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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. *"Overall, I believe this is a valuable study that is of interest to many of the readers of BG. I see the main scientific progress in testing new scenarios similar to those suggested by Ruddiman & Ellis, 2009 with a carbon cycle model. The conclusion that the effects on CO_2 are too small to explain a substantial part of the Holocene CO_2 increase will not be surprising to climate/carbon cycle experts based on previous*

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publications, but is important due to its quantification."
Thank you.

2. *"I see need for revisions though in several aspects (see specific comments for details): (1) The method is straightforward and mostly clearly described, but it has strong limitations that are not sufficiently discussed. In particular no land use apart from permanent agriculture is considered, while it is well possible that shifting cultivation, the use of fire, and wood harvest had a much larger carbon cycle effect in the early millennia than agriculture. The manuscript needs to make clear that it does not deliver the final conclusion to the Holocene CO_2 discussion, but just tests one aspect."*
We now provide a discussion on the issue of shifting cultivation and fire in section 4.2 and section 4.3. We explicitly summarize our conclusions and limitations of the study in section 5 that now reads: "Cumulative carbon emissions of preindustrial ALCC have not been sufficient to explain the Holocene rise in atmospheric CO_2, regardless of the choice of scenario, the strength of CO_2 -fertilization, albedo changes, and climate-carbon cycle feedbacks. We have demonstrated that placing ALCC emissions at an earlier time leaves the ocean more time to absorb excessive CO_2 and results in a smaller atmospheric CO_2 signal. Holocene CO_2 changes are thus primarily driven by natural processes such as changes in the ocean calcium carbonate cycle and natural terrestrial carbon stock changes (Elsig et al., 2009; Kleinen et al., 2010).
This study does not tackle a potentially profound early human impact on local scale environmental conditions by alterations of the natural vegetation cover and cultivation of the soils. Improved global data sets for preindustrial ALCC and explicitly simulating different land management practices (spatio-temporal evolution of LAP, shifting cultivation, wood harvesting, wet rice agriculture etc.) will be crucial for a refined assessment of the human impact on the climate, the contemporary residual terrestrial sink and to address the human impact on the methane cycle."

To reconstruct evolution of agricultural practices in the space and time considered in this study is a major scientific effort in itself. Beyond the differentiation between permanent and non-permanent (shifting cultivation) agriculture, one would also want to differentiate between irrigated and rain-fed fields, a crucial input factor to simulate NPP in naturally moisture-limited ecosystems, such as Egypt or Mesopotamia. In addition, rice cultivation is associated with profoundly different effects on greenhouse gas emissions than arable farming. We believe that simulating shifting cultivation is a primary goal for future assessments of prehistoric ALCC. Yet, the enhancement of carbon emissions due to non-permanent agriculture will not alter our main findings. We have explored the uncertainty range of ALCC emissions and their effect on atmospheric CO_2. This point is now more thoroughly discussed in Section 4.2.

3. *"The choice of scenarios needs more historical basis. Simple scaling with global factors does not justify calling scenarios plausible or upper bound estimates. If possible, I'd suggest including an additional overshoot scenario, since this has also been suggested by Ruddiman & Ellis and has very different consequences on CO_2 evolution."*

We do not use the term "plausible" anymore and we emphasize that our approach is to use illustrative, stylized scenarios. The third sentence in the abstract reads: "A set of illustrative scenarios is applied to test the robustness of these conclusions and to address the large discrepancies between published ALCC reconstructions."

The last sentences of section 1 are: "Sensitivity to extreme preindustrial deforestation is analyzed using scenarios that approach the present scale of global ALCC well before Industrialisation. Due to a lack of more detailed data for early Holocene ALCC and land use practices, we use highly stylized scenarios and address the effects of shifting cultivation and forest management practices on CO_2 emissions implicitly. The impact of harvesting on croplands on carbon emissions and atmospheric CO_2 is quantified by comparing simulations with and without harvesting. Finally, we examine this scenario range for its consistency with available information on LAP and with the carbon budget of the last millennium as inferred from a single deconvolution analysis (Siegenthaler

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and Oeschger, 1987)."
We have added an overshoot scenario. The results for this overshoot scenario do not alter conclusions.

4. *"The conclusion is not as novel as suggested, but confirms (admittedly in part less comprehensive) previous studies; this should be discussed more, also to highlight the new and improved aspects of this study."*
We refer to previous studies in the main text. For example, the second paragraph reads: "Ruddiman (2003, 2007) attributed the observed 20 ppmv increase in atmospheric CO_2 after 8 ka BP to agricultural activities and an assumed climate-carbon cycle feedback. This "early anthropogenic" hypothesis is not supported by published estimates of anthropogenic carbon emissions prior to the industrial period (Joos et al., 2004; Strassmann et al., 2008) and simulated airborne fractions, which are both too low to explain the observed trend and imply a smaller anthropogenic impact. In simulations by Pongratz et al. (2009b), ALCC did not cause an increase of atmospheric CO_2 above natural variability before late medieval times, with an average preindustrial airborne fraction of ALCC emissions of 21% (800-1850 AD). Inverse modelling based on recently published high resolution ^{13}C measurements on the Antarctic Dome C ice core constrains the net contribution of Holocene changes in terrestrial carbon storage to the observed CO_2 rise to 36$\pm$37 GtC or 3 ppmv since 5 ka BP (Elsig et al., 2009)."

The last sentences in section 4.6 read: "The notion reiterated in several papers (Ruddiman, 2003, 2007; Ruddiman and Ellis, 2009) that ALCC caused CO_2 to rise, climate to warm, and thereby prevented a new ice age is not tenable. Inverse top-down as well as bottom up studies like this one come to the same conclusion (e.g., Joos et al., 2004; Claussen et al., 2005; Elsig et al., 2009; Strassmann et al., 2008)."

The novel aspect of the study is described by (section 1): "The low bias stemming

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from the neglection of variations in LAP and the effect of shifting cultivations, and the discrepancies between different ALCC estimates leave a high uncertainty in estimates for historical ALCC emissions and preclude a precise quantification of the preindustrial human impact on the carbon cycle at this point. Earlier studies have not fully addressed this uncertainty. In addition, they are restricted to the past millennium (Brovkin et al., 2006; Pongratz et al., 2009b), assess only the total cumulative carbon emissions before industrialization (Joos et al., 2004; Strassmann et al., 2008), do not quantify carbon accumulation in the atmosphere (Olofsson and Hickler, 2008, Kaplan et al., 2010) or are of highly qualitative nature (Ruddiman, 2003, 2007; Williams, 2003; Nevle and Bird, 2008). Here, we present transient simulations of the impact of preindustrial land use change on atmospheric CO_2 throughout the Holocene based on spatially explicit ALCC maps. An assessment of uncertainty in the evolution of ALCC and its implications for the modern carbon budget is included."

Specific comments

5. *"I can't find the comparison to interannual variability in the text and I believe the setup does not allow a statistical analysis of it: A 31-years climatology is applied, but the discrepancy of this annual/decadal variability to the centennial/millennial timescale of the study is striking."*

We added the following text in Section 4.6: "The simulated interannual variabiliy (IAV) range of atmospheric CO_2 is about $\pm$1.5 ppm and results directly from the IAV of the prescribed climatology. In scenario HY, atmospheric CO_2 clearly rises beyond this range after late Medieval times. After 1500 AD, the ALCC-related deviation from the natural IAV is striking. This corresponds to the finding of Pongratz et al. (2009b) and Junclaus et al. (2010), who simulated intrinsic IAV of the coupled climate-carbon cycle system. Postulating an extent of land use areas that is twice as high as in the HY scenario is not sufficient to explain an atmospheric signal of more than 2 ppmv before the Medieval period (see H2)."

6. *"Previous studies came to the same conclusion – please add that you refer to the newly suggested type of scenarios with much higher per-capita land use in early times."*
We replaced the respective sentence in the abstract by: "Results show that even extreme assumptions for preindustrial land conversion and high per-capita land use do not result in CO_2 emissions that would be sufficient to explain the late Holocene CO_2 increase."

7. *"P. 924: The notion that Pongratz et al., 2008, rely only on constant per-capita land use values is wrong. Additional datasets that are part of this publication explicitly correct for changes in per-capita land use based on historical literature. p. 925: Earlier studies have not addressed. . . – Pongratz et al. did quantify carbon fluxes under constant vs. changing land use per person."*
We mistakenly cited the Pongratz et al., 2008 paper instead of the Pongratz et al., 2009 paper. The corrected text (Section 1) reads:
".. as well as the similar "best-guess" reconstruction that was used in the study of Pongratz et al. (2009b), rely on population maps as a proxy for agricultural areas and the simplistic assumption that the agricultural land area required to support a given population is constant (land area per person, LAP). Pongratz et al. (2008) presented alternative ALCC scenarios that take into account the effects of technological advances and increasing land productivity. Unfortunately, no scenario with high early ALCC areas and accordingly slower land cover dynamics in the centuries before Industrialisation has been used to simulate the effect on atmospheric CO_2."

8. *"p. 925: I'd add that it is due to the uncertainty and unavailability of data (not due to ignorance) that shifting cultivation etc. has not been included by most studies that cover more than the last few centuries. l. 13: Misleading to mention shifting cultivation here, since the present study does not address it either."*
Thanks for this remark, we have added this:
"Due to the paucity of data for the preindustrial era, shifting cultivation, wood harvest,

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forest management, and their impact on the terrestrial carbon cycle are not captured in many studies (Strassmann et al., 2008; Pongratz et al., 2008), including the present one."

9. *"Scaling with one global value neglects the regional differences – a factor of 2 may be "plausible" on global average, but not regionally. e.g. China halved its LAP between the 15th and 18th century alone (Perkins in Grigg, 1974), mainly due to the expansion of wet rice. Similarly, the introduction of New-World cultivars to the OldWorld as well as technological improvements have likely altered the LAP in certain regions much more than by a factor of 2. I grant that such historical data might not be easily available on the spatial and temporal scale of the study, but I would suggest the authors include some more historical information (as provided e.g. in Grigg, 1974, Vasey, 1992) to determine or justify the applied factor. Since carbon fluxes depend substantially on the location of deforestation, I would not call this scenario a "plausible" one."*
In the revised text, we refrain from calling H2 'plausible'. However, we point to the facts that European ALCC areas in H2 are roughly in line with the reconstruction of Kaplan et al. (2009) (Section 1) and that no inconsistency of the H2-ALCC-emissions with the carbon budget of the last millennium can be detected (Section 4.4). Based on this, the GLOBAL TOTAL emissions in H2 seems to be plausible, although we do not argue that it represents a realistic reconstruction of ALCC areas on each continent.

10. *"Please be specific if you refer to land used per person in an agricultural system or land used per person (globally). Only the first has likely decreased with time due to agrotechnological development, the trend of the second is unclear since early global population has performed agriculture only to a very small fraction, so that smaller land used per person in an agricultural system with time is offset by an increasing fraction of people performing agriculture. The shape of the scenarios strongly depends on the fraction of agrarian population and should be discussed accordingly."*
Thanks for this input, we expanded on this issue in Section 4.3 and discuss the concept

of a global mean land area per person (LAP) in view of the share of farming population in the early Holocene and anthropogenic fires.

11. *"No "overshoot" scenario of global agricultural areas is investigated, although this had been supported as plausible by references in Ruddiman and Ellis, 2009. Due to the slower (if at all) recovery of soil carbon this scenario may yield a larger CO_2 increase than the others. I refrain from judging a paper based on what it is NOT, but note that including such a scenario would add a very strong point by investigating all suggested scenarios."*
We have added an overshoot scenario (see also reply 3 to reviewer no. 2).

12. *"How is agricultural area allocated within each grid cell (is it on forest or other natural vegetation)?"*
Added text for clarification 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."

13. *"p. 927, l. 7: Area of shifting cultivation would come on top of the H2 scenario, and can't be seen as part of it."*
We canceled this sentence, but discuss this issue more profoundly in Section 4.2: "It is undisputed that shifting cultivation..."

14. *"p. 927, l. 17: If in X1 areas completely unaffected in HY are now agricultural, how do you then "scale"?"*
See Section 2.1: "After 1000 BC, the areas are linearly interpolated to the 2005 AD distribution of HY."

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15. *"p. 929, l. 4: Add that "net change" refers to within one pixel."*
Added text: Only the net change (difference of deforestation and abandonment) within one grid cell is simulated.

16. *"p. 929, new parameters: Since carbon fluxes change by 30% compared to previous publication, a more thorough validation is needed here."*
We added a comparison of modeled versus observation based carbon stock estimates (Section 4.1 and Figures 5 and 6).

17. *"p. 930, l. 14 f: comparison of "net flux" with (primary) "land use emissions" is confusing."*
The point made here is that ALCC emissions can explain the inferred (independent) net atmosphere-biosphere carbon exchange in the 19th century. This implies that the land sink/source was marginal. The CO_2 fertilisation feedback flux is commonly accounted for by the land sink/source term.

18. *"p. 931, l. 17: I don't see how Fig. 3 shows the size of the product pools."*
The product pools are shown in the upper panel and are labelled accordingly.

19. *"p. 933, l. 8ff, "The small land use emissions. . .": This sentence seems out of context in a paragraph about the residual sink. Further clarify that you refer to observed, not modeled, CO_2."*
Rewrote sentence: "The pre-1850 AD ALCC emissions simulated for all five scenarios are compatible with the reconstructed evolution of CO_2 during this period."

20. *"p. 935, l. 11 f: Shifiting cultivation, wood harvest, or burning should all not be "implicitly" subsumed under the high scenarios of the present study: These processes*

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are of inherently different quality than agricultural expansion, with very different consequences on the carbon fluxes, and these are not addressed by this study."
We added a discussion on this point in Section 4.2: "It is undisputed that shifting cultivation,...". As the scope of our study is on the impact on atmospheric CO_2 and not on the local scale carbon balance of a (cultivated) ecosystem, this "subsummation" is justified.

21. *"p. 936, l. 21: Clarify that cumulative emissions are primary, not net."*
Done.

22. *"reference to ice age: I don't think the Ruddiman&Ellis, 2009 paper deals with glacial onset."*
This reference refers to the claimed ALCC-CO_2 link

23. *"More Discussion is needed on the disregard of shifting cultivation, wood harvest, anthropogenic fires"*
Done, see Sections 4.2 and 4.3.

24. *"More Discussion is needed on the disregard of dynamic natural vegetation. (I agree that CO_2 changes due to changes in natural vegetation should not be part of the paper, but the CO_2 fluxes caused by agriculture depend on the natural background vegetation that is cleared, and this changes substantially on the millennial timescales of the present study.)"*
We mention this issue in Section 2.2: "In an earlier study that considered climatic variations on the millennial time scale but no explicit representation of ALCC, the simulated increase in terrestrial carbon storage is in the range of 820 to 850 GtC over the past 20 kyrs, and 28 to 75 GtC over the past 6 kyrs (Joos et al., 2004). These effects are largely independent of ALCC-related effects, as ascertained with simulations

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driven by variable ALCC and natural changes. Here, for simplicity of interpretation, we keep all boundary conditions other than LU constant." As mentioned, we have conducted simulations with changing boundary conditions (climate, sea-land-ice distribution, orbital forcing of shortwave radiation) to separate natural from anthropogenic forcings. These simulations are documented in Stocker, 2009 (Master's Thesis, p. 91-113, download here: http://www.climate.unibe.ch/?L1=people&L2=personal&L3=beni&PUB=yes). The results show that interactions between natural vegetation shifts and ALCC can be safely neglected in the context of this study.

25. *"More Discussion is needed on how including realistic CO_2 and interactive climate would alter the conclusions drawn concerning the present-day missing sink."*
The concept of a residual land sink or missing sink is described in section 2.3. This concept is widely used in the carbon cycle community and we refer the reviewer to the literature (e.g. Denman et al., 2007, Prentice et al. IPCC, 2001, Oeschger and Siegenthaler, Tellus, 1987) for further discussion. This may also be helpful for the reviewer in the context of his comment regarding p30, line 14. As far as the interactions between CO_2, climate and land use are concerned we refer the reviewer to Strassmann et al, "Simulating effects of land use changes on carbon fluxes: past contributions to atmospheric CO_2 increases and future commitments due to losses of terrestrial sink capacity", Tellus B, 60/4, 583-603,2008. We have added the following sentence at the end of section 3: "This conclusion is robust with regard to uncertainties in the interactions between ALCC, climate and CO_2 and nitrogen fertilization." .

26. *"p. 937, l. 21 ff: compare your 4 ppm to other studies"*
Due to the inclusion of harvest effects on soil carbon, the 4 ppm have been revised upward to 5 ppm. Added text in section 4.6): "The result of HY agrees with numbers reported for the best-guess scenario of Pongratz et al. (2009)."

27. *"p. 938: That the same cumulative emissions cause a smaller change in late prein-*

dustrial CO_2 if placed early in time is an important point not discussed in the referenced publications. I suggest more emphasis on the respective model quantification."
We additionally highlight this result by referring to it in the conclusion section 5. The quantification of carbon accumulation in the different reservoirs (which is key to the link between emission rate and airborne fraction) is thoroughly discussed in Section 4.5 and illustrated by Figure 3.

28. *"p. 938, l. 7: I am surprised that CO_2 fertilization does not alter the results very much. This is in disagreement with previous studies (e.g. Pongratz et al., 2009) – please explain why."*
The statement of the reviewer is not correct. We agree with Pongratz et al., 2009 in terms of net emissions until the end of the simulation period (roughly 120 GtC) and have similar results for primary emissions (see table 1). We added the following text: "The CO_2-fertilisation feedback reduces primary emissions by about 20-30% , depending on level of atmospheric CO_2 (see Fig.3). Simulations with suppressed CO_2 fertilization yield accordingly higher atmospheric CO_2 levels but this effect is less than 1 ppm in scenarios where the increase in atmospheric CO_2 is small, e.g. HY and H2 at preindustrial. The increase in atmospheric CO_2 when CO_2-fertilisation is shut off in the model is illustrated by the thin lines in Fig.1, lower panel."

29. *"l. 8: "Holocene changes are primarily driven by natural processes. . ." – this seems too strong a statement here, considering the limitations of the referenced studies (and all studies so far), including the present one that does not investigate shifting cultivation, fire, co-changes in natural vegetation,.."*
The reviewer stated in the second sentence of his review: "The conclusion that the effects on CO_2 are too small to explain a substantial part of the Holocene CO_2 increase will not be surprising to climate/carbon cycle experts based on previous publications, but is important due to its quantification." We agree with this assessment by the reviewer and have not changed the text. In view of our own analysis and the studies

referenced in our article, we feel confident to draw the above conclusion. Based on our assessment of uncertainties and their significance for atmospheric CO_2, we argue that the limitations may not allow an exact quantification of the human impact at this point but do not prevent us from concluding, that humans are not the main driver of Holocene CO_2 changes.

30. *"l. 11: Please indicate which equation is used here to relate CO_2 to radiative forcing."*
Reference added: Myhre et al. (1998): New estimates of radiative forcing due to well mixed greenhouse gases, GRL, vol. 25.

31. *"l. 20 f: Matthews et al, 2004 find a warming in contrast to Brovkin et al, 2004. The sign of the historical land cover forcing is far from being clear."*
Thank you for this comment. Added text: Combining the CO_2 effect and the albedo forcing of historical land use change may have even resulted in a slight cooling (Brovkin et al., 2006), although the net effect is not clear (Matthews et al., 2004).

32. *"Tab. 1: Is the number 187 GtC emissions AD 1850-2004 correct (seems high as compared to the 188 GtC in Strassmann et al., 2008 AD 1700-1999)?"*
The number is correct. The reviewer no. 1 refers to results from the "standard model setup" in Strassmann et al., 2008, where greenhouse gas emissions, incl. fossil emissions, and interactive climate is included. The 187 GtC is from a run with constant climate and no fertilisation feedback (see Tab. 1, lowest row, in Strassmann et al., 2008). Remaining differences between our results and the results from Strassmann et al., 2008 are due to changes in the PFT parameters (discussed in Section 4.1) and an updated climatology.

33. *"Fig. 3: The distribution of emissions to ocean, biosphere, atmosphere differs substantially from Pongratz et al, 2009. Can you explain this by the longer timescale of*

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your study or by model differences?"
Differences arise from differences in time scales considered as explained in the manuscript (e.g. 4. paragraph in the result section). The airborne fraction in HY and H2 are larger for the industrial than for the pre-industrial period. The airborne fraction over the industrial period is 29% for HY, which corresponds exactly to the value of Pongratz et al., 2009.

34. *"Introduction & Methods: reference to the HYDE3.1 land cover dataset is incorrect (the referenced publications cover only 1700 to present. Only the population, not land cover data until 10,000 is published so far.) Cite website instead."*
Done

35. *"Olofsson-reference: correct author list (it is J. Olofsson and T. Hickler)"*
Done

36. *"Tab. 2: LAP by Ramankutty et al. – the range is across regions or uncertainty?"*
It is a decrease over the 20th century; added text in table 2.

37. *"Fig. 3: Since all other figures and tables use 1850 instead of 1700, it would be more consistent to use 1850 here, too."*
We prefer to use 1700 AD in Fig. 3 to distinguish between the industrial and preindustrial period. This becomes clearer when 1700 AD is used instead of 1850 AD.

38. *"Fig. 2: Showing the map for present day would be clearer than discussing it."*
Done

39. *"Formally, this study investigates anthropogenic land cover change, not land use change. It would be clearer to stick to the terminology of the land use and cover change community (e.g. Turner II et al., 1995)"*

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We generally replaced ’LUC’ by ’ALCC’. However, in certain cases, we sticked to the term ’land use’ instead of using ’ALCC’. These cases are:
-land use area instead of ALCC area: It would be confusing to speak of a “change area”, when actually referring to the area that has been changed so far.
-land use per capita instead of per capita ALCC: same as above: we are referring to the land that is being used and not to the land that is being converted.
-land use transitions instead of ALCC transitions.
-land use preferences instead of ALCC preferences.

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