ka to 2ka BP) using summed probability distributions of radiocarbon dates (data after Balsera et al., 2015). The red line indicates the onset of agriculture in the region. The lower panels show areas under human use at 6ka (left) and 4ka (right) using kernel density estimates.*

3.2 Date of first agriculture

Radiocarbon dates can also be used to track the timing and process of dispersal events, such as the diffusion of plant and animal domesticates from their initial centres of domestication. Since the distribution of samples is often patchy, geostatistical techniques such as kriging and splines are used to spatially interpolate the information in order to provide quantitative estimates of the timing of spread. Work carried out in Europe (Bocquet-Appel et al., 2009), Asia (Silva et al., 2015), and Africa (Russell et al., 2014) demonstrates that there are different rates of diffusion even within a region, reflecting the possible impact of natural features (e.g. waterways, elevation, ecology) on diffusion rates (Davison et al., 2006; Silva and Steele, 2014). Numerous studies provide robust local estimates for the earliest regional occurrence of agriculture and these are being synthesized to provide a global product within LandCover6k (Figure 2).

3.3 Global land-use and livestock maps

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Maps of the distribution of archaeological sites or of areas linked to a given food production system have been produced for individual site catchments or small regions (e.g. Zimmermann et al., 2009; Barton et al., 2010; Kay et al., in press). LandCover6k is developing global land-use maps for specific time windows, based on a global hierarchical classification of land-use categories (Morrison et al., 2018). At the highest level, the maps distinguish between areas where there is no (or only limited) evidence of land use, and areas characterized by hunting/foraging/fishing activities, pastoralism, agriculture, and urban/extractive land use (Fig. 4). Further distinctions are subsequently made within each of these categories to encompass the diversity of land-use activities in each land-use type (Fig. 4). The LandCover6k land-use maps (see e.g. Fig. 5) will be based on different methods ranging from kernel-density estimates to expert knowledge depending on the quality and quantity of the archaeological information available from different regions.

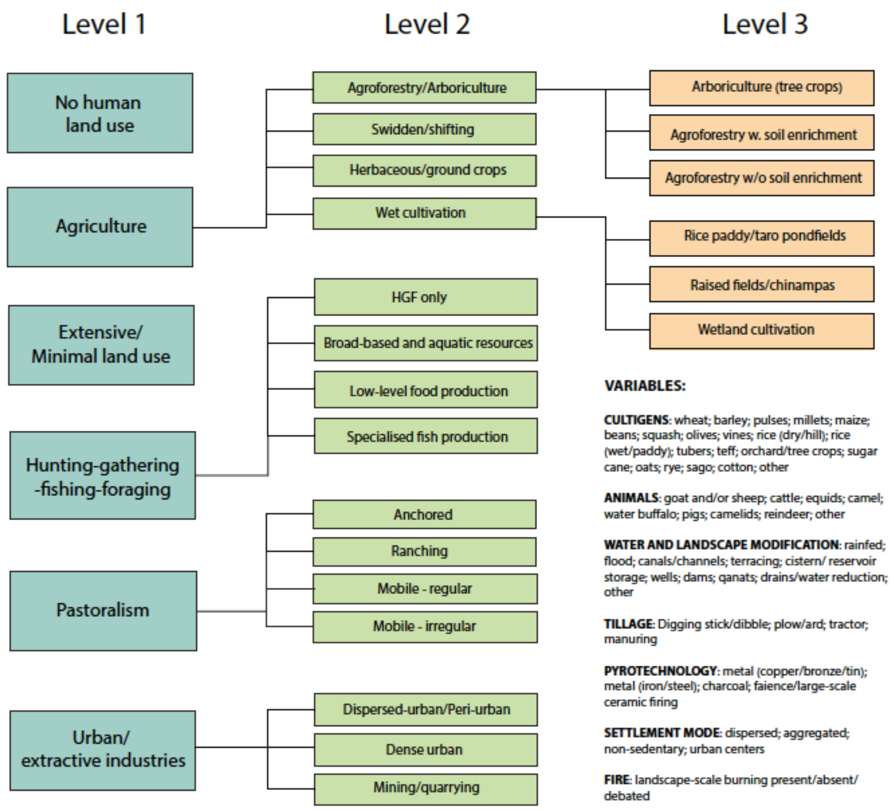

Figure 4: *The hierarchical scheme of land-use classes used for global mapping in LandCover6ka (updated from Morrison et al, 2018).*

There is considerable variation in how intensely land is used both for crops and for grazing within broad land-use categories both geographically and through time (Ford and Clarke, 2015; Styring et al., 2017). Maps of land-use types do not provide direct information on the intensity of farming practices or how they translate into per-capita land use. Archaeological data about agricultural yields, combined with information from analogous contemporary cultures, historical information (e.g. Pongratz et al., 2008) and theoretical estimates of land use required to meet dietary and energy requirements (e.g. Hughes et al., 2018), can be used to provide regional estimates of per-capita land

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use for specific land-use categories. LandCover6k will synthesise this information to allow regionally specific estimates of per-capita land use to be derived from the global land-use maps.

Information about the extent of grazing land is an important input to LULC scenarios but, from a carbon-cycle modelling perspective, the amount of biomass removed by grazing is also a key parameter. Biomass loss varies not only with population size but also with the type of animal being reared (Herrero et al., 2013; Phelps & Kaplan, 2017) and thus information about what animals were present at a given location and estimates of population sizes are needed for LULC scenarios. Although the conditions of bone preservation vary across the globe due to factors such as soil acidity, animal bones are routinely excavated (Lyman, 2008; Reitz & Wing, 2008). Morphometric analysis of bones, along with collateral information such as age-related culling patterns, make it possible to determine whether these are the remains of domesticated species. We thus have a relatively precise idea of when livestock were introduced into a region and what types of animal were being reared at a given time, and can also make informed estimates of population size. Although the level of detail will vary geographically, this information can be used to produce global livestock maps.

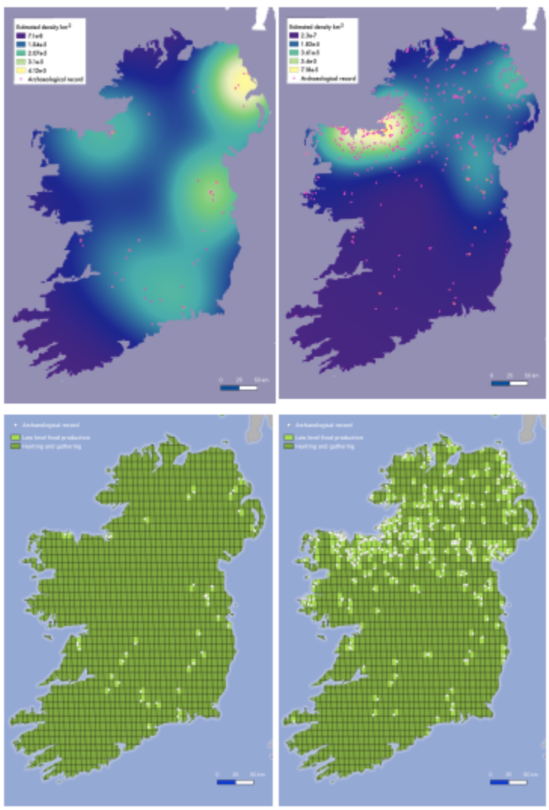

Figure 5: *An example of regional land-use mapping. The plots show the distribution of archaeological sites superimposed on kernel density estimates of the extent of land-use based on the density of sites (top panels), and superimposed on the LandCover6ka land-use classes (bottom panels) for the Middle Neolithic (3600-3400 cal BC, 5600-5400 BP) (left panels) and the Early Neolithic (3750-3600 cal BC, 5750-5600 BP) (right panels) of Ireland. Data points derive from ^{14}C dated archaeological sites and distributions of settlements and monuments that have been assigned*

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to each archaeological period following the dataset published in McLaughlin et al. (2016). In areas characterized by low-level food production, agricultural land (crop growing and grazing, combined) probably occupies between 10-15% of the total grid cell area in eastern and western coastal areas, whilst inland agricultural land likely represent 5% or less of the total grid cell area.

4. Incorporation of archaeological data in LULC scenarios

The existing LULC scenarios are substantially dependent on historical regional population estimates at key times, which are then linearly interpolated to provide a year-by-year estimate of population. Estimates of regional population growth based on suitably-screened ^{14}C data can be used to modify existing population growth curves (Figure 6), both in terms of establishing the initial date of human presence and by modifying a linear growth curve to allow for intervals of population growth and decline.

Information on the timing of the first appearance of agriculture at specific locations can be used to constrain the temporal record of LULC changes in the scenarios. This information can also be used to allocate LULC changes geographically across regions (Figure 6). Global land-use maps can be used to identify areas where there was no permanent agricultural activity at a given time (e.g. either unsettled areas or areas occupied by hunter-gatherer communities) and provide a further constraint on the geographic extent of LULC changes (Figure 6). The type of agriculture, including whether the region was predominantly used for tree or annual crops or for pasture, modifies the area of open land specified in the scenarios. Information on the extent of rain-fed versus irrigated agriculture can also be used to refine the distribution of these classes in the LULC scenarios. Per-capita land-use estimates provide a further refinement of the LULC scenarios, allowing a better characterization of the distinction between e.g. areas given over to extensive versus intensive animal production (rangeland versus pasture in the HYDE 3.2 terminology). There will remain areas of the world for which this kind of fine-grained information is not available. Nevertheless, by incorporating information where this exists, the LandCover6k products will contribute to a systematic refinement of LULC scenarios. Iterative testing of the revised scenarios will ensure that they are robust.

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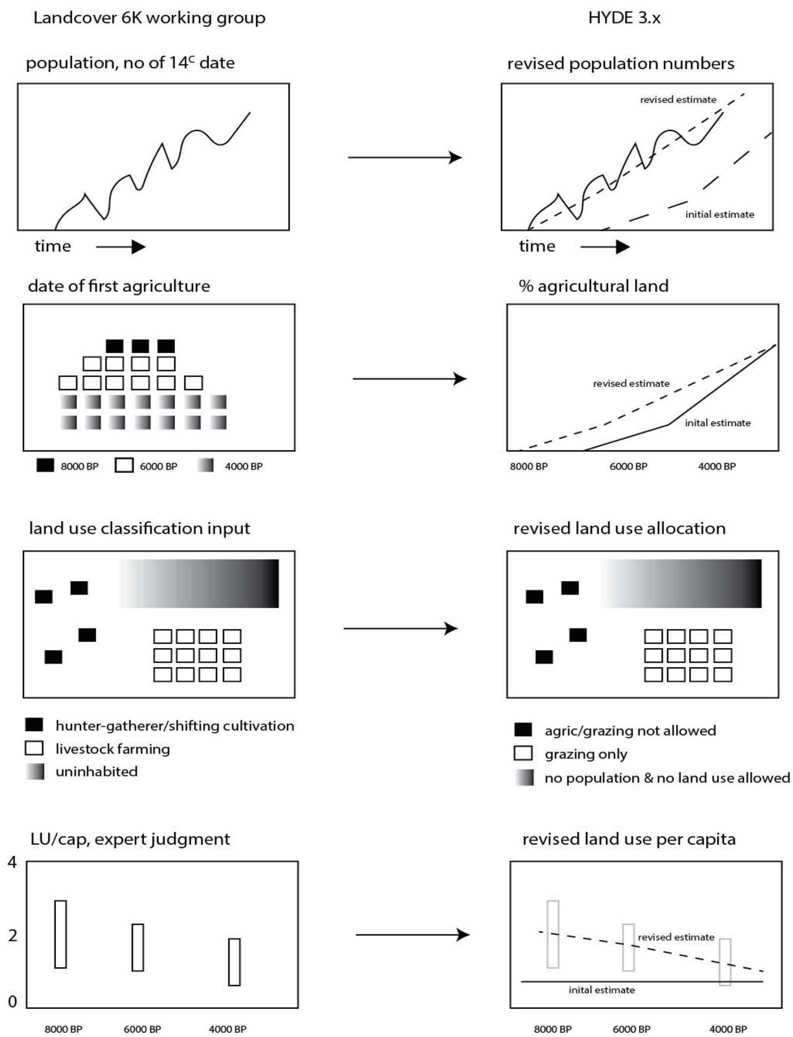

Figure 6: *Schematic illustration of the proposed implementation of ^{14}C-based population estimates, date of first agriculture, land-use maps, and land-use per capita information in the HYDE model.*

5. Using pollen-based reconstructions of land cover changes to evaluate LULC scenarios

LandCover6k uses the REVEALS model (Sugita, 2007) to estimate vegetation cover from fossil pollen assemblages. REVEALS predicts the relationship between pollen deposition in large lakes and the abundance of individual plant taxa in the surrounding vegetation at a large spatial scale (ca. 100 km x 100 km; Hellman et al., 2008a, b) using models of pollen dispersal and deposition. REVEALS can also be used with pollen records from multiple small lakes or peat bogs (Trondman et al., 2016) although this results in larger uncertainties in the estimated area occupied by individual taxa. The estimates obtained for individual taxa are summed to produce estimates of the area occupied by either plant functional (e.g. summer-green trees, evergreen trees) or land cover (e.g. open land, grazing land, cropland) types.

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The geographic distribution of pollen records is uneven. There are also many areas of the world where environments that preserve pollen (i.e. lakes, bogs, forest hollows) are sparse. Site-based reconstructions of land cover are therefore interpolated statistically to produce spatially continuous reconstructions (Nielsen et al., 2012; Pirzamanbein et al., 2014; Pirzamanbein et al., 2018). LandCover6k uses a 1˚ resolution grid and all available pollen records in each grid cell to produce an estimate of land cover per grid cell through time. The more pollen records per grid cell and pollen counts per time window, the smaller the estimated error on the land-cover reconstruction.

A major limitation in applying REVEALS globally is requirement for information about the relative pollen productivity (RPP) of individual pollen taxa, which is largely lacking for the tropics. Furthermore, RPP estimates are available for cultivated cereals but not for other cultivars or cropland weeds, so the LandCover6k reconstructions will generally underestimate cropland cover. Nevertheless, the REVEALS approach has been used to reconstruct changes in the amount of open land through time across the northern extratropics (Figure 7) and will eventually be available for other regions. It may also be possible to use alternative pollen-based reconstructions of land cover changes (e.g. Tarasov et al., 2007; Fyfe et al., 2014; Dawson et al., 2016; Zanon et al. 2018).

LandCover6k has already produced reconstructions for the northern extratropics. These reconstructions are transient over the Holocene with a time resolution of 500 years until 0.7ka BP, and three historical time windows (modern–0.1ka BP, 0.1–0.35ka BP, and 0.35–0.7ka BP). Comparison of the reconstructions of the extent of open land with the LULC deforestation scenarios will provide a first evaluation of the realism of the revised LULC scenarios (e.g. Kaplan et al., 2017). Underestimation or overestimation of open land in the LULC scenarios is not necessarily an indication that these scenarios are inaccurate because (a) pollen-based reconstructions cannot distinguish between anthropogenic and climatically determined natural open land (e.g. natural grasslands, steppes, wetlands) and (b) REVEALS underestimates cropland cover because there are no RPP estimates for cultivars other than cereals. However, overestimation of the area of open land in the LULC scenarios might suggest problems either in the archaeological inputs or their implementation, especially for times or regions when other evidence indicates cereals were the major crop.

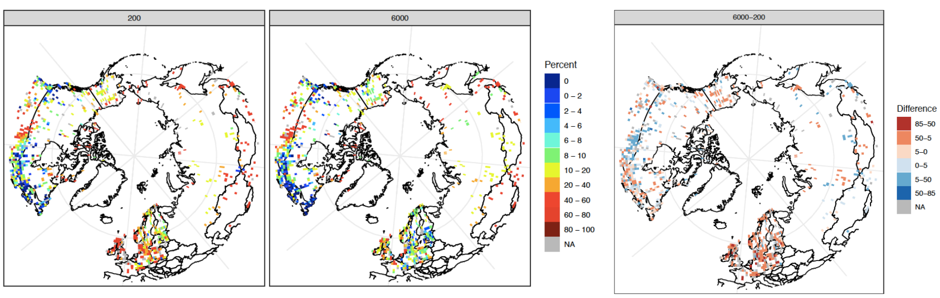

Figure 7: *Northern extratropical (>40°N) mean fractional cover of open land at 6ka BP (left panel) and 0.2ka BP (centre panel) estimated using REVEALS, and the difference in fractional cover between the two periods (right panel), where red indicates an increase in open land and blue a decrease (after Dawson et al., 2018).*

6. Testing the reliability of improved scenarios using climate-model simulations

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A second test of the realism of the improved LULC scenarios is to examine whether incorporating LULC changes improves the realism of the simulated climate when compared to palaeoclimate reconstructions (Figure 8). The mid-Holocene (6 ka) is an ideal candidate for such a test because benchmark data sets of quantitative climate reconstructions are available (e.g. Bartlein et al., 2011), the interval has been a focus through multiple phases of PMIP and control simulations with no LULC have already been run, and evaluation of these simulations has identified regions where there are major discrepancies between simulated and observed climates e.g. the observed expansion of northern hemisphere monsoons, climate changes over Europe, the magnitude of high-latitude warming, and wetter conditions in central Eurasia (Mauri et al., 2014; Harrison et al., 2015; Bartlein et al., 2017). There are discernible anthropogenic impacts on the landscape in many of these regions by 6 ka, and they therefore provide a good focus for testing improvements to the LULC scenarios.

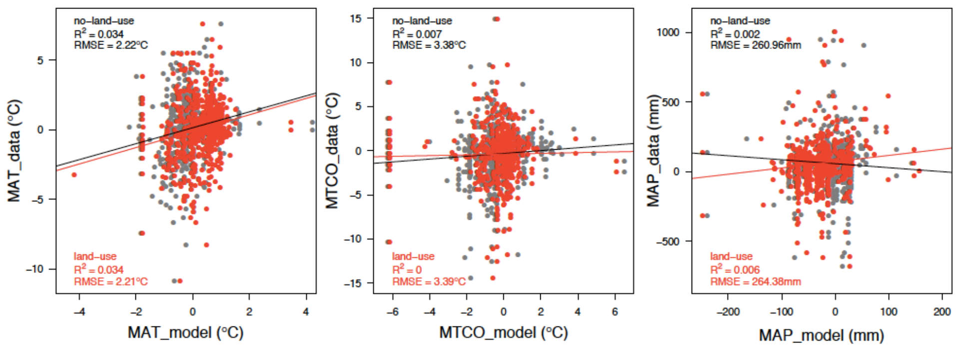

Figure 8: *Quantitative comparison of the change in climate between the mid-Holocene (6ka) and the pre-industrial period as shown by pollen-based reconstructions (from Bartlein et al., 2011) and in simulations with and without the incorporation of land-use change (from Smith et al., 2016). The imposed land-use changes at 6ka were derived from the KK10 scenario (Kaplan et al., 2011). The plots show comparisons of mean annual temperature (MAT), mean temperature of the coldest month (MTCO) and mean annual precipitation (MAP) for the northern extratropics (north of 30° N). Although the incorporation of land use produces somewhat warmer and wetter climates in these simulations, overall the incorporation of land-use produce no improvement of the simulated climates at sites with pollen-based reconstructions.*

7. Testing the reliability of improved scenarios using carbon-cycle models

Carbon-cycle modelling will be used as a further test of the realism of the improved LULC scenarios. Two constraints are available for testing the realism of past LULC reconstructions. First, reconstructions of LULC history must converge on the present-day state, which is known from satellite land-cover observations and national statistics on the amount of land under use. Reconstructing the extent of past LULC thus reduces to allocating a fixed total amount of land conversion from natural to agricultural use over time. More conversion in earlier periods implies less conversion in later periods. At the continental to global scale, cumulative LULC emissions scale linearly with the agricultural area. LULC scenarios that converge to the present-day state also converge to within a small range of cumulative historical emissions (Stocker et al., 2011; Stocker et al., 2017). Deviations from a linear relationship between extent and emissions are due to differences in biomass density in potential natural and agricultural vegetation of different regions affected by anthropogenic LULC. Differences in cumulative emissions for alternative LULC reconstructions with an identical present-day state are due the long response time of soil carbon content following a change in carbon inputs and soil cultivation. Conserving the total extent of LULC (and allocating a fixed total expansion over time) is thus approximately equivalent to conserving cumulative historical LULC emissions. Thus, more LULC CO_2 emissions in earlier periods imply less CO_2 emissions in more recent periods.

The total C budget of the terrestrial biosphere provides a second constraint on LULC emissions through time. The net C balance of the land biosphere, which reflects the sum of all natural and anthropogenic effects on terrestrial C storage, can be reconstructed from ice-core data of past CO_2 concentrations and $\delta^{13}C$ composition (Elsig et al. 2009). Providing that all of the natural contributions to the land C inventory can be specified from independent evidence, the anthropogenic sources can be estimated as the difference between the total terrestrial C budget and natural contributions (Figure 9) at any specific time.

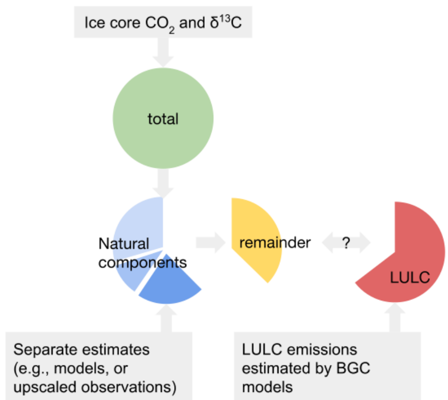

Figure 9: *Illustration of the terrestrial C budget approach. The remainder (yellow slice 'remainder') is calculated as the total terrestrial C balance (green circle 'total') minus the sum of separate estimates of natural components (blue slices 'Natural components'), and can be compared to LULC CO_2 emission estimates by carbon-cycle models.*

Transient simulations with a model that simulates CO_2 emissions in response to anthropogenic LULC can be used to test the reliability of the LULC changes through time, by comparing results obtained with prescribed LULC changes through time against a baseline simulation without imposed LULC. The simulations will be driven by climate outputs (temperature, precipitation and cloud cover) from an existing existing transient climate simulation made with the ECHAM model (Fischer and Jungclaus, 2011) and CO_2 prescribed from ice-core records. The CO_2 emission estimates from these two simulations will then be evaluated using C budget constraints. This evaluation will allow us to pinpoint potential discrepancies between known terrestrial C balance changes and estimated LULC CO_2 emission in given periods over the Holocene.

8. Implementation of LULC in Earth System Model simulations

We propose a series of simulations to examine the impact of LULC, using the revised LULC scenarios from LandCover6k and building on experiments that are currently being run either in

CMIP6-PMIP4 (*midHolocene, past1000*) or within PMIP although not formally included as CMIP6-PMIP4 experiments.

The *mid-Holocene* (and its corresponding *piControl*) is one of the PMIP entry cards in the CMIP6-PMIP4 experiments (Kageyama et al., 2018; Otto-Bliesner et al., 2017) and it is therefore logical to propose this period for LULC simulations. The LULC sensitivity experiment (*midHoloceneLULC*) should therefore follow the CMIP6-PMIP4 protocol, that is it should be run with the same model components and following the same protocols for implementing external forcings as used in the two CMIP6-PMIP4 experiments (Table 1). Thus, if the *piControl* and *midHolocene* simulations is run with interactive (dynamic) vegetation, then the LULC forcing should be imposed within this framework but vegetation changes should be simulated in regions with no LULC change. These new mid-Holocene simulations would allow for a better understanding of the relationship between climate changes and land-surface feedbacks (including snow albedo feedbacks), and the role of water recycling at a regional scale. Thus, modelling groups who are running the *midHolocene* experiment with a fully interactive carbon cycle could also run the LULC experiment as a "free atmospheric CO_2" simulation.

Table 1: Boundary conditions for CMIP6-PMIP4 and the mid-Holocene LULC experiments

Boundary conditions		1850CE (DECK *piControl*)	6ka (*midHolocene*)	6ka LULC (*midHoloceneLULC*)
Orbital parameters	Eccentricity	0.016764	0.018682	0.018682
	Obliquity	23.459	24.105	24.105
	Perihelion – 180	100.33	0.87	0.87
	Vernal equinox	Noon, 21 March	Noon, 21 March	Noon, 21 March
Greenhouse gases	Carbon dioxide (ppm)	284.3	264.4	264.4
	Methane (ppb)	808.2	597.0	597.0
	Nitrous oxide (ppb)	273.0	262.0	262.0
	Other GHG	DECK *piControl*	0	0
Other boundary conditions	Solar constant	TSI: 1360.747	As *piControl*	As *piControl*
	Palaeogeography	Modern	As *piControl*	As *piControl*
	Ice sheets	Modern	As *piControl*	As *piControl*
	Vegetation	Interactive	Interactive	LC6k pasture and crop distribution imposed
		DECK *piControl*	As *piControl*	LC6k pasture and crop distribution imposed
	Aerosols	interactive	Interactive	Interactive
		DECK *piControl*	As *piControl*	As *piControl*

The real strength of the revised LULC scenarios is to provide boundary conditions for transient simulations. The CMIP6-PMIP4 simulation of 850-1850 CE (*past1000*) already incorporates LULC

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changes as a forcing (Jungclaus et al. 2017), based on a harmonized data set that provides LULC changes from 850 through to 2015 CE (Hurtt et al., 2017), which in turn draws on output from the HYDE3.2 data set (Klein Goldewijk et al., 2017a). The *past1000* protocol (Jungclaus et al., 2017) acknowledges that this default land-use data set is at the lower end of the spread in estimates of early agricultural area indicated by other scenarios and recommends that modelling groups run additional sensitivity experiments using alternative maximum and minimum scenarios. The revised scenarios created by LandCover6k could be used as an alternative to these maximum and minimum scenarios. Other than the substitution of the LandCover6k scenario, the specifications of other forcings would then follow the recommendations for the CMIP6-PMIP4 *past1000* simulation.

A transient simulation for a longer period of the Holocene would provide a more stringent test of the impact of LULC on the coupled earth system. We suggest that this transient simulation (*holotrans*) should start from the pre-existing *midHolocene* simulation to ensure that the ocean and land carbon cycle is in equilibrium (Table 2). In order to be consistent with the CMIP6-PMIP4 *midHolocene* protocol (Otto-Bleisner et al., 2017), changes in orbital forcing should be specified from Berger and Loutre (1991) and year-by-year changes in CO_2, CH_4 and N_2O should be specified following Joos and Spahni (2008). LULC changes should be implemented by imposing crop and pasture area through time as specified in the revised LULC scenarios; elsewhere, the simulated vegetation should be active. It will be necessary to run the Holocene transient simulation in two steps. A first simulation (*holotrans_LULC*) should be run using prescribed atmospheric CO_2 concentration prescribed in the atmosphere even though the carbon cycle is fully interactive, because this will establish the consistency of the carbon cycle in the land surface model. However, once this is done it will be possible to re-run the simulations with interactive CO_2 emissions. Table 3 provides a summary of the proposed ESM simulations.

Table 2: Boundary conditions for baseline PMIP Holocene transient (6 ka BP to 1850 CE) and LULC transient simulations

		Mode	**Source/Value**	**LULC experiment**
Orbital parameters		transient		As baseline simulation
Greenhouse gases	CO_2	transient	Dome C	As baseline simulation
	CH_4		Combined EPICA & GISP record	As baseline simulation
	N_2O		Combined EPICA NGRIP, & TALDICE record	As baseline simulation
Solar forcing		transient	Steinhilber et al. (2012)	As baseline simulation
Volcanic forcing		transient	To be determined	As baseline simulation
Palaeogeography		Constant at PI values	Modern	As baseline simulation
Ice sheets		Constant at PI values	Modern	As baseline simulation
Vegetation		interactive		LC6k transient pasture and crop distribution imposed
Aerosols		Constant at PI values		As baseline simulation

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Unlike the situation for the mid-Holocene, where there is a global climate benchmark data set (Bartlein et al., 2011), quantitative evaluation of the *holotrans* simulated climate can only be made for key regions. Quantitative climate reconstructions through the Holocene are currently only available for Europe (Davis et al., 2003) and North America (Viau et al, 2006; Viau and Gajewski, 2009). However, there are time series reconstructions for individual sites outside these two regions (e.g. Nakagawa et al., 2002; Wilmshurst et al., 2007; Ortega-Rosas et al., 2008). Furthermore, the simulated time-course of CO_2 emissions can be compared to the ice core records.

Table 3: Summary of proposed simulations.

Name	Mode	Purpose
piControl	equilibrium	Standard CMIP6-PMIP4 simulation
midHolocene	equilibrium	Standard CMIP6-PMIP4 simulation
midHoloceneLULC	equilibrium	Sensitivity to LULC changes
holotrans	transient	Baseline fully transient simulation from 6ka onwards, with no LULC
holotrans_LULC	transient	Fully transient simulation from 6ka onwards, with LULC imposed

The CMIP6-PMIP4 *mid-Holocene* simulations are stylized experiments, lacking several potential forcings (in addition to LULC), including changes in atmospheric dust loading, in solar irradiance, and volcanic forcing. We suggest that additional sensitivity tests could be run to take these additional forcings into account. In the case of solar and volcanic forcing, this would also ensure that the transient *holotrans* simulations mesh seamlessly with the *past1000* simulation. Changes in solar variability during the Holocene should be specified from Steinhilber et al. (2012). There are records of volcanic forcing for the past 2000 years (Sigl et al., 2015; Toohey and Sigl, 2017), and these are used in the *past1000* simulation. Observationally constrained estimates of the volcanic stratospheric aerosol for Holocene are currently under development (M. Sigl, pers comm.) and could be implemented as an additional sensitivity experiment when available. Changes in atmospheric dust loading are not included in the *past1000* simulation but are important during the earlier part of the Holocene (Pausata et al., 2016; Tierney et al., 2017; Messori et al., 2019). Although continuous reconstructions of dust loading through the Holocene are not available, it would be possible to use estimates for particular time-slices (Egerer et al., 2018) to test the sensitivity to this forcing.

Outcomes and Perspectives

LandCover6k has developed a scheme for using archaeological information to improve existing scenarios of LULC changes during the Holocene. While the final global data set are still in production, fast-track priority products have been created and their impact on current scenarios is being tested.

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Although the work of LandCover6k will provide more solid knowledge about anthropogenic modification of the landscape, some information will inevitably be missing and some key regions will be poorly covered. There will still be large uncertainties associated with LULC scenarios. We have therefore proposed a series of tests that will help to evaluate the realism of the final scenarios, based on independent evidence from pollen-based reconstructions of land cover, reconstructions of climate, and carbon-cycle constraints. These tests should help in identifying which of the potential LULC reconstructions are most realistic and constraining the sources of uncertainty.

We have proposed the use of offline vegetation-carbon-cycle simulations solely as a test of the realism of the revised LULC scenario. Quantifying the LULC contribution to CO_2 emissions during the Holocene would require additional simulations in which other forcings (climate, atmospheric CO_2, insolation) are kept constant. The difference in simulated total terrestrial C storage between these simulations and LULC simulations provides an estimate of *primary emissions* (Pongratz et al., 2014) and avoids additional model uncertainty regarding the sensitivity of land C storage to atmospheric CO_2 or climate being included in emission estimates. There are other sensitivity tests that would be useful. For example, vegetation-carbon-cycle models differ in their ability to account for gross land use transitions within grid cells (Arneth et al., 2017). This is critical for simulating effects of non-permanent agriculture where land is simultaneously abandoned and re-claimed within the extent of a model grid cell. Such shifting cultivation-type agriculture implies forest degradation in areas recovering from previous land use and leads to substantially higher LULC emissions compared to model estimates where only net land-use changes are accounted for (Shevliakova et al., 2009). It would therefore be interesting to run additional simulations accounting for net land use change, and indeed separating out the effects of wood harvesting and shifting cultivation.

We anticipate that it will be possible to incorporate realistic LULC for the mid-Holocene as part of the sensitivity experiments planned during PMIP4. Such experiments will complement the CMIP6-PMIP4 baseline experiments, by providing insights into whether discrepancies between simulated and observed 6 ka climate could be the result of incorrect specification of the land-surface boundary conditions. However, the incorporation of archaeological information into LULC scenarios clearly makes it possible to target other interesting periods for such experiments, for example to explore if land-use changes played a role in abrupt events such as the 4.2 ka event, or to examine the impact of population declines in the Americas as a consequence of European colonisation (1500-1750 CE) or the changes in land use globally during the Industrial era (post 1850 CE).

In addition to providing a protocol for the PMIP 6ka sensitivity experiments, we have devised a protocol for implementing the optimal LULC reconstructions for the Holocene in transient experiments. The goal here is to provide one of the necessary forcings that could be used for transient simulations in future phases of PMIP. This will allow an assessment of LULC in these simulations, and therefore help address issues that are a focus for other MIPs e.g. LUMIP or LS3MIP.

Code and data availability. All the climate model forcing data sets, their references, and their code will be provided on the PMIP4 website (https://pmip4.lsce.ipsl.fr/doku.php/exp_design:lgm, PMIP4 repository, 2017). All the pollen-based REVEALS land-cover reconstructions, and the land use data and associated code will be archived in PANGAEA (https://www.pangaea.de).

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