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Interactive comment on "Development and testing of scenarios for implementing Holocene LULC in Earth System Model Experiments" *by* Sandy P. Harrison et al.

Sandy P. Harrison et al.

s.p.harrison@reading.ac.uk

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Response to comments by Almut Arneth

We thank Almut for her comments and suggestions. Comments in italics, response in normal script, suggested changes to text in bold.

...... one major aspect that seems missing from the approach. People need not only to eat, they also need to cook and heat, and to live. Has the group not discussed to -in addition to archaeological data- to also mine written historical records? This is probably most relevant for the last 1000+ years (rather than mid- Holocene), but surely

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Discussion paper

there can be assumptions about wood requirements for building materials (analogue to a per-capita area needed to be fed: how many people would live in an 'average' house/farm and how much would this would need), shipping fleets (records from shipyards), charcoal making, furnaces for metal forging etc. I would imagine that at least in some regions this would have contributed perhaps already many centuries ago to deforestation. Could the authors comment on this aspect? We agree that wood harvesting is an important issue. Historical wood demand estimates have been made at a regional scale (e.g. McGrath et al., 2015) and indeed estimates of wood harvest are included in LUH2 (https://luh.umd.edu/data.shtml). However, there are very few direct estimates of wood consumption on the longer Holocene timescale that is the focus of the LandCover6k work. While it would be possible to implement approaches based on e.g. population estimates and assuming constant wood use per capita, this is unlikely to be more than a first approximation but a rigorous site-by-site evaluation of wood use through time across the globe though worthwhile would be very time-consuming. Thus, we envisage that the first round of Holocene LULC experiments would focus on the impacts of agricultural expansion and that gathering data to refine population-based estimates of wood harvest could be a future focus on the work of LandCover6k. However, since we agree that this is an important issue and we should make this clear, we propose to add a paragraph to the section describing the archaeological data sources (line 255), as follows: The harvesting of wood for domestic fires, building, and for industrial activities such as transportation, pottery-making and metallurgy is an important aspect of human exploitation of the landscape in the pre-industrial period (McGrath et al., 2015). It has been argued that even Mesolithic hunter-gatherer communities shaped their environment through wood harvesting (Bishop et al., 2015). Approaches have been developed to quantifying the wood harvest associated with archaeological settlements at specific times based on the evidence of types of wood use, household energy requirements, population size, and calorific value of the wood used (see e.g. Marston, 2009; Janssen et al., 2017). However, quantitative information on ancient technology and lifestyle is sparse and direct estimates of the amount of wood harvest through time are likely to remain highly uncertain (Marston et al., 2017; Veal, 2017). Nevertheless, by combining modelling approaches with improved estimates of population size should allow changes in wood harvesting to be taken into account in LULC scenarios. Additional references Bishop, R.R., Church, M.J., Peter A. Rowley-Conwy, P.A., 2015. Firewood, food and human niche construction: the potential role of Mesolithic hunter–gatherers in actively structuring Scotland's woodlands. Quaternary Science Reviews, 108: 51-75. Janssen, E., Poblome, J., Claeys, J., Kint, V., Degryse, P., Marinova, E., Muys, B., 2017. Fuel for debating ancient economies. Calculating wood consumption at urban scale in Roman Imperial times. Journal of Archaeological Science: Reports 11: 592-599.

Marston, J.M., 2009. Modeling wood aquisition strategies from archaeological charcoal remains. Journal of Archaeological Science 36: 2192-2200. Marston, J.M., Holdaway, S.J., Wendrich, W., 2017. Early- and middle-Holocene wood exploitation in the Fayum basin, Egypt. The Holocene 27: 1812-1824. McGrath, M. J., Luyssaert, S., Meyfroidt, P., Kaplan, J. O., Burgi, M., Chen, Y., Erb, K., Gimmi, U., McInerney, D., Naudts, K., Otto, J., Pasztor, F., Ryder, J., Schelhaas, M. J., & Valade, A. (2015). Reconstructing European forest management from 1600 to 2010. Biogeosciences, 12(14), 4291-4316. doi:10.5194/bg-12-4291-2015 Veal, R., 2017. Wood and charcoal for Rome: towards an understanding of ancient regional fuel economics, In de Haas, T. & Gijs, T. (eds), Rural communities in a globalizing economy: new perspectives on the economic integration of Roman Italy, Brill, (New York and Leiden): pp.388-406.

Specific comments

Lines 63-65: For correctness, I would avoid using the term "feedback" here in the sense of change in process A affects process B, feeding back to A. LUC impacts on the carbon cycle are nothing more than an additional emission (or uptake), similar to other anthropogenic emissions, and the biophysical processes are related to albedo or ET change – but these are not feedbacks. We agree that this was not correctly phrased and will change this to: Direct climate impacts occur through changes in the surface-energy budget resulting from modifications of surface albedo, evapotranspiration, and canopy structure (biophysical impacts, 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 impacts, e.g. Pongratz et al., 2010; Mahowald et al., 2017) and turnover times, which changes the C sink/source capacity of the terrestrial biosphere.

Lines 89-99: might be worth pointing out that the large discrepancies between Hyde and KK10 arise mostly from the assumptions about per-capita land requirements; to my knowledge their estimates of historical population changes through time (at least global totals) are more or less the same. We agree that we could be more explicit here and will change the sentence to read: However, differences in the underlying assumptions about land-use per capita, 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).

Lines 125-132: Given that these MIPs are already well under way, could you pls comment how realistic it is that the communities will be able to take up these protocols in time? Is it not more likely that the work will be most useful for many other studies that may not follow the tight schedule of the current AR6 MIP-frenzy, including work that would be useful also in context of the IPBES; and/or might feed into the next IPCC cycle ? Although the deadline for inclusion of material in the next IPCC Assessment report is looming, analyses of the CMIP6 simulations are not entirely tied to the current cycle and will continue after this year. Furthermore, the focus for most groups to date has been on Tier 1 type simulations and additional simulations will be made in the next years. This is certainly the case for the Palaeoclimate Modelling Intercomparison Project where, although the baseline mid-Holocene simulations are mostly completed, sensitivity simulations such as those we propose here will mostly not be started until 2020. However, we agree that we need to make it clear that the intention here is to provide a protocol for new model simulations. In order to do this, and in response to comments by RC1, we have modified this paragraph as follows: The Past Global Change (PAGES, http://www.pastglobalchanges.org/) LandCover6k Working Group (http://pastglobalchanges.org/ini/wg/landcover6k) is currently working 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). LULC changes are taken into account in simulations currently being made in the current phase of the Coupled Model Intercomparison Project (CMIP6) for the historic period and the future scenario runs (Eyring et al., 2016). They are also included in simulations of the past millennium (Jungclaus et al., 2017), in order to ensure that these runs mesh seamlessly with the historic simulations. However, the Land Use Harmonisation data set (LUH2: Hurtt et al., 2017) only extend back to 850 CE and thus LULC changes are currently not included in the CMIP6 palaeoclimate simulations, including mid-Holocene simulations, that are used as a test of how well state-of-the-art climate models reproduce large climate changes. In this paper, we discuss how archaeological data will be used to improve global LULC reconstructions for the Holocene. Given that there are large uncertainties associated with the primary data and further uncertainties may be introduced when this information is used to modify existing LULC scenarios, we outline a series of tests that will be used 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 current phase of the Palaeoclimate Modelling Intercomparison Project (PMIP: Otto-Bleisner et al., 2017; Kageyama et al., 2018). However, the data sets and protocol will also be useful in later phases of 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).

Lines 141/142: style; one ‘required/requirements’ might be sufficient. . .? We will change this to read: Generalising from site-specific data to landscape or regional scales involves making assumptions about human behavior and cultural practices.

Figure 4: ‘Wetland cultivation’ in Level 3 – would that mean wetland drainage for agriculture? I assume it does, please clarify. The three categories under wet cultivations are: 1) creation of artificial wetlands for wetland crops, e.g., rice paddies, taro, 2) draining of wetlands in preparation for upland crops and pasture, e.g. polders or raised field systems, and 3) cultivation of existing wetlands (wetland cultivation). Thus, this last category does not mean drainage but rather preservation and use of existing wetlands. The terminology is explained in the cited Morrison et al. reference. However, we will modify the paragraph (lines 217-227) to make this clearer (and also to deal with comments made by Erik Kjellstrom), as follows: 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) based on land-use types that are widely recognised from the archaeological record. 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). Except in the cases where land use is minimal (no human land use, extensive/minimal land use), further distinctions are subsequently made to encompass the diversity of land-use activities in each land-use type (Fig. 4). A third level of distinction is made in the case of two categories (agroforestry, wet cultivation) where there are very different levels of intervention in different regions. Explanations of this terminology are given in Morrison et al. (2018). 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.

Lines 146-162 – bit of an unspecific list, can be more precise, give more concrete examples? The aim of this text was to provide a general overview of the LandCover6k approach, to put subsequent sections into a broader context. each of the things listed are an explicit part of our strategy and thus further described. Since this obviously was not clear, we will revise the text and make explicit reference to the Figure describing the LandCover 6 scheme (Figure 2) and to the sections of the paper in which we develop each idea, as follows: Because of the inherent uncertainties, we advocate an iterative approach to incorporate archaeological data into LULC scenarios in LandCover6k (Fig. 2). We propose to revise the LULC scenario by incorporation of diverse archaeological inputs (Fig. 2, phase 1; see Sections 3 and 4) and to test the revised LULC scenarios for their plausibility and consistency with other lines of evidence (Fig. 2, phase 2 with iterative testing; see Sections 5-7). As a first test, the revised LULC scenarios of the extent of cropland and grazing land through time will be compared with independent data on land-cover changes, specifically pollen-based reconstructions of the extent of open land (see e.g. Trondman et al., 2015; Kaplan et al., 2017) (Section 5). Further testing the LULC scenarios involve sensitivity tests using global climate models (Section 6) and global vegetation-carbon cycle models (Section 7). 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) (Section 6). The parallel evolution of CO_2 and its isotopic composition (δ13C) 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) (Section 7). 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. Phase 3 of the protocol (Fig. 2) proposes specific implementation of the revised LULC in Earth System Model simulations (Section 8).

We will also modify the caption to Figure 2 as follows: 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 (Phase 2); iterative testing of the LULC scenario reconstruction (phase 2) will ensure that these inputs are reliable before they are used of ESM simulations (phase 3). The uppermost three LULC simulations capitalize on already planned baseline simulations without LULC; the lowermost two simulations are envisaged as new sensitivity experiments.

Section 3.1 – this section wasn't entirely clear to me. What samples are we talking about exactly, what is being dated, where do the samples come from? Could you provide an illustrative example? We will modify this section to make it clearer that we are referring to dated archaeological material, as follows: Radiocarbon is the most routinely used absolute dating technique in archaeology, especially for the Holocene. Many thousands of radiocarbon dates on archaeological material are available from the literature. A number of regional and pan-regional initiatives are compiling these records through exhaustive survey of the archaeological literature (e.g. the Canadian Archaeological Radiocarbon Database: https://www.canadianarchaeology.ca/).

We will also modify the text describing the sources of bias: There are biases that could affect the expected one-to-one relationship between number of people and number of radiocarbon dates on archaeological material, including lack of uniform sampling through time and space caused by different archaeological research interests and traditions in different regions) and increased preservation issues with increasing age.

Since there are several different ways this approach is being applied, we do not feel a single illustrative example would be adequate. We will therefore modify the final sentence of this paragraph to indicate that the references given refer to specific regional examples, as follows: 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 (western Europe: Shennan et al., 2013; Wyoming: Zahid et al., 2016; South Korea: Oh et al., 2017; see also Freeman et al., 2018) as well as climatic oscillations (Ireland: Whitehouse et al., 2014; Japan: Crema et al., 2016).

Figure 5: I liked the Figure, is nice to see a concrete, illustrative example of the planned approach. However, it was not entirely obvious to me what the top and bottom panels in Fig. 5 are meant to convey: is it to show the improvements that can be made by adding the new information to the existing LandCover 6a? Or what is exactly the added value of the two combined? And what's the reasoning behind the 10-15% and the 5% mentioned in lines 269/270? This figure illustrates alternative approaches to mapping land use, with the upper panels showing the distribution of archaeological sites and how these data are generalised to an provide an estimate of the extent of land use. The lower panels show the same data but superimposed on the land use classification scheme used by LandCover6k. It is unrealistic for these periods - or even today - to consider that the entire 64km2 is continuously covered with fields, and the percentages given are estimates of how much of each grid cell was being used in cells assigned to low-level agriculture in different parts of Ireland. We will modify the caption to make this clearer, as follows: An example of regional land-use mapping. The upper panels show the distribution of known archaeological sites superimposed on kernel density estimates of the extent of land-use based on the density of sites, and the lower panels show these data superimposed on the LandCover6k land-use classes 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 14C dated archaeological sites and distributions of settlements and monuments that have been assigned to each archaeological period following the dataset published in McLaughlin et al. (2016). The assigned land-use classes are inferred from archaeological material from one (or more) sites within the grid box. It should not be assumed that

the whole gridcell was being used for agriculture during the Middle and Early Neolithic. Informed assessment suggests that agricultural land (crop growing and grazing, combined) probably occupied between 10-15% of the total grid area in the low-level food production regions of the eastern and western coastal areas, whilst agricultural land likely represents 5% or less of the total grid cell area in inland areas.

Lines 288/289: how do you obtain information about past irrigation? From archaeological data (irrigation structures?) I assume? Likewise, per-capita land needs surely change over time, agreed. But how can these estimates be obtained, could you provide more explanation and/or references to methods as to how to do this? We will expand the text to clarify these points, as follows: Information on the extent of rain-fed versus irrigated agriculture, as indicated by the presence of irrigation structures associated with archaeological sites, can also be used to refine the distribution of these classes in the LULC scenarios. Per-capita land-use estimates and their changes through time (see e.g. Hughes et al., 2018; Weiberg et al., 2019) 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).

Additional references Weiberg, E., Hughes, R. E., Finné, M., Bonnier, A., & Kaplan, J. O. (2019). Mediterranean land use systems from prehistory to antiquity: a case study from Peloponnese (Greece). Journal of Land Use Science, 1-20. doi:10.1080/1747423x.2019.1639836 Hughes, R., Weiberg, E., Bonnier, A., Finné, M., & Kaplan, J. (2018). Quantifying land use in past societies from cultural practice and archaeological data. Land, 7(1), 9. doi:10.3390/land7010009

Figure 6, just for illustrative purpose only: the panels 'land use classification input' and 'revised land use allocation' look identical, might be illustrative to not only change the legend but also the drawing. These two panels necessarily look identical because the archaeological data shown in the lefthand panel are explicitly incorporated into the scenario. Unlike in the other examples, it is difficult to show the before/after situation here. However, we can expand the caption to make this clearer, as follows: Schematic illustration of the proposed implementation of 14C-based population estimates, date of first agriculture, land-use maps, and land-use per capita information in the HYDE model (here indicated as HYDE3.x). The archaeological data are represented as values for a grid cell in geographic space at a given time for date of first agriculture and land use, but as a time series for a specific grid cell for population and land-use per capita. In the case of population estimates, date of first agriculture and land-use per capita data, we show the initial estimate and the revised estimate after taking the archaeological information into account in the HYDE3.x plot. It should be assumed in the case of the land-use mapping that the original estimate was that there was no land use in this region.

Line 327-329: what's the basis for the optimism that 'eventually' these pollen-based reconstructions will also be available elsewhere (presumably: the tropics), is there initial work that points in that direction? And what's the pros/cons of the "other" pollen-based reconstructions that are mentioned? There is indeed work going on the collect RPP data in other parts of the world, and we will expand the text to explain this and to explain the pros/cons of the other techniques, as follows: The REVEALS approach has been used to reconstruct changes in the amount of open land through time across the northern extratropics (Figure 7; Dawson et al., 2018) through the Holocene with a time resolution of 500 years from 11.5ka to 0.7ka BP, and three historical time windows (modern–0.1ka BP, 0.1–0.35ka BP, and 0.35–0.7ka BP). A major limitation in applying REVEALS globally is requirement for information about the relative pollen productivity (RPP) of individual pollen taxa, which is currently largely lacking for the tropics. However, LandCover6k has been collecting RPPs for China, South-East India, Cameroon, Brazil and Argentina and pollen-based land-cover reconstructions will be available for at sufficient parts of the tropics to allow testing of the scenarios. Another limitation of REVEALS estimates is that RPP estimates are available for cultivated cereals but not for other cultivars or cropland weeds, so the LandCover6k reconstructions will generally underestimate cropland cover (Trondman et al., 2015). It may also be possible to use alternative pollen-based reconstructions of land cover changes, such as the Modern Analogue Approach (MAT: e.g. Tarasov et al., 2007; Zanon et al. 2018); pseudo-biomization (e.g. Fyfe et al., 2014) or STEPPS (Dawson et al., 2016). While none of these methods require RPPs, MAT and STEPPS can only be applied in regions where the pollen datasets have dense coverage (such as Europe and North America) and pseudo-biomization is affected by the non-linearity of the pollen-vegetation relationship that the REVEALS approach is designed to remove.

Lines 385/386: "known" today is not quite true unfortunately. There are still sizeable discrepancies in today's land cover estimates in terms of major classes such as cropland, pasture, forest, 'other' (let alone in the degree to which these are being used). Partially this arises from disagreements in terms of how a pasture or forest is defined. There is no need to add a long discussion but pls. revise the sentence slightly to express that there is also uncertainty for today. We agree that this statement was a little too optimistic and will change the text to read: First, reconstructions of the total land under agricultural use must converge on the present-day state, which is relatively well constrained by satellite land-cover observations and national statistics on the amount of land under use.

Lines 383-399: The scaling aspect is important. However, cumulative LUC C emissions differ substantially depending on whether "net" or "gross" area changes are being calculated. The total agricultural area might be the same in both approaches, but the 'gross' approach considers expansion and reduction that might occur within a gridcell. The most prominent example is shifting cultivation, and today is mostly restricted to tropical regions. However, others have pointed out that such gross transition of course also are relevant on other parts of the world (see e.g., Fuchs et al., GCB, 2015), and were possibly even more so further back in time. The challenges that arise from this aspect are mentioned later in the Outcomes section but I wonder if it's not better to introduce these already here. We agree that it would be important to account for the difference, and this is one reason that we discuss this issue in the Outcomes section (lines 532 et seq.). Unfortunately, the only way to do this globally at the present time is by making assumptions about farming practices (e.g. how much land is abandoned or fallowed in a given year). The archaeological record does not provide a very strong basis for quantifying this. We will modify the text describe the carbon-cycle simulations to clarify that these simulations will necessitate making assumptions about the nature of land-use turnover, as follows: Transient simulations with a model that simulates CO2 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. This will necessitate making informed decisions about the fraction of land under cultivation that is abandoned or left fallow each year, and the maximum extent of land affected by such episodic cultivation. 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 CO2 prescribed from ice-core records. The CO2 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 CO2 emission in given periods over the Holocene.

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