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Biogeosciences Discussions

Interactive comment on "Sensitivity of Holocene atmospheric CO_2 and the modern carbon budget to early human land use: analyses with a process-based model" *by* B. Stocker et al.

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Dear Editor and reviewers

We would like to thank you for providing us the time to carefully address all comments. This process took longer than usual as the first author was away from office for six months until August 1.

We thank all three reviewers for their comments and advise that helped to improve the presentation of our results. We now describe and discuss the results of an "overshoot scenario" as requested by the reviewers. Results of this additional scenario are

included in figures and tables. The reviewers asked for the evaluation of simulated carbon inventories. In the new figures 5 and 6 modeled carbon inventories in soils and vegetation are compared with observation-based estimates from Batjes, 2008 and Luyssart et al., 2007. These comparisons are discussed in the main text (section 4.1). The reviewers asked for an extended discussion on several issues such as the impact of shifting cultivation on land use emissions. We have slightly expanded the discussion section to cover the requests and added subsection headings to the discussion section to improve readability.

In addition to the changes requested by the reviewers, harvest on croplands is now explicitly taken into account in the standard model setup. All model runs have been repeated with the harvesting routing active. Figures and tables have been revised accordingly. The impacts of harvesting on terrestrial carbon storage and atmospheric CO_2 is assessed by simulations with and without harvesting on croplands (Table 2).

Finally, an (unidentified) error in the labelling of the y-axis in Figure 1, top (global land use area over time) is corrected (range is 0-50$\cdot 10^6$ km^2 instead of 0-5$\cdot 10^6$ km^2).

Conclusions remain unchanged from the submitted manuscript.

Yours sincerely
B. Stocker, K. Strassmann, F. Joos

General comments

1.a) *"My largest concern with the study is the very low values of cumulative CO_2 emissions from ALCC predicted by the model. As shown in Figure 1, and commented in the text, cumulative emissions approach only 150 GtC towards the end of the simulation in all except the X2 scenario.These values seem very low to me."*
Estimates for cumulative emissions have been revised upwards as the effects of har-

vest on cropland soils have been neglected previously. Simulated net emissions now range from 159 to 192 GtC until the end of the simulation. This is 36% more than the result of Pongratz et al., 2009.
Simulated primary emissions of different scenarios are in the range of 233-247 GtC for the entire simulation period. This is within the range of previously published values (see Table 1).
Discrepancies with the estimate of Strassmann et al., 2008 and a possible under- or overestimation are discussed in Section 4.1 and Figures 5 and 6. Based on this assessment, we state that living biomass is generally overestimated by our vegetation model, which results in a likely overestimation of the ALCC-related carbon emissions from removing above-ground biomass in turn. Simulated reductions in soil carbon on croplands are 25-40%. This is in good agreement with observations (Davidson 1993).

1.b) *"I will make a very simple "back of the envelope" calculation to illustrate what I mean. Most preindustrial people converted forestland to farmland, as opposed to grasslands or other marginal habitats, importantly because heavy steel plows and widespread irrigation needed to cultivate natural grasslands and other semi arid regions were not available before the late 19thcentury."*
The fact that some of the earliest and most prominent civilizations (Egypt, Mesopotamia) relied on irrigation systems seems to be in contradiction with this argument.

1.c) *"This fact alone – grasslands were not widely cultivated before industrial times because of technological limitaions is a major limitation of the X1 and X2 scenarios,because they relate to present-day agricultural land use patterns which were likely very different in preindustrial time."*
Even in the naturally forested ecosystems of Europe, early agriculturalists made use of naturally open land before investing significant energy into logging (Williams, 2003). Widespread logging requires efficient technologies as tilling grassland soils does.

Scenario X1 does NOT relate to present-day agricultural land use patterns before 1000 BC. Instead, it is congruent with the pattern of the HYDE 3.1 data, but scaled with a factor of about 8. The land use pattern of HYDE 3.1 is linked to the population map for the respective time. Within one grid cell, grasslands are not preferentially claimed for agricultural use in our model. This is now explicitly mentioned in Section 2.2 ("Croplands and pastures are claimed from forests and natural grasslands according to their respective area shares on natural land, as simulated by LPJ. This potentially overestimates ALCC emissions as grasslands may have been converted into pastures preferentially.").

1.d) *"Typical forest ecosystems have an aboveground biomass of 10E4 to 10E5 kg dry matter per 0.1ha (Niklas & Enquist, Nature 410, 2001). Global human population at 1000 BC was between 50 and 300 million, and by 1 AD probably at least 300m (Dearing, Clim. Past, 2006). According to the current manuscript and several others, preindustrial per-capita land use of 3 ha per person is not unreasonable. Calculating out these numbers and assuming dry biomass is 50% C, we would expect cumulative ALCC emissions at 1000 BC to be 7.5-500 GtC depending strongly on both the estimate of human population and forest biomass; at AD 1, given a more definite estimate of 300 m for global population, the range for cumulative emissions is 45-500 GtC. While the highest-end estimates of cumulative emissions are might be unrealistic, given these lower limits it seems that the values presented in this paper are very much on the low end."*
Spatially explicit assessments are to be preferred and yield a better constrained and narrower range than the "45 to 500 GtC" given by the reviewer.

The population estimate of 300 million is based on a model simulation (Lemmen 2009) and represents the upper limit of the published range (see ftp://ftp.mnp.nl/hyde/supplementary/population/table_st1.xls). The estimate used in Hyde 3.1 is 188 million.

Multiplying 300 million with a global average per capita land use of 3 ha (10$\cdot 10^4$ m^2) yields an area under human land use of 9$\cdot 10^{12}$ m^2. This value lies between ALCC areas at 0 AD in OS and H2 (see Fig. 1).

1.e) *"Furthermore, this study does not appear to take into account the role that long-term agricultural land use has in reducing soil carbon stocks through erosion and reduced slow-turnover litter input."*
We address this issue explicitly in the revised version (Section 4.1). "ALCC-related carbon emissions result from the reduction in biomass inventory due to the clearing of forests and soil carbon losses due to an imbalance of litterfall and soil respiration as well as due to top soil erosion. The cultivation of cropland soils is associated with enhanced oxidation of soil organic matter due to tillage, decreased litter input due to harvesting and the removal of biomass from the field. This results in a reduction of the soil carbon inventory by about 24-43% relative to the state before cultivation (Davidson 1993, Houghton, 1999). Most of this carbon loss occurs within the first decades of cultivation and no further carbon losses are detected in soils that had been cultivated for longer periods (Davidson 1993).

The model applied here yields a reduction in soil carbon after conversion of forests to cropland of order 25 to 40%. The range arises from differences in NPP before and after conversion which depend on local climate conditions. Soil carbon is reduced by 43% after conversion of grassland to croplands. These reductions in soil carbon are in the upper range of published estimates. "

1.f) *"Finally the authors' estimates of cumulative 'primary' carbon emissions through the present day (153-183 Gt) are below most previous estimates. They are well below Olofsson & Hickler (275), Straussman's earlier estimate (284), and that of Olson (240-360).Given that the authors use a revised, untested version of LPJ, it is possible that*

the total biomass simulated by the model is unrealistically low."
Estimates have been revised upwards since the initial submission of the present article. Cumulative emissions between 1850 and present (for this period, results can be compared with a number of other studies) are higher than most previous estimates. The analysis presented in Section 4.1 and Figures 5 and 6 suggests that simulated biomass is generally overestimated by the model.

1.g) *"The authors do not provide values for simulated total terrestrial carbon storage for the present day (or any other time period for that matter). It would be helpful to show at least some evaluation of the model in light of observations of, e.g., aboveground biomass."*
Text added. See Section 4.1 and Figures 5 and 6.

2.a) *"With regards to the land use scenarios used in the current study, the authors explain in the introduction that constant land-use is not a valid assumption, but later on they repeatedly refer to their HYDE (HY) and H2 scenarios as "plausible". Both statements cannot be true."*
We revised the wording with respect to calling scenarios plausible or not.

2.b) *"It can be easily seen in the HYDE dataset that there is almost no ALCC in the Western Hemisphere before AD 1500; this result is simply not supported by archaeological and paleoecological records (e.g., well known evidence of deforestation from Inca and Maya civilizations). The sensitivity test scenarios X1 and X2 are so unrealistic so as to not be useful; the X2 scenario simulates no land clearance after AD 1000, while the X1 simulates only a very small amount, despite the increasingly better documented record of ALCC that occurred during this time. While no study has claimed that preindustrial per-capita agricultural land use was as high as 8-30 ha/person, the authors neglect land use requirements for fuel and construction ma- terials, and that even non-agricultural societies can effect significant deforestation (cf. Australian aborigines).*

When the authors use these implausible scenarios and end up with implausible model results, they conclude that those scenarios were invalid. This obvious conclusion is the result of a badly designed study, not a thoughtful sensitivity test"

We do not agree with the reviewer's conclusion. Scenario X1 and X2 are illustrative. The results show that changes in atmospheric CO_2 remain small even when assuming unrealistically high agricultural activities in preindustrial period.

3.a) *"Finally, but very importantly, the authors note that early on that the possibility of largescale burial of terrestrial carbon in peat would complicate their use of $^{13}CO_2$ trends to constrain terrestrial carbon emissions.But then they use a deconvolution analysis based on the $^{13}CO_2$ trend that completely ignores peat burial of carbon."*

We do not understand this comment. $^{13}CO_2$ trends are not used to constrain terrestrial carbon emission in this study. As mentioned in the text, we use a single deconvolution analysis (see Siegenthaler and Oeschger, 1987).

3.b) *"Had the authors considered a reasonable amount of peat burial, they would have been forced to conclude that larger net anthropogenic emissions are needed to balance the global carbon budget. A recent study by Frolking and Roulet (Global Change Biol, 2007) estimated Holocene carbon accumulation in peat to be 250-450 GtC; another study by Z. Yu calculated 270 Gt C. Any value in this range would be far larger than the cumulative ALCC emissions of 153-183 Gt estimated in the current study and require a large modification of the ALCC or other sources of C to rectify. Any revision of the current manuscript must acknowledge Holocene peat accumulation as a major C sink and explain more clearly how their results would be affected by taking peat accumulation into account. Even better would be to show a scenario that included peat accumulation. Without considering peat, I do not see how any of the authors' (strong) conclusions can be justified or even taken seriously. "*

A multitude of processes contribute to the evolution of atmospheric CO_2 and land carbon stocks over the Holocene. These include among others carbon build-up

on today's peatland, terrestrial inventory changes in response to altered climatic conditions, terrestrial carbon release from areas that get flooded during sea level rise, coral reef build-up, or ocean-sediment interaction in response to deglacial terrestrial carbon inventory changes. It should be noted that current peat carbon inventories do not equal global cumulative sink fluxes into peatlands over the Holocene, as peat and wetlands that were existent at the beginning of the Holocene might have been lost at the same time due to sea level rise and climate change. The net carbon flux of peat accumulation and parallel peat losses is not adressed by the references given above.

We have added text in the introduction to discuss this argument put forward by the reviewer: "The net carbon uptake by peat and wetlands over the Holocene is still an open and largely unresolved question. Current studies show large increases in peat carbon storage over the Holocene (McDonald et al., 2006, Yu et al., 2010). These studies rely on data from currently existing peat reservoirs. By definition, they are not able to assess the loss in carbon stocks to the atmosphere for those peat and wetland areas that disappeared over the last millennia and in the wake of the glacial-interglacial transition with retreating ice sheets and flooding of shelve areas."

We have added text in Section 4.1 to cover the interaction between peat development and ALCC: "The fact that peat and permafrost regions are not explicitly simulated is expected to have only a small effect on the simulated carbon release, as the overlap of land use areas in the past with current peatlands is relatively small on the global scale and non-existent for the case of permafrost regions."

Our estimates for cumulative ALCC emissions does not rely on providing a complete budget of the Holocene atmospheric CO_2 evolution, but assesses the impact of ALCC using a process-based vegetation model in a "bottom-up" approach based on a range of illustrative scenarios. In the analysis of the residual sink, carbon fluxes into peatlands are implicitly included in the residual land sink.

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