nature portfolio

Peer Review File

Future land carbon removals in China consistent with national inventory

REVIEWER COMMENTS

Reviewer #1 (Remarks to the Author):

The manuscript "The role of forestation in China's carbon neutrality ambition" presents a significant contribution to the field, utilizing the OSCAR-China model to project the carbon sequestration potential of forestation efforts. However, the study would benefit from a more explicit discussion on the assumptions and limitations inherent in the model, particularly regarding the long-term sustainability of carbon sinks and the potential impacts of future disturbances such as wildfires or pest infestations. This clarification is crucial for readers to understand the robustness of the projections.

Additionally, while the methodology is generally sound, the paper could be improved by providing a more detailed account of the parameters and processes used in the Monte Carlo simulations. This enhanced level of transparency would not only aid in the reproducibility of the study but also allow for a more thorough peer-review process, ensuring the credibility and reliability of the findings.

Lastly, the manuscript would be strengthened by critically engaging with the existing literature to identify areas where the current work diverges or aligns with previous studies. This comparison could provide a more nuanced understanding of the originality and impact of the research, as well as highlight any gaps in knowledge that this study addresses.

Reviewer #2 (Remarks to the Author):

Given that forestation or afforestation is often hyped and overstated as a tool to mitigate climate change, it is very important to estimate the potential C-sink contribution from afforestation as well as the realistic timing of this sink over the 21st century. This paper does exactly that for China. Using a bookkeeping model, historic data and afforestation targets for China, the authors estimate the forest C-sink for a range of scenarios and conclude that continued afforestation efforts may offset 43% of the residual fossil fuel emissions in 2060, highlighting the need for further emission reductions in other sectors for China to reach C-neutrality in that year.

I appreciate the effort and find the result and the message important. I am an experimentalist, so I do not have the expertise to fully evaluate the details of the modelling methods.

I have one major concern and some minor issues that need to be addressed in the text.

Major:

Line 213 ff: “In the extreme case of forests being managed primarily for wood production, the capacity for carbon capture could be completely eliminated32.” This is not a fair statement. Managed forests still capture C by photosynthesis, but the overall landscape C storage may become constant, since the captured C will form a flow of C out of the forest in wood products. However, these products also store C, maybe with a half-life of 25 years (do not know the number for China). Thus, there is a potential to store C outside the forest area in the wood products. It may be too complicated to add scenarios to include this type of C storage outside the sector, however, the paper needs to be clear in stating that the estimates relate only to the C on the forest area. But then mention that with managed forest there is a further potential to store C in products in a future biobased society and refer to some papers that evaluate this potential.

New forests planted on previously degraded or agricultural land, have nutrient rich soils, are dispersal limited for forest specialist organisms, and thus may not benefit biodiversity this century. Therefore, I think the best use of these new forest areas will be as managed forests that both store C in biomass and increasingly store C in products outside the forest.

Minor:

Line 54: “in the NGHGI to a source of 0.12 Gt C yr-1 by bookkeeping models” It is not clear to me where this number is shown in Fig. 1? It could be the orange bar in Fig.1b but that is labeled BLUE not GCB.

Line 167-8: “, it decreases in intensity to even becomes a carbon release of 0.01 ± 0.02 Gt C yr-1 in 2100 under the latter scenario”. This cannot be described as ‘even a release’, since the estimate is not different from zero!

Reviewer #3 (Remarks to the Author):

China is the world leader in emissions of the main greenhouse gas - carbon dioxide. This country produces more than 1/4 of the world's greenhouse gas emissions. Therefore, it should be noted the high relevance of the research topic.

The paper describes the model OSCAR-China, for accounting for greenhouse gas absorption in the LULUCF sector, adapted for China. The results of an assessment of carbon fluxes from 1900 to 2018 and forecast until 2100 are presented. Forecast developed by integrating three climate change scenarios with three land-use change scenarios in alignment with China's national policies. These data coincide with the established literature. The prospects and limitations of areas in China to achieving carbon neutrality are described in detail.

However, two points should be noted.

1. Why are historical data presented up to 2018?

2. Various external factors, such as forest fires, pest attacks, drought and other extreme climatic events are not taken into account in the model.

3. The title of the paper does not correspond to the content. Since the volumes of absorbed greenhouse gases are not fully compared with the projected emissions volumes in the future up to 2060 and 2100, the role of the LULUCF sector in decarbonization is not disclosed. China can not achieve carbon neutrality through land use changes without rebuilding sectors such as Energy and Industrial Processes.

I think that the paper provides a comprehensive description of the completed research, which does not require additions. I recommend changing the title.

Response to the reviewers

To reviewer #1:

Reviewer #1: **General comments:**

The manuscript "The role of forestation in China's carbon neutrality ambition" presents a significant contribution to the field, utilizing the OSCAR-China model to project the carbon sequestration potential of forestation efforts.

[Response] We thank the reviewer for the insightful suggestions and comments on our work. We hope that the revised manuscript satisfactorily addresses all issues raised. Specific responses are offered below.

[*Reviewer #1* Comment 1] *However, the study would benefit from a more explicit discussion on the assumptions and limitations inherent in the model, particularly regarding the long-term sustainability of carbon sinks and the potential impacts of future disturbances such as wildfires or pest infestations. This clarification is crucial for readers to understand the robustness of the projections.*

[Response] Thank you for your insightful comment. We agree that a more explicit discussion of the assumptions and limitations of our model is essential for understanding the robustness of our projections.

As mentioned in the Discussion section of the revised manuscript, "our estimate primarily centers on the potential of LULUCF under fairly optimistic assumptions" **(Page 12, Lines 255-256)**, where disturbances such as extreme wildfires, pest infestations, and climate extremes like droughts and heat waves are not fully considered. Regarding wildfires, OSCAR explicitly includes them as part of the carbon cycle. Fire intensity in the model is influenced by environmental factors such as CO_2 concentration, temperature, and precipitation, allowing OSCAR to simulate changes in fire behavior in response to evolving climatic conditions(Gasser et al., 2017, 2020). However, we acknowledge that this representation is simplified and may not fully capture the complexities of wildfire behavior (e.g., human intervention) and its broader impact on

carbon sinks. At present, accurately modeling pest infestations remains a challenge due to the variability and unpredictability of such events (Sullivan et al., 2022). While this factor is not currently integrated into the model, we recognize its importance and will explore ways to improve OSCAR's capacity to account for it in future work.

Given these considerations, we agree with the reviewer that expanding this aspect of the discussion will improve the manuscript's robustness: "Moreover, our estimate primarily centers on the potential of LULUCF under fairly optimistic assumptions. However, this potential could be significantly affected by various external factors that are not fully considered here. These include disturbances such as extreme wildfires and pest infestations, along with other climate extremes like droughts and heat waves, which can severely disrupt forest growth and reduce carbon sequestration capacity[40–42]. For instance, while our model accounts for wildfires by simulating fire intensity based on climate conditions and CO_2 levels, it does not fully capture extreme wildfire events or human interventions, such as efforts to limit and control natural wildfire[11,12]. In addition to natural disturbances, socio-economic factors, such as forest management practices (e.g., wood harvest, thinning, and selective logging) and land use policies, are critical in determining the actual achievable sink level. However, in the current model, only wood harvest has been explicitly accounted for, while other factors—such as competition for land with food production, economic incentives for afforestation, and sustainable land management practices—are not yet integrated[43,44]." **(Pages 12-13, Lines 255-269).**

[*Reviewer #1* Comment 2] *Additionally, while the methodology is generally sound, the paper could be improved by providing a more detailed account of the parameters and processes used in the Monte Carlo simulations. This enhanced level of transparency would not only aid in the reproducibility of the study but also allow for a more thorough peer-review process, ensuring the credibility and reliability of the findings.*

[Response] Thank you for your valuable feedback. We agree that providing greater transparency would enhance the reproducibility and credibility of our study. Both the

Monte Carlo method and the parameter calibration process follow the approach detailed in Gasser et al. (2020), which we referenced to avoid repeating the complex procedures in detail. To ensure full transparency, the model's input data (including parameters and drivers) and output are available on https://zenodo.org/records/11182160, and all relevant model code can be accessed via https://github.com/yuehe1313/OSCAR-China.

[*Reviewer #1* Comment 3] *Lastly, the manuscript would be strengthened by critically engaging with the existing literature to identify areas where the current work diverges or aligns with previous studies. This comparison could provide a more nuanced understanding of the originality and impact of the research, as well as highlight any gaps in knowledge that this study addresses*.

[Response] Thank you for your insightful comment. In the revised manuscript, we have expanded the Introduction to better engage with existing literature, highlighting how our work aligns with or diverges from previous studies, while addressing key limitations and contributing new insights to the field.

Firstly, previous studies estimating carbon emissions and removals from LULUCF often carry substantial uncertainties due to the misalignment between the definitions used by models and those used in national inventories (Gidden et al., 2023; Grassi et al., 2018). In the revised manuscript, we added more references to further support our clarification that "In model-based studies, only carbon fluxes from direct anthropogenic activities (e.g., land-use changes, wood harvest and subsequent regrowth) are categorized as LULUCF (noted E_{LUC})[9,17–20]." **(Page 3, Lines 46-48),** and for national inventories, "partly due to the near-impossibility of separating direct and indirect effects in practice (as only the sum, noted F_{NET}, can be physically observed), NGHGIs consider all carbon fluxes occurring on managed land as LULUCF (noted $F_{NET(man)}$)[13,14,21]." **(Page 3, Lines 50-53).**

Secondly, the uncertainty is further exacerbated by the land-use change data driving the models. In the original manuscript, we noted that: "*In particular, the widely used Land-*

Use Harmonization dataset (LUH2) fails to capture the observed increase in forest area in China documented by the Food and Agriculture Organization (FAO) data, yet this increase has been noted in previous studies." **(Page 3, Lines 60-63).** In our approach, we address this by using observation-based data that better reflects actual forest area changes in China.

Third, as mentioned in the original manuscript, previous studies have primarily focused on either the direct effects of LULUCF (i.e. ignoring the natural sink) or the changes in forest biomass (i.e. ignoring soil carbon), which are both not comparable with the NGHGI LULUCF, limiting their applicability for comprehensive policy analysis. We have expanded this point as follows: "Lastly, a key limitation in many observation-based studies is their focus on the impact of forestation on forest biomass sinks alone, often using age-biomass relationships to estimate carbon sequestration[23–29]. While these empirical statistical models provide useful insights into forest biomass sinks, they do not account for the broader LULUCF sector's contribution, nor can they be directly aligned with national inventory estimates of carbon sinks in the LULUCF sector." **(Pages 3-4, Lines 65-71).**

Our approach addresses these gaps in several ways: (1) Our model is aligned with the NGHGI definitions, ensuring that we capture the full scope of LULUCF carbon fluxes, consistent with national reporting. (2) We use observation-based land-use change data that more accurately reflects China's actual forest area changes, thus reducing uncertainties caused by biased drivers. (3) To further enhance model reliability, we use forest biomass carbon stock data from the 9th National Forest Inventory (NFI) and China's net land sink from the latest Regional Carbon Cycle Assessment and Processes report (RECCAP2) initiative as post-processing constraints. This approach ensures that our model simulations are consistent with national LULUCF sector estimates. As a result, our model shows that past forestation efforts have created a carbon sink of -0.24 ± 0.03 Gt C yr^{-1} from 1994 to 2018, which aligns well with the national inventory (-0.23 Gt C yr^{-1}), suggesting a fair reliability of our model for future projections.

To reviewer #2:

Reviewer #2: **General comments:**

Given that forestation or afforestation is often hyped and overstated as a tool to mitigate climate change, it is very important to estimate the potential C-sink contribution from afforestation as well as the realistic timing of this sink over the 21st century. This paper does exactly that for China. Using a bookkeeping model, historic data and afforestation targets for China, the authors estimate the forest C-sink for a range of scenarios and conclude that continued afforestation efforts may offset 43% of the residual fossil fuel emissions in 2060, highlighting the need for further emission reductions in other sectors for China to reach C-neutrality in that year. I appreciate the effort and find the result and the message important. I am an experimentalist, so I do not have the expertise to fully evaluate the details of the modelling methods. I have one major concern and some minor issues that need to be addressed in the text.

[Response] Thank you for your considered review. Following your suggestions and comments, we have carefully revised the manuscript. We hope this revised version addresses all issues satisfactorily.

[*Reviewer #2* Comment 1] *Line 213 ff: "In the extreme case of forests being managed primarily for wood production, the capacity for carbon capture could be completely eliminated32." This is not a fair statement. Managed forests still capture C by photosynthesis, but the overall landscape C storage may become constant, since the captured C will form a flow of C out of the forest in wood products. However, these products also store C, maybe with a half-life of 25 years (do not know the number for China). Thus, there is a potential to store C outside the forest area in the wood products. It may be too complicated to add scenarios to include this type of C storage outside the sector, however, the paper needs to be clear in stating that the estimates relate only to the C on the forest area. But then mention that with managed forest there is a further potential to store C in products in a future biobased society and refer to some papers that evaluate this potential. New forests planted on previously degraded or agricultural land, have nutrient rich soils, are dispersal limited for forest specialist organisms, and*

thus may not benefit biodiversity this century. Therefore, I think the best use of these new forest areas will be as managed forests that both store C in biomass and increasingly store C in products outside the forest.

[Response] Thank you for your suggestion. We would like to address your concerns by clarifying the role of harvested wood products (HWP) and their influence on LULUCF carbon dynamics in greater detail. Here is the equation used in the OSCAR model (Gasser et al., 2020):

$$E_{LUC} = \sum_{i,b}\left(\sum_{w} E_{hwp}^{i,b,w} + E_{bk,fire}^{i,b} + E_{bk,harv}^{i,b} + E_{bk,graz}^{i,b} + Rh_{bk,1}^{i,b} + Rh_{bk,2}^{i,b} - NPP_{bk}^{i,b}\right)$$

First, as illustrated in this equation, our model (OSCAR-China) already accounts for the delayed carbon emissions from the wood product pool in the calculation of E_{LUC}. In this equation, *i* and *b* denote regions and biomes, respectively, while *w* represents wood product sub-pools (i.e., fuel wood, pulp-based products, and hardwood-based products). Harvest wood products decay according to product-specific timescales, leading to delayed emissions ($E_{hwp}^{i,b,w}$). This modeling approach is detailed in Gasser et al. (2020).

In the Results section, we have already described HWP's contribution to E_{LUC} as follows: "*E_{LUC} is dominated by vegetation regrowth, supplemented by a delayed response of soil systems, and partially offset by the oxidation of harvested wood products (Figure 3b).*" **(Page 8, Lines 163-165).**

Second, we agree with the reviewer that the fate of wood products plays a crucial role in LULUCF related carbon sequestration, particularly in a future bio-based economy. Long-lived wood products, such as those used in construction, can store carbon for extended periods, whereas short-lived products, like paper, release carbon more quickly back into the atmosphere. In the revised manuscript, we have updated the text to more clearly discuss the impact of wood harvest: "Moreover, if newly planted forests were more heavily exploited for wood harvest (following SSP5-8.5, Supplementary Fig.4), the direct carbon removal would be reduced by about 0.02 Gt C yr^{-1} in 2060. This reduction occurs because the accelerated transfer of carbon from forests to wood

products shortens the system's carbon retention time, diminishing long-term carbon sequestration. In the extreme case where forests are heavily exploited for wood production, the capacity for carbon capture could be entirely lost unless the lifespan of wood products is also extended. Long-lived wood products provide prolonged carbon storage, while short-lived products release carbon into atmosphere more rapidly. In the context of a future bio-based society, maximizing the lifespan of wood products becomes crucial for enhancing carbon sequestration and mitigating climate change[35–37]." **(Pages 10-11, Lines 220-230).**

[*Reviewer #2* Comment 2] *Line 54: "in the NGHGI to a source of 0.12 Gt C yr-1 by bookkeeping models" It is not clear to me where this number is shown in Fig. 1? It could be the orange bar in Fig.1b but that is labeled BLUE not GCB.*

[Response] Sorry for the confusion. Initially, we had presented the value from the BLUE model (0.12 Gt C yr^{-1}), which showed the largest carbon source among the three bookkeeping models used in the Global Carbon Budget (GCB) annual report. However, after further consideration, we agree that it is more appropriate to present the average of the three bookkeeping models. Therefore, we have revised the sentence to: "Comparison of LULUCF fluxes over 1994-2018 following both definitions reveal a substantial gap in China: while the NGHGI reports from a sink of -0.23 Gt C yr^{-1} in the NGHGI to a source of 0.12 Gt C yr^{-1} , by bookkeeping models in the Global Carbon Budget (GCB), based on the average of three bookkeeping models (i.e., OSCAR-GCB, BLUE and H&C), indicates a sources of 0.01 Gt C yr^{-1} (Figure 1)." **(Page 3, Lines 53-57).**

[*Reviewer #2* Comment 3] *Line 167-8: "it decreases in intensity to even becomes a carbon release of 0.01 ± 0.02 Gt C yr-1 in 2100 under the latter scenario". This cannot be described as 'even a release', since the estimate is not different from zero!*

[Response] Thank you for pointing this out. We now revise the sentence as follows: "it decreases in intensity to an estimated carbon flux of 0.01 ± 0.02 Gt C yr^{-1} in 2100 under the latter scenario." **(Pages 8-9, Lines 176-177).**

To reviewer #3:

Reviewer #3: **General comments:**

China is the world leader in emissions of the main greenhouse gas - carbon dioxide. This country produces more than 1/4 of the world's greenhouse gas emissions. Therefore, it should be noted the high relevance of the research topic. The paper describes the model OSCAR-China, for accounting for greenhouse gas absorption in the LULUCF sector, adapted for China. The results of an assessment of carbon fluxes from 1900 to 2018 and forecast until 2100 are presented. Forecast developed by integrating three climate change scenarios with three land-use change scenarios in alignment with China's national policies. These data coincide with the established literature. The prospects and limitations of areas in China to achieving carbon neutrality are described in detail. However, two points should be noted.

[Response] Thanks for your careful review and valuable suggestions. We have carefully considered your feedback and made revisions to address your points. We believe these changes further strengthen the manuscript and provide additional clarity.

[*Reviewer #3* Comment 1] *Why are historical data presented up to 2018?*

[Response] Thank you for your valuable comment. The historical data is presented up to 2018 because we utilize a high-quality land cover dataset, which is based on multi-source observations and aligns well with national inventory data (Yu et al., 2022). This dataset covers the period from 1900 to 2019, and its consistency ensures the reliability of our historical simulations. However, because the OSCAR-China model requires consecutive years of data to construct land-use transition matrices, we are limited to calculating LULUCF fluxes up to 2018.

While it is possible to integrate other remote sensing datasets for more recent years, doing so would risk introducing inconsistencies in land-use classification and methodology, which could compromise the accuracy of our results. Maintaining a consistent and harmonized dataset across the entire historical period is crucial for the reliability of our model outputs.

[*Reviewer #3* Comment 2] *Various external factors, such as forest fires, pest attacks, drought and other extreme climatic events are not taken into account in the model.*

[Response] We acknowledge that various external factors are not considered or fully represented in our model. To this end, we have expanded the discussion in the manuscript as follows: "Moreover, our estimate primarily centers on the potential of LULUCF under fairly optimistic assumptions. However, this potential could be significantly affected by various external factors that are not fully considered here. These include disturbances such as extreme wildfires and pest infestations, along with other climate extremes like droughts and heat waves, which can severely disrupt forest growth and reduce carbon sequestration capacity[40–42]. For instance, while our model accounts for wildfires by simulating fire intensity based on climate conditions and CO_2 levels, it does not fully capture extreme wildfire events or human interventions, such as efforts to limit and control natural wildfire[11,12]. In addition to natural disturbances, socio-economic factors, such as forest management practices (e.g., wood harvest, thinning, and selective logging) and land use policies, are critical in determining the actual achievable sink level. However, in the current model, only wood harvest has been explicitly accounted for, while other factors—such as competition for land with food production, economic incentives for afforestation, and sustainable land management practices—are not yet integrated[43,44]." **(Pages 12-13, Lines 255-269).**

[*Reviewer #3* Comment 3] *The title of the paper does not correspond to the content. Since the volumes of absorbed greenhouse gases are not fully compared with the projected emissions volumes in the future up to 2060 and 2100, the role of the LULUCF sector in decarbonization is not disclosed. China can not achieve carbon neutrality through land use changes without rebuilding sectors such as Energy and Industrial Processes. I think that the paper provides a comprehensive description of the completed research, which does not require additions.* ***I recommend changing the title.***

[Response] Thank you for your thoughtful feedback. We understand your concern that the current title may imply a broader analysis of China's overall decarbonization efforts,

including sectors such as Energy and Industrial Processes, which are not explored in our paper. In response to your suggestion, we propose to change the title from "*The role of forestation in China's carbon neutrality ambition*" to "Future land carbon removals in China consistent with national inventory". This revised title better reflects the specific scope of our study and clarifies the focus on land-based carbon sequestration, aligning more closely with the paper's objectives.

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REVIEWERS' COMMENTS

Reviewer #1 (Remarks to the Author):

The authors have addressed the previous concerns effectively by providing additional analyses and a more thorough discussion on the uncertainties and external factors that may impact their projections. The revisions have enhanced the clarity and robustness of the study.

The additional details on the methodology and the inclusion of a more comprehensive sensitivity analysis have improved the transparency and reproducibility of the research. The authors have also successfully articulated the implications of their findings within the context of China's carbon neutrality goals, which is a significant contribution to the field.

The revisions made by the authors have adequately addressed the points raised during the initial review. The manuscript is now in a form that is suitable for publication.

Reviewer #2 (Remarks to the Author):

In this revision the authors have made the improvements requested by me and the other reviewers. They also have provided additional information that address our previous concerns

Reviewer #3 (Remarks to the Author):

The authors took my comment into full account.