nature portfolio

Peer Review File

Dynamic urban land extensification is projected to lead to imbalances in the global land-carbon equilibrium

Web links to the author's journal account have been redacted from the decision letters as indicated to maintain confidentiality.

16th Oct 23

Dear Dr McManamay,

First of all, please allow me to apologise for the delay in sending a decision on your manuscript titled "Dynamic urban land extensification and imbalances to the global land-carbon equilibrium". It has now been seen by 2 reviewers, and we include their comments at the end of this message. They find your work of interest, but some important points are raised. We are interested in the possibility of publishing your study in Communications Earth & Environment, but would like to consider your responses to these concerns and assess a revised manuscript before we make a final decision on publication.

We therefore invite you to revise and resubmit your manuscript, along with a point-by-point response that takes into account the points raised. Please highlight all changes in the manuscript text file.

In the following, we list our main editorial concerns to be met during the revision.

****
• Provide compelling new insights into the potential effects of projected urban expansion on the land carbon dynamics.

• Justify your choice of the carbon accounting methodology and modeling framework used in the projection and consideration of the interactions between urban and other land use over the other approaches.

• Provide a clear and comprehensive description of the methods used and discuss the limitations and uncertainty of your findings.
****

We are committed to providing a fair and constructive peer-review process. Please don't hesitate to contact us if you wish to discuss the revision in more detail.

Please use the following link to submit your revised manuscript, point-by-point response to the referees' comments (which should be in a separate document to any cover letter), a tracked-changes version of the manuscript (as a PDF file) and the completed checklist:

[link redacted]

** This url links to your confidential home page and associated information about manuscripts you may have submitted or be reviewing for us. If you wish to forward this email to co-authors, please delete the link to your homepage first **

We hope to receive your revised paper within six weeks; please let us know if you aren't able to submit it within this time so that we can discuss how best to proceed. If we don't hear from you, and the revision process takes significantly longer, we may close your file. In this event, we will still be happy to reconsider your paper at a later date, as long as nothing similar has been accepted for publication at Communications Earth & Environment or published elsewhere in the meantime.

Please do not hesitate to contact us if you have any questions or would like to discuss these revisions further. We look forward to seeing the revised manuscript and thank you for the opportunity to review your work.

Best regards,

Jinfeng Chang, PhD
Editorial Board Member
Communications Earth & Environment
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EDITORIAL POLICIES AND FORMATTING

We ask that you ensure your manuscript complies with our editorial policies. Please ensure that the following formatting requirements are met, and any checklist relevant to your research is completed and uploaded as a Related Manuscript file type with the revised article.

Editorial Policy: Policy requirements (Download the link to your computer as a PDF.)

Furthermore, please align your manuscript with our format requirements, which are summarized on the following checklist:
Communications Earth & Environment formatting checklist

and also in our style and formatting guide Communications Earth & Environment formatting guide
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*** DATA: Communications Earth & Environment endorses the principles of the Enabling FAIR data project (http://www.copdess.org/enabling-fair-data-project/). We ask authors to make the data that support their conclusions available in permanent, publically accessible data repositories. (Please contact the editor if you are unable to make your data available).

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href="http://www.nature.com/sdata/policies/repositories">http://www.nature.com/sdata/policies/repositories.

If a community resource is unavailable, data can be submitted to generalist repositories such as figshare or Dryad Digital Repository. Please provide a unique identifier for the data (for example a DOI or a permanent

URL) in the data availability statement, if possible. If the repository does not provide identifiers, we encourage authors to supply the search terms that will return the data. For data that have been obtained from publically available sources, please provide a URL and the specific data product name in the data availability statement. Data with a DOI should be further cited in the methods reference section.

Please refer to our data policies at http://www.nature.com/authors/policies/availability.html.

REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

In this manuscript, McManamay et al. investigate how allowing urban land area in the GCAM integrated assessment model (IAM) to evolve over time might affect simulated cropland area, crop production, and carbon sequestration. Rather than building a dynamic urban module into GCAM, the authors overlay high-resolution projections of urban land area onto existing high-resolution projections of cropland, forest, and grassland area from GCAM. This method will fail to capture feedbacks and nonlinearities, as the authors discuss, but is a reasonable first step toward and justification for actually simulating urban dynamics in GCAM.

In all SSPs except SSP1, projected urban expansion tends to come more from cropland than from forest or grassland; the most productive cropland is disproportionately affected. In the most extreme estimate, projected urban expansion could reduce global net primary productivity (NPP) by as much as 2.3 GtC/yr by 2100.

However, I was left extremely confused by the discussion around the carbon implications. Combined with some methodological questions, this has led me to suggest this manuscript be reconsidered after major revisions.

More details can be found in the next page.

Review: “Dynamic urban land extensification and imbalances to the global land-carbon equilibrium”

General comments

In this manuscript, McManamay et al. investigate how allowing urban land area in the GCAM integrated assessment model (IAM) to evolve over time might affect simulated cropland area, crop production, and carbon sequestration. Rather than building a dynamic urban module into GCAM, the authors overlay high-resolution projections of urban land area onto existing high-resolution projections of cropland, forest, and grassland area from GCAM. This method will fail to capture feedbacks and nonlinearities, as the authors discuss, but is a reasonable first step toward and justification for actually simulating urban dynamics in GCAM.

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However, I was left extremely confused by the discussion around the carbon implications. Combined with some methodological questions, this has led me to suggest this manuscript be reconsidered after major revisions.

Specific comments

As mentioned above, my greatest concern with this manuscript is the lack of clarity about the carbon implications of urban expansion. The Abstract states that urban expansion’s effects on NPP could cause a 50% increase in “projected CO2 emissions,” with the Discussion (L199-200) quantifying the possible range as 19–67%. I was left deeply confused about what exactly is being compared here—i.e., what these are percentages *of*.

If the authors are saying that total anthropogenic CO2 emissions estimates would be increased by up to 67%, that is an extraordinary statistic that must be explained; it would suggest a serious deficiency in GCAM. (The explanation can’t involve nonlinearities in Earth system response to urban expansion, because the CO2 effect is being calculated in postprocessing rather than with urban extensification actually in the GCAM.) Is it instead CO2 emissions *from land* or *from land-use change*? Even if so, it’s surprising. How much change in area does GCAM (without urban expansion, of course) simulate for cropland, pasture, etc.?

I also have questions about the actual calculations and units. L200 says that urban expansion could increase year-2100 CO2 emissions for SSP5 by 67%. How is that calculated? Looking at SSP5 in Fig. 7, the increase from the solid blue to solid red line is clearly less that 67%. Is it from the dashed blue to dashed red lines? That can’t be right, because the dashed blue line actually has net carbon sequestration while the dashed red range has net C emissions, so percentage change can’t even be calculated there. Moreover, the units under discussion are unclear. The text (L184-5) refers to Mt CO2 per year, but the Y-axis label says Gt CO2 (no “per year”). My best guess is that the units are supposed to be Gt CO2/yr. But CO2 from what? The

present-day emissions estimates are pretty far away from both total anthropogenic CO2 emissions (~40 Gt CO2/yr) and land-use change emissions (~4 Gt CO2/yr; Friedlingstein et al., 2022, *Earth System Science Data*, doi:10.5194/essd-14-4811-2022). Is that discrepancy due to this graph actually showing Gt C instead of Gt CO2? Is it due to errors in GCAM?

This analysis and the discussion around it must be reworked for clarity.

Other notes about carbon:

- It seems like your estimate of CO2 impact may be conservative, since it does not include neither (a) land that will need to be converted to cropland (or increased carbon intensity needed for higher-input agriculture) in order to replace production losses due to cropland converted to urban land, (b) the CO2 emitted during conversion of forest or grassland to urban land, or (c) the CO2 emitted from soil for years after conversion. These should be discussed.
- Methodological question: In calculating CO2 impact, is it effectively assumed that urban land has NPP = 0? That seems fine, but it should be mentioned.
- NPP, at least as it is usually defined, does not account for how disturbances and wood harvest affect the C balance. Is that also true here? If so, how might doing so affect the results?

Other notable questions/concerns:

- Do CLUBS/SELECT consider competition for urban land from agriculture? If not, would that suggest the CLUBS/SELECT urban expansion numbers to be overestimates?
- Need to be consistent with definition of "staple". L143 includes soybean, but L160 doesn't. L161 says "staples" lose 1–13% of 2010 production levels, but L194 says 1–26%.
- Why are croplands more affected than either forests or grasslands? What about how CLUBS/SELECT and GCAM determine land use areas might contribute to this? Is it something having to do with proximity to existing urban areas?
- L203–209: This is confusing. Why does SELECT estimate only "impervious surface areas" that are somehow *not* "urban areas"? (What even *are* such areas? Rural houses, roads, and runways?)
- Are crop yields in GCAM responsive to climate? If not, the possible impacts of this on the results—especially with regard to impact of urban expansion on the need for production increases—should be discussed.

Minor comments/corrections

- Throughout:
  - When only referring to cropland (i.e., not also pasture/rangeland), use "cropland" instead of "agriculture."
  - "O'Neil" should be "O'Neill"
- L69: "principles market equilibrium"

- L92-3: I'm not sure how the second part of this sentence follows from the first. IAMs and ESMs are often totally separate models.
- L101: "consequences **of** the equilibrium"
- L116-7: This is unclear: "Urban lands are presented as fractional values with grid cells, representing the proportion of impervious land."
- L131: Somewhere before here, please explain that the "SSP" results are actually means across all RCPs associated with that SSP. (It's mentioned in the Methods, but that comes later in the paper.)
- L140–7: This paragraph should mention that SSP1 actually has more urban expansion come from grasslands than from cropland.
- L147: What does "significantly" mean here?
- L168: It looks like *corn* and rice, not *wheat* and rice, that drop below present-day levels in SSP5.
- L175: Unclear whether "(48 – 69 Gt)" refers to "1.7%" or ALL "modern global NPP estimates".
- L196: Should "offset" be "exacerbate"? It seems like urban expansion makes the need for increased production worse, not better.
- L198: Why is the upper range of NPP losses 5% here but 4% at L176?
- L200: How can administrative boundaries take up any land area? Aren't they one-dimensional lines?
- L205: Should "Build" be "Built"?
- L228–31: Why are these biodiversity-related statistics being discussed here?
- L233–4: This clause is confusing. What is the population range, exactly?
- L240: "lead" should be "led".
- L243: "cropland" should be "area".
- L245: Why is Bren d'Amour et al. (2017) cited here, where you're discussing a conclusion from your own results? Does this need something like "as also found by"?
- L271–273: How is this different from what was done in the previous "numerous studies" (L222), such as Bren d'Amour et al. (2017)?
- L275: "to **the** agricultural sector"
- L280: Shouldn't upper bound be 13% ($4x10^5$ / $7x10^6$) instead of 12%? Or is this a rounding thing?
- Please add subsection headers to Methods.
- L298: Please provide a table showing the "15 plausible combinations" of SSPs x RCPs.
- L317: Replace "5 SSPs, 4 RCPs" with "15 SSP-RCP combinations" for clarity.
- L321: "interject" is not the right word.
- L331: "project"?
- L340-1: "over-allocated urban lands or has inaccuracies" seems to put all the potential blame on CLM. CLUBS-SELECT might be the problem too. Also, why couldn't *negative* ΔUfi result from this as well?
- L348: "comprised"?
- L584: "between SSP5 and" should be "in SSP5 between"
- L587–588: In addition to the reference to Gao & O'Neill (2020), mention that this is CLUBS+SELECT.
- Fig. 3:

    - Global plot has 15 bars but US plot has 16. This means that the X-axis labels for the US plot don't align with the bars of the global plot.
    - "Bioergy" typo
- Fig. 7:
    - RCP legend is unclear. Which is dashed?
    - Why is there such a sudden drop in emissions around 2037 for SSP5 with RCP2.6?

Reviewer #2 (Remarks to the Author):

This is an interesting paper examining the impacts of urban expansion on the global land-carbon equilibrium. The research is meaningful as urbanization and land use change have important influences on the global carbon cycle, while current analysis lack adequate representation of these processes. But the authors need to revise their manuscript.

The research methods are sound, but there are some limitations:

The authors claimed that "When considering increased production required for growing populations, urban extensification could cut required yield increases by almost half". However, the manuscript doesn't mention any population distribution data.

There are large uncertainties in predicting urban expansion extent by 2100, as indicated by the wide range of 1.2-3.7 million km2 given. Sensitivity analyses on different urban expansion scenarios would help assess impacts of uncertainties.

The paper predicts reduced crop yields and NPP would increase CO2 emissions but does not quantify specific carbon emission amounts. Adding quantified estimates would make the conclusions more convincing.

Interactions between urban expansion and non-urban land use changes are not fully discussed, which may also affect prediction results.

The title is insufficient to summarize the content of the article. The analysis goes far beyond global land-carbon equilibrium, and also includes NPP, food, etc. The article does not clearly describe how these two points are converged to land carbon. The principles of the carbon module in GCAM are also unclear.

It lacks flowcharts of methods. The alignment of NPP data(2010-2015) and LUCC(till 2100) data is not clearly explained. The source of food data is not explained.

The article is like an experimental report. It feels like some existing LUCC data has been used to do some analysis on several variables, without a complete storyline or an attempt to answer or solve any problem. The author needs to use a flowchart to outline the structure of the article.

Imbalance is an important conclusion. The author states: "Our results suggest that the exclusion of finer-scale land projections within integrated assessment models and by association, Human-Earth System Models, can lead to systemic global imbalances and disequilibria in natural resources, commodities, and land-atmospheric interactions." But I did not see which experiment supports this point. Did the author do a comparison between the exclusion of finer-scale land projections and the inclusion of finer-scale land projections?

It is unclear what commodities refer to in the article. "A significant difference between our assessment and other studies is that we examined the intersection and competition between dynamic changes in urban land and those of non-urban lands, both driven by non-stationary and competing resource demands." It is unclear which experimental process reflects this.

Policy measures to address urban expansion are not mentioned - adding suggestions would make the paper more impactful.

We thank both reviewers for their helpful comments and attention to detail. We have attempted to revise the manuscript according to these suggestions as much as possible. Please find our responses in bold blue text below.

REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

General comments
In this manuscript, McManamay et al. investigate how allowing urban land area in the GCAM integrated assessment model (IAM) to evolve over time might affect simulated cropland area, crop production, and carbon sequestration. Rather than building a dynamic urban module into GCAM, the authors overlay high-resolution projections of urban land area onto existing high-resolution projections of cropland, forest, and grassland area from GCAM. This method will fail to capture feedbacks and nonlinearities, as the authors discuss, but is a reasonable first step toward and justification for actually simulating urban dynamics in GCAM.

Although there was no formal request or suggestion here, we did want to point out that we have clarified in the text, both in the abstract and introduction and elsewhere, that our analysis is more accurately an experiment of 1st-order impacts that does not account for model adjustments that would be simulated within a multisector model, such as GCAM.

In all SSPs except SSP1, projected urban expansion tends to come more from cropland than from forest or grassland; the most productive cropland is disproportionately affected. In the most extreme estimate, projected urban expansion could reduce global net primary productivity (NPP) by as much as 2.3 GtC/yr by 2100.

However, I was left extremely confused by the discussion around the carbon implications. Combined with some methodological questions, this has led me to suggest this manuscript be reconsidered after major revisions.

We now have attempted to clarify our approach more accurately in the methods and the results. Our estimates of increased CO2 emissions from the land system due to losses in NPP (carbon sequestration) from urban extensification were correct. However, we found that we had used incorrect units of measurement for CO2 emissions estimates from GCAM. CO2 emission outputs from GCAM are in Million metric tons (Mt) of Carbon, rather than CO2. Therefore, we have now corrected these estimates using molecular weight. Additionally, we could see how evaluating all CO2 emissions for all sectors was somewhat confusing; therefore, we have now solely focused on land emission budgets. Land emissions in GCAM range from negative (net sequestration) to positive (net emissions) values based on land cover and RCP, etc. Therefore losses in NPP will directly relate to land emission budgets.

We have now provided Table 4 as a provision of raw values. Additionally, we have updated Figure 7.

Specific comments
As mentioned above, my greatest concern with this manuscript is the lack of clarity about the carbon implications of urban expansion. The Abstract states that urban expansion's effects on NPP could cause a 50% increase in "projected CO2 emissions," with the Discussion (L199-200)

quantifying the possible range as 19–67%. I was left deeply confused about what exactly is being compared here—i.e., what these are percentages *of*.

We now have removed percentages as these can be confusing and now only report raw differences in Gt CO2. Additionally, we now only focus on land emission budgets, rather than emissions from all sectors. Part of the reason in the high statistic was that we had assumed wrong units for CO2 emissions in GCAM, which are measured in Mt of Carbon, rather than Mt of CO2.

For clarity, We have now provided Table 4 as a provision of raw values.

Here is how the percentage was calculated:

Percent change in CO2 emissions from land sector =
(CO2 emissions for dynamic urban – CO2 emissions for static urban)/ (CO2 emissions for static urban) *100

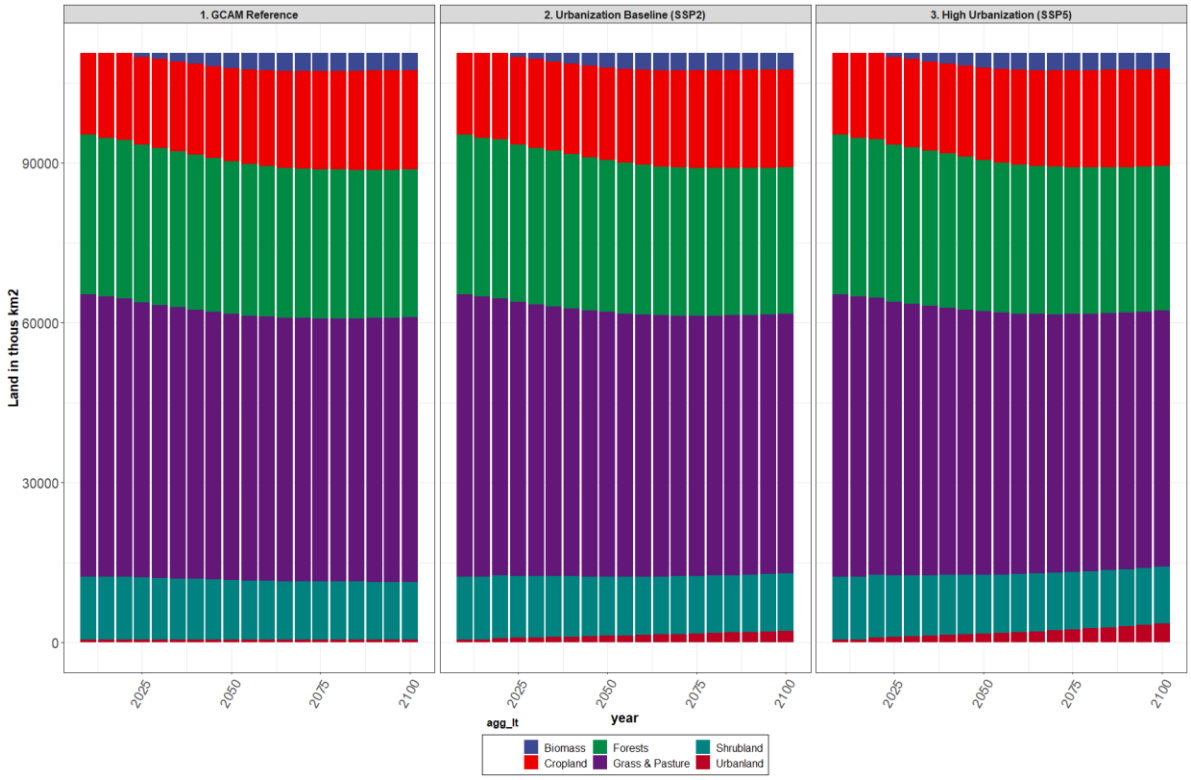
If the authors are saying that total anthropogenic CO2 emissions estimates would be increased by up to 67%, that is an extraordinary statistic that must be explained; it would suggest a serious deficiency in GCAM. (The explanation can't involve nonlinearities in Earth system response to urban expansion, because the CO2 effect is being calculated in postprocessing rather than with urban extensification actually in the GCAM.) Is it instead CO2 emissions *from land* or *from land-use change*? Even if so, it's surprising. How much change in area does GCAM (without urban expansion, of course) simulate for cropland, pasture, etc.?

Please see previous explanation.
However, a 1st order experiment like ours CAN still expose non-linearities in system responses. For example, even if urbanization only comprises 3 to 5% of Earth's land surface, crop production may decline by 26%, depending on crop. Changes in CO2 emissions from the land surface can be 5X higher. Linear responses are linear functions of inputs, and that is clearly what we do not see. These are non-linear responses.

However, you are correct that we are estimating these effects as post-processing rather than in GCAM, which would have provided adaptive adjustments to land budgets via prices for land. However, there are limits to these adaptive adjustments. Through preliminary simulations (unpublished data), we have that urban dynamism (IN GCAM) leads to permanent changes in the multisector system.

That being said, we cannot fully understand the magnitude of the role of urbanization unless we isolate it as a post-processing procedure – analogous to partial dependence in multivariate models. GCAM will mask the role through adjustment to a degree.

Related to the last question, we have provided a plot below showing the land area without urban change (left GCAM reference), and a comparison with SSP2 and SSP5. As you can see, urban land is a relatively small area, but is approximate to total biomass lands.



I also have questions about the actual calculations and units. L200 says that urban expansion could increase year-2100 CO2 emissions for SSP5 by 67%. How is that calculated? Looking at SSP5 in Fig. 7, the increase from the solid blue to solid red line is clearly less that 67%. Is it from the dashed blue to dashed red lines? That can't be right, because the dashed blue line actually has net carbon sequestration while the dashed red range has net C emissions, so percentage change can't even be calculated there. Moreover, the units under discussion are unclear. The text (L184-5) refers to Mt CO2 per year, but the Y-axis label says Gt CO2 (no "per year"). My best guess is that the units are supposed to be Gt CO2/yr. But CO2 from what? The present-day emissions estimates are pretty far away from both total anthropogenic CO2 emissions (~40 Gt CO2/yr) and land-use change emissions (~4 Gt CO2/yr; Friedlingstein et al., 2022, *Earth System Science Data*, doi:10.5194/essd-14-4811-2022). Is that discrepancy due to this graph actually showing Gt C instead of Gt CO2? Is it due to errors in GCAM?

Please refer to above responses. We have removed the percentages because of issues mentioned (i.e., negative emissions) and interpretation. Also, we have now only focused on CO2 emissions from the land system – as this emission estimates are most relevant.

Also, the units (Mt) originally presented in the text are incorrect. They should be Gt, as is depicted in the figures. And yes, it should be Gt per year.

We have corrected this in the results and methods. And indicated that this is related to land system only.

This analysis and the discussion around it must be reworked for clarity.

We have updated the methods for clarity, and changed how we presented the results – steering clear of presentations of percentages and provision of raw values.

We have now provided Table 4 as a provision of raw values. Additionally we have updated Figure 7.

Other notes about carbon:
• It seems like your estimate of CO2 impact may be conservative, since it does not include neither (a) land that will need to be converted to cropland (or increased carbon intensity needed for higher-input agriculture) in order to replace production losses due to cropland converted to urban land, (b) the CO2 emitted during conversion of forest or grassland to urban land, or (c) the CO2 emitted from soil for years after conversion. These should be discussed.

We have now included these limitations at the end of the first paragraph of the discussion. Lines 182-186.

• Methodological question: In calculating CO2 impact, is it effectively assumed that urban land has NPP = 0? That seems fine, but it should be mentioned.

Yes, thank you – we now include this in the methods. Lines 460.

• NPP, at least as it is usually defined, does not account for how disturbances and wood harvest affect the C balance. Is that also true here? If so, how might doing so affect the results?

We have now included these limitations section (lines 267-291) and mention wood harvest specifically in Lines 282

Other notable questions/concerns:
• Do CLUBS/SELECT consider competition for urban land from agriculture? If not, would that suggest the CLUBS/SELECT urban expansion numbers to be overestimates?

CLUBS and SELECT is a very sophisticated model system calibrated and based on empirical patterns and accounts for urban processes (dynamic urban maturation). SELECT does use habitat land masks utilized elsewhere to constrain urbanization, which prevent development on waterbodies, protected areas, steep topographies, etc.
However, like other urban land expansion models that we are aware of, CLUBS/SELECT does not consider competition between urbanization and other land sectors – because currently there is no widespread empirical evidence to suggest that other land uses ever "outcompete" urbanization – perhaps there are very localized examples, but this is not the case at a global scale. The reason is that the price or value of urban land far exceeds any other land type:
https://davidalbouy.com/research/g0pih18il9x00enhdsowgtoj0f3x6w

Urban land generally expands as needed based on population growth (and subsequent economic pressures) and will consume all other land cover types that exist in areas where expansion is feasible –

typically this is relatively flat areas and not open water. Even zoning restrictions change are eventually reconsidered to accommodate growth – driven my economics. Perhaps only until the global land value system changes, will global societies value agricultural and forest lands sufficiently enough to dampen urbanization.

However, eventually if lands become extremely scarce and areas to support crop production become significant, this competition could change. Once GCAM is updated with an ability to model urban land, urban land will then formally compete with other land sectors through shifting price per unit area. Unfortunately, we do not have that capability fully implemented in GCAM.

• Need to be consistent with definition of "staple". L143 includes soybean, but L160 doesn't. L161 says "staples" lose 1–13% of 2010 production levels, but L194 says 1–26%.

Corrected throughout. We now include soybean in all instances, which shift numbers to 1-12%. The 1-26% value was the ranges for individual crops, but for ease of interpretation, we have removed this from the discussion.

• Why are croplands more affected than either forests or grasslands? What about how CLUBS/SELECT and GCAM determine land use areas might contribute to this? Is it something having to do with proximity to existing urban areas?

The location of new urban growth is governed by CLUBS/SELECT. Urban land growth is higher in close proximity to existing urban areas, but also based on suitability for new growth dependent upon topography and avoidance of steep terrain. As we see in reality, this means that relative flat areas (i.e. agricultural is most impacted).

Non-urban lands (croplands, forested areas, etc) are governed by GCAM and Demeter. GCAM only provides basin-level land allocations for new cropland, forest, and grassland based on shifting socioeconomic demands, whereas Demeter downscales these land budgets to a 1-km resolution based on proximity to existing cropland, forest, and grassland respectively.

So location matters and our analysis is spatially explicit based on areas of likely growth of both urban and non-urban lands.

We add the following to lines 226-229:
Congruent with other studies, our analysis suggests that croplands are the most impacted based on the spatially explicit nature of urban growth's intersection with dynamic changes in other land sectors. However, we find that forested lands could also be significantly compromised by urban expansion, losing up to 1 million km^2 globally.

• L203–209: This is confusing. Why does SELECT estimate only "impervious surface areas" that are somehow *not* "urban areas"? (What even *are* such areas? Rural houses, roads, and runways?)

We've now updated the section for clarity.

Global estimates of the spatial extent of urban lands range dramatically, due to inconsistent definitions for "urban land" (Liu et al. 2014). SELECT utilizes the Global Human Settlement Layer (GHSL), a 38-m empirical Landsat-derived time series dataset (EC 2023) for model development and calibration. Urban lands from the SELECT model are synonymous with GHSL as built-up land or impervious surfaces, i.e. manmade materials such cement, asphalt, steel, glass (Gao and O'Neill 2020), which suggests that the cascading effects of urbanization accurately reflect resource losses (e.g., crop yield).

• Are crop yields in GCAM responsive to climate? If not, the possible impacts of this on the results—especially with regard to impact of urban expansion on the need for production increases—should be discussed.

GCAM does not have endogenous climate feedbacks built in to model climate impacts on crop yields, as would an individual crop model. Studies have calculated yield impacts outside of GCAM (ensuring similar climate scenarios targeted in GCAM) and then incorporated updated yields back into GCAM to explore endogenous responses, or shifts in crop type, technologies, etc.

We've now included this as apart of our limitation section in the discussion (Lines 284-288).

Minor comments/corrections

• Throughout:

o When only referring to cropland (i.e., not also pasture/rangeland), use "cropland" instead of "agriculture."

All of the instances where either agriculture or cropland is mentioned follow this correct definition.

o "O'Neil" should be "O'Neill"

Changed throughout.

• L69: "principles market equilibrium"

Added "of" after "principles."

• L92-3: I'm not sure how the second part of this sentence follows from the first. IAMs and ESMs are often totally separate models.

Updated the sentence.
Agreed – Originally the idea that we were trying to convey is that IAMs can communicate with ESMs and lack of urban representation is a problem for both systems.

• L101: "consequences **of** the equilibrium"

Changed

• L116-7: This is unclear: "Urban lands are presented as fractional values with grid cells,

representing the proportion of impervious land."

Changed to *"Urban lands are presented represented as fractional values (0 to 1) of impervious surface within grid cells"*

• L131: Somewhere before here, please explain that the "SSP" results are actually means across all RCPs associated with that SSP. (It's mentioned in the Methods, but that comes later in the paper.)

In this particular instance (e.g. line 131), is referring to SSP results from SELECT, which has only 1 solution per SSP, and does not consider RCPs.
Results are not generically averaged by SSP. In some cases, individual combinations of SSP-RCP are presented for a specific scenario. We explain this in Figure captions.

• L140–7: This paragraph should mention that SSP1 actually has more urban expansion come from grasslands than from cropland.

Added to the paragraph.

• L147: What does "significantly" mean here?

Removed "significantly"

• L168: It looks like *corn* and rice, not *wheat* and rice, that drop below present-day levels in SSP5.

changed

• L175: Unclear whether "(48 – 69 Gt)" refers to "1.7%" or ALL "modern global NPP estimates".

Clarified as "By 2050, total NPP losses range from being negligible (0.05 Gigatons, Gt) to 0.8 Gt, which constitutes almost 1.7% of contemporary global NPP estimates (48 – 69 Gt) (Gough 2011).

• L196: Should "offset" be "exacerbate"? It seems like urban expansion makes the need for increased production worse, not better.

Really "offset" is better. We are trying to say that GCAM is increasing crop production for growing global populations – However, our results suggest that urbanization could remove up to 50% of the estimated increases in production.

• L198: Why is the upper range of NPP losses 5% here but 4% at L176?

Changed to exact figure 4.8%.

• L200: How can administrative boundaries take up any land area? Aren't they onedimensional lines?

Changed to "built-up land"

• L205: Should "Build" be "Built"?

Changed

• L228–31: Why are these biodiversity-related statistics being discussed here?
Removed reference to biodiversity statistics.

• L233–4: This clause is confusing. What is the population range, exactly?

Removed this reference/clause

• L240: "lead" should be "led".
changed
• L243: "cropland" should be "area".
added
• L245: Why is Bren d'Amour et al. (2017) cited here, where you're discussing a conclusion from your own results? Does this need something like "as also found by"?

added "as also found by"

• L271–273: How is this different from what was done in the previous "numerous studies" (L222), such as Bren d'Amour et al. (2017)?

We distinguish our studies from others in lines 213 to 221.

Global cropland datasets used in Bren d'Amour et al. (2017) were static, and hence, increasing socioeconomic pressures on existing croplands and the need for cropland expansion was not accommodated. Additionally, Bren d'Amour et al. (2017) uses only 1 urban growth projection for 1 year (2030).

In our study, non-urban land types (both cropland, grassland, and forest lands) are dynamic over time to accommodate the shifting socio-economic pressures simulated within GCAM.
GCAM land allocations are downscaled by Demeter for all non-urban lands. So our experiment was determining how dynamic urban land expansion intersects dynamic cropland, grassland and forests. This creates an interactive effect and is influenced by many factors.
Our experiment was conducted for 2700 different simulations of land cover outcomes.

• L275: "to **the** agricultural sector"

Added "the"

• L280: Shouldn't upper bound be 13% (4x105 / 7x106) instead of 12%? Or is this a rounding thing?

Changed to 13%

• Please add subsection headers to Methods.

Added subsection headers to methods

• L298: Please provide a table showing the "15 plausible combinations" of SSPs x RCPs.

Table 4 was added to provide values of land emission comparisons. And this provides all SSP-RCP combinations.

• L317: Replace "5 SSPs, 4 RCPs" with "15 SSP-RCP combinations" for clarity.

replaced

• L321: "interject" is not the right word.

Changed to "intersect"

• L331: "project"?

Projections

• L340-1: "over-allocated urban lands or has inaccuracies" seems to put all the potential blame on CLM. CLUBS-SELECT might be the problem too. Also, why couldn't *negative* ΔUfi result from this as well?

We now include "either SELECT or CLM5 basemap. However, due to previous comparisons and accuracy assessments, SELECT is a far more accurate depiction of urban lands than CLM5.

• L348: "comprised"?

Changed to "compromised"

• L584: "between SSP5 and" should be "in SSP5 between"

Changed

• L587–588: In addition to the reference to Gao & O'Neill (2020), mention that this is CLUBS+SELECT.

added

• Fig. 3:
o Global plot has 15 bars but US plot has 16. This means that the X-axis labels for the US plot don't align with the bars of the global plot.

Grassland was missing from global plot. Now has been added.

o “Bioergy” typo

corrected

• Fig. 7:
o RCP legend is unclear. Which is dashed?

Figure has been updated

o Why is there such a sudden drop in emissions around 2037 for SSP5 with RCP2.6?

Note that we have changed this figure to include only land emissions. Units have been corrected.

Major changes in RCPs are due to technological/behavioral adaptations in land cover. This is primarily due to reforestation efforts in SSP1 and SSP5 for RCP 2.6, and increases in bioenergy development in SSP2 and SSP3 for RCP 4.5, and shifts in croplands versus forests..

We now provide an explanation/discussion of these patterns in Lines 244 to 245 and 298-304.

An overview of changes resulting in patterns is here:

- **SSP5 -2.6. Reforestation, less cropland. RCP 8.5 BAU**
- **SSP1 2.6. reforestation, less so in RCP 6.0**
- **SSP2 – 4.5. Increasing bioenergy, decreasing forest. 6.0 Same proportions, slight bioenergy growth**
- **SSP3 – 4.5. noticeable increases in bioenergy mid-century and slight increase in crop lands – decreasing forest. 6.0 decreased forest and increased croplands. Some bioenergy growth.**

Reviewer #2 (Remarks to the Author):

This is an interesting paper examining the impacts of urban expansion on the global land-carbon equilibrium. The research is meaningful as urbanization and land use change have important influences on the global carbon cycle, while current analysis lack adequate representation of these processes. But the authors need to revise their manuscript.

The research methods are sound, but there are some limitations:

The authors claimed that "When considering increased production required for growing populations, urban extensification could cut required yield increases by almost half". However, the manuscript doesn't mention any population distribution data.

Population changes are modeled within Global Change Analysis Model (GCAM). We utilize GCAM outputs reflecting increasing crop yield and land required to support growing populations.

We now provide more information on GCAM in last section of Methods lines 444 to 460.

There are large uncertainties in predicting urban expansion extent by 2100, as indicated by the wide range of 1.2-3.7 million km2 given. Sensitivity analyses on different urban expansion scenarios would help assess impacts of uncertainties.

This is good point. We recognize that there are many different future urban projections that could be used. We discuss this limitation, among other limitations, in our discussion, lines 444 to 460.

We elected to use SELECT over other urban projections because of its ability to capture mechanistic urbanization processes – future urban land projections are, in part, an outcome of past urban trajectories and urban maturity where urbanization rates are temporally dynamic and locally dependent, with parameters that can be adjusted in tune with SSPs – a major difference from other urban land model approaches (Gao and O'Neill 2019; 2020). We perceive SELECT as providing more realism, but also an important capability to accommodate more flexibility and thematic consistency with the assumptions underlying the SSPs

Even though we used only 1 set of urban projections (which do vary by SSP), our non-urban land types include 2700 different simulations of land cover outcomes. This provides immense uncertainty analysis.

The paper predicts reduced crop yields and NPP would increase CO2 emissions but does not quantify specific carbon emission amounts. Adding quantified estimates would make the conclusions more convincing.

We agree. We now provide quantitative estimates by the addition of Table 4. Rather than report percentages, we now report raw increases in CO2 emissions in abstract, results, and discussion.

Interactions between urban expansion and non-urban land use changes are not fully discussed, which may also affect prediction results.

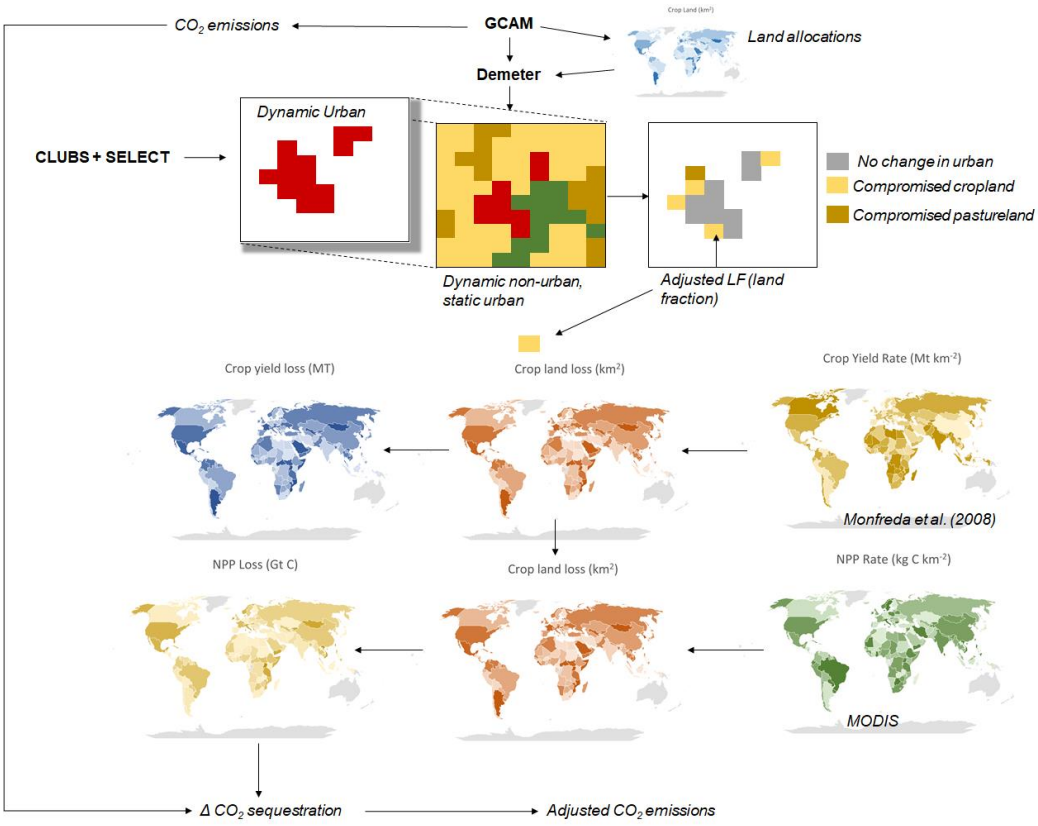
We tried to expand on the results of compromised non-urban lands in results (lines 119-127) and in the discussion (lines 226-229).

The title is insufficient to summarize the content of the article. The analysis goes far beyond global land-carbon equilibrium, and also includes NPP, food, etc. The article does not clearly describe how these two points are converged to land carbon. The principles of the carbon module in GCAM are also unclear.

We contemplated changing the title, but we feel that the title does accurately reflect our work. We focus on impacts of urban extensification to other non-urban lands, and examine the implications on carbon, captured by both NPP and emissions. The point is that integrated assessment models, like GCAM, utilize equilibrium principles to balance many sectors, including land, natural resources, and carbon emissions. It is true that our analysis focuses on crop yields; however, using the term "food" places a different emphasis on what our paper is attempting to convey.

It lacks flowcharts of methods. The alignment of NPP data(2010-2015) and LUCC(till 2100) data is not clearly explained. The source of food data is not explained.

We have now added a flowchart and added Supporting Information to support the article. We've also updated the entire methods section by dividing it up with section headers and providing more information. Sources of NPP and crop yields are clearly cited now.



The article is like an experimental report. It feels like some existing LUCC data has been used to do some analysis on several variables, without a complete storyline or an attempt to answer or solve any problem. The author needs to use a flowchart to outline the structure of the article.

We have now added a flow chart to assist in understanding the methodology, and we have updated the text throughout the manuscript.

Imbalance is an important conclusion. The author states: "Our results suggest that the exclusion of finer-scale land projections within integrated assessment models and by association, Human-Earth System Models, can lead to systemic global imbalances and disequilibria in natural resources, commodities, and land-atmospheric interactions." But I did not see which experiment supports this point. Did the author do a comparison between the exclusion of finer-scale land projections and the inclusion of finer-scale land projections?

We apologize for this confusion. We now clarify that we are referring to the exclusion of "urban land projections", rather than "finer-scale land" projections. Originally, we meant "finer-scale" by the inclusion of new dynamic land classes, specifically urbanization, even though it represents a very small fraction of global land surface.

It is unclear what commodities refer to in the article.

We have removed the reference to "commodities".

"A significant difference between our assessment and other studies is that we examined the intersection and competition between dynamic changes in urban land and those of non-urban lands, both driven by non-stationary and competing resource demands." It is unclear which experimental process reflects this.

That describes our entire methodological process. CLUBS-SELECT drives dynamic changes in urbanization by shifting population and socioeconomic processes. GCAM-demeter is driving dynamic changes in cropland, forestland, bioenergy lands, grasslands, etc. We are combining to two to examine how urban land can compromise the other growing or contracting landscapes to understand implications of global equilibrium from GCAM.

Policy measures to address urban expansion are not mentioned - adding suggestions would make the paper more impactful.

The last paragraph of the discussion is now dedicated to policy measures. Lines 315-328.

20th Dec 23

Dear Dr McManamay,

Your manuscript titled "Dynamic urban land extensification and imbalances to the global land-carbon equilibrium" has now been seen by our reviewers, whose comments appear below. In light of their advice we are delighted to say that we are happy, in principle, to publish a suitably revised version in Communications Earth & Environment under the open access CC BY license (Creative Commons Attribution v4.0 International License).

We therefore invite you to revise your paper one last time to address the remaining concerns of reviewer #1. In particular, please incorporate text from the rebuttal letter in the Discussion part of your manuscript. At the same time, we ask that you edit your manuscript to comply with our format requirements and to maximize the accessibility and, therefore, the impact of your work.

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REVIEWERS' COMMENTS:

Reviewer #2 (Remarks to the Author):

The authors have addressed all my questions.

Reviewer #1 (Remarks to the Author):

See attachment. (next page)

Re-review: “Dynamic urban land extensification and imbalances to the global land-carbon equilibrium”

General comments

The authors have done a good job responding to the concerns raised by the other reviewer and me. However, I have some remaining concerns that probably rise to the level of “resubmit with minor revisions.”

Main comments

The authors note that they had incorrectly interpreted GCAM outputs as Mt C when in fact they are Mt CO2. This implies that all carbon-related numbers should be about a factor of 3.664 lower in the revised manuscript, but as far as I can tell, they haven’t changed almost at all.

There are some things that should be added to (or expanded in) manuscript:

- Add “land in thous km2” figure from Rebuttal to Supplement.
- Methods or Discussion: Mention that CLUBS/SELECT don’t consider competition between urbanization and other land types (with the reasonable justification outlined in the Rebuttal).
- Discussion: Expand discussion of why croplands are disproportionately affected. The text in the Rebuttal is great; the actual added text (L235-8) is too vague.

In subsequent Rebuttals, please ensure that you refer to the correct line numbers. These were in many cases incorrect, which made review difficult.

Minor comments

I see what you’re saying now about the new L183-7. However, as written it’s hard to take that message, I think primarily because of “offset.” I suggest changing that text from:

> We estimate that by 2100, urban extensification could compromise anywhere from 1% to 12% of current global production levels for staple crops, but when considering increasing agricultural demands to accommodate growing world populations, losses in yields for individual crops, such as corn, could offset the required increases in crop production by almost half.

to:

> We estimate that by 2100, urban extensification could compromise anywhere from 1% to 12% of current global production levels for all staple crops combined. The yield loss from individual crops, such as corn, represents almost 50% of the required production increase needed to accommodate growing world populations.

I see now that you’ve actually already written something much clearer in the Abstract; maybe just repurpose that?

- L187-91: Should GtC be GtC/yr? If so, percentages seem low—present-day global NPP is ~60 GtC/yr. If not, percentages seem high.
- L201-3: How does this imply the results are conservative?

Response to Reviewer #1.

Re-review: "Dynamic urban land extensification and imbalances to the global land-carbon equilibrium"

General comments
The authors have done a good job responding to the concerns raised by the other reviewer and me. However, I have some remaining concerns that probably rise to the level of "resubmit with minor revisions."

Main comments
The authors note that they had incorrectly interpreted GCAM outputs as Mt C when in fact they are Mt CO2. This implies that all carbon-related numbers should be about a factor of 3.664 lower in the revised manuscript, but as far as I can tell, they haven't changed almost at all.

No, actually, it's the exact opposite. As stated in our response document, we had incorrectly interpreted GCAM outputs as Mt CO2, when in fact they are Mt C. Therefore, we needed to multiply the GCAM outputs by a factor of 3.664. And so yes, the GCAM output did indeed change (as reflected in Figure 7).

However, the estimates of increases in CO2 emissions from the land surface due to NPP losses did not change because we had originally calculated those estimates correctly. Those are simply added to the GCAM emissions.

Additionally, we now focus only on land emissions – not all sources of emissions – this changed values for GCAM emissions immensely. As evidence, Figure 7 has dramatically changed, and so we do not see how the reviewer can say that the values "haven't changed almost at all".

There are some things that should be added to (or expanded in) manuscript:

• Add "land in thous km2" figure from Rebuttal to Supplement.

We have now added the figure to the Supporting information document as Figure S1.

• Methods or Discussion: Mention that CLUBS/SELECT don't consider competition between urbanization and other land types (with the reasonable justification outlined in the Rebuttal).

We have now added this text to the discussion, lines 276 to 282.

• Discussion: Expand discussion of why croplands are disproportionately affected. The text in the Rebuttal is great; the actual added text (L235-8) is too vague.

We have now expanded the discussion in lines 220-226.

In subsequent Rebuttals, please ensure that you refer to the correct line numbers. These were in

many cases incorrect, which made review difficult.

Our apologies, we've tried to provide the lines where changes have been made.

Minor comments

I see what you're saying now about the new L183-7. However, as written it's hard to take that message, I think primarily because of "offset." I suggest changing that text from:

We estimate that by 2100, urban extensification could compromise anywhere from 1% to 12% of current global production levels for staple crops, but when considering increasing agricultural demands to accommodate growing world populations, losses in yields for individual crops, such as corn, could offset the required increases in crop production by almost half.

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We estimate that by 2100, urban extensification could compromise anywhere from 1% to 12% of current global production levels for all staple crops combined. The yield loss from individual crops, such as corn, represents almost 50% of the required production increase needed to accommodate growing world populations.

I see now that you've actually already written something much clearer in the Abstract; maybe just repurpose that?

We have now changed text as suggested.

• L187-91: Should GtC be GtC/yr? If so, percentages seem low—present-day global NPP is ~60 GtC/yr. If not, percentages seem high.

Yes it is Gt C per year. We now add -yr to the text.

We provide our estimates in Table 3. Additionally, we already cite the source of contemporary global NPP estimates (Gough et al. 2011), which range from 48 to 69 Gt C yr^{-1}.

Therefore, by 2100, our maximum NPP loss could be 2.3 Gt C yr^{-1}, which is up to 4% (based on the 48 Gt C yr-1). For good measure, we also add a range of percentages for good measure, i.e. 3% to 4%.

• L201-3: How does this imply the results are conservative?

We deleted this sentence.