Interactive comment on "The Land Use Model Intercomparison Project (LUMIP): Rationale and experimental design" by David M. Lawrence et al.

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Land use change is a necessary component of CMIP6 and a thorough and well argued case is made in this paper on how it should be done. Overall, this is a hugely ambitious MIP but one that if pulled off with a decent number of modelling groups would make profound strides forward. I think it will confront modelling groups and implementing these experiments will be challenging. But these experiments seem to be well thought through, appropriately designed and effectively described. My recommendation is therefore accept with minor revisions.

We thank Dr. Pitman for his positive comments about LUMIP in general. We acknowledge that the protocol is ambitious and that some of the simulations will be challenging to execute, but we are hopeful that through this paper and associated follow up organization/guidance that LUMIP will be a successful component of CMIP6.

In the text from line 60 to 83 I got rather lost as to the argument. For example, the link between the sentences on line 69 seems opaque. The sentence starting "Levis" is about crop modelling, the previous sentence is about irrigation. I know what you are trying to say but it does not really follow logically through this paragraph.

Rereading that paragraph, we see the point and have substantially rewritten it to improve its flow.

Line 111. Adaptation is local in most instances. I think its a big call to suggest CMIP6 models can inform us about adaptation given their spatial resolution. Maybe the best way to argue this is that LUMIP might provide approaches to this question at far higher resolution in RCMs?

Good point. We think removing the term adaptation from this question is more realistic. The input with respect to adaptation through LUMIP-related research would be indirect at best. We therefore removed the term adaptation here and in the abstract.

Lines 112-119 are well stated. Hugely ambitious but well stated. The #5 does not really seem to fit to me however - although it is an important question. I am not proposing any changes but it might be worth a little more rationale?

Yes, the questions that LUMIP intends to address are ambitious, but the intention is that LUMIP will draw on the breadth of expertise from a wide range of researchers who will utilize CMIP6/LUMIP simulation data. Regarding topic #5, we elect to retain this question as it is an area that has received some attention recently with respect to understanding the direct and indirect consequences of land-use change. We have reworded slightly to try to make this clearer: "the extent that the direct effects of higher CO_2 concentrations on increases in global plant productivity are modulated by past and future land use.

Line 128 - I got confused here. I am not clear what the text "did not translate as such in land-dover data sets" really means

We have modified the sentence to try to make this clearer: "Note that land-cover data and forest/non-forest data, as well as land-use transitions, will be provided in the new dataset in order to help minimize misinterpretation of the land-use dataset that occurred in CMIP5 where, for example, the

strong afforestation in RCP4.5 was not captured in Community Earth System Model (CESM) simulations because of differing assumptions embedded within the CESM land use translator (a software package that translates the LUH data into CESM land-cover datasets) and the LUH dataset (Di Vittorio et al. 2014)."

Line 130-135 - just a comment. This is the Porsche of LULCC science. I remain fearful that for most CMIP6 models the sophistication of the science presented here will disengage groups. A response "no it won't" is fine and time will tell.

No it won't. ☺ But seriously, we acknowledge again that LUMIP is ambitious, but we believe we have designed a set of experiments that will allow a range of researchers to make real progress in terms of our understanding of land cover and land management impacts on climate. The LUH2 dataset is intentionally more comprehensive and contains more data layers than any single modeling group is likely to be able to ingest. The goal is to help drive the whole field forward by pushing / encouraging groups to expand the scope of their models, possibly for CMIP6, but also beyond CMIP6. The author list of the LUMIP paper, which consists of the LUMIP Scientific Steering Group, includes representatives of many of the major modeling centers that are working on land use issues. These representatives have been heavily involved in both the experimental design and the production of the LUH2 dataset so none of this is going to come as a surprise to them.

Lines 219-225 0 I really did not know what you were trying to get across here.

We recognize that the definition of constant land use can be confusing. We have extensively rewritten the entire section 2.1 to try to better clarify.

Line 225 and 226 - I was confused here too. If the experiment is "constant land use" and you define fixed land use for a "relevant year" that implies to me you change land use annually and that implies anything but "fixed". Some clarification would be helpful.

See above.

Line 263-266 - this is a really important and valuable requirement.

We agree. This is especially critical for models that represent land-use history prior to 1850.

Line 276, 282, 314 Figure X means what ?

Apologies. We have corrected the figure numbers throughout the text.

Most of Section 2 is pitched at a good level of detail - balancing information that a reader might want with what a modeller doing the experiment might want. I do not think I could implement the experiments from this document - nor do I think that is a sensible thing to attempt. Is there going to be some place where full instructions will be given?

The descriptions are meant to be as comprehensive as possible, but especially with the factorial set of simulations for and land-use and land-managements land-only experiments, the details will be somewhat specific to each modeling group. We do/will maintain a website where more detailed instructions will be available where necessary and where we will maintain a forum for discussion of experimental setup. This is already noted in the text: "A forum for discussion of the experiments and for distribution of minor updates or clarifications to the experimental design will be hosted at the LUMIP website (https://cmip.ucar.edu/lumip)."

As someone who has worked in this place I can see the value of the different hierachy of experiments - with coupled, uncoupled etc. I wonder if that should be explained for the non expert - why your experiments are constructed in the way they are. I know this would be clear to the authors but it might not be to a non-land cover modeller?

The reviewer may have missed this, but we have already included a statement to this effect in the text. We believe that this provides sufficient justification for including both coupled and uncoupled simulations. "(a) The land-hist and land-noLu simulations will provide context for the global coupled CMIP6 historical simulations, enabling the disentanglement of the LULCC forcing (changes in water, energy and carbon fluxes due to land-use change) from the response (changes in climate variables like temperature and precipitation that are driven by LULCC-induced surface flux changes), though differences in the coupled model and observed climate forcing will need to be taken into account."

Line 474 - model evaluation is testing your model against observation. Model benchmarking is asking the question how well a model should perform given the information content in the forcing. I do not think they should be confused although I acknowledge they most certainly are in the community. You could resolve this by simply saying "need to improve diagnostics for land surface model evaluation and/or benchmarking in general".

We agree that the community needs to clarify the term benchmarking, but this is not the forum for that. We elect to remove the term benchmarking from this sentence completely.

line 495 - please no! Not student t-tests for LULCC. At the least you need a Findell test but there is far more to it and you need to account for field significance.

Good point. Mentioning t-tests was kind of a throwaway parenthetical that shouldn't have been included. We removed from the text and have included a new sentence mentioning the importance of field significance testing. "Lorenz et al. (2016) emphasize the importance of testing for field significance, especially in the context of evaluating the statistical significance of remote responses to LULCC."

Line 555-557 - It is great to see coupling strength in here and a sensible solution implemented

We agree. A more focused attention on the role of land-atmosphere coupling strength modulation of the land-use change signals is required. The opportunity to collaborate with LS3MIP on this will hopefully be productive.

Line 568-70 - seems vague. I appreciate you cannot resolve all aspects of this paper but this seemed particularly vague on extremes.

Not sure how to resolve this comment. Consideration of the impact of land use on extremes is a relatively new area of research and perhaps that explains the vagueness of the text. We felt it was important to highlight this as an area of analysis focus and believe that this paragraph serves that role. Took the opportunity to remove the term benchmarking, though.

Line 600- is the reporting of subgrid variables a request or a requirement. I think it should ideally be required but that might put considerable stresses on many groups in terms of data handling. No specific recommendation here, but suggesting it should be clearer.

We don't think that we can technically make anything a 'requirement' in terms of reporting, but the sub-grid request is a Tier 1 (highest priority) request in CMIP6.

Minor edits

Line 3 First sentence of abstract does not make sense. Add "changes" after large
Line 19 "with respect to-" does not make sense.
Line 21 - The acronyms do not necessarily make sense to some readers and I think might be better avoided in the abstract. I do not know what ScenarioMIP is (!) and perhaps I should.

Thanks for the edits, we have corrected them. For the final comment about not knowing what the other MIPs are, we elect to make the text clearer (that they are other CMIP6 MIPs) and retain mention of them in the abstract.

Line 59 - is this correct? 40% of the total radiative forcing? I would have guessed its 40% of the change in RF.

Correct, it is the change in RF. We have amended the sentence accordingly.

Line 66 "Other examines are numerous" is not a sentence.

We have corrected the sentence to: "Other examples of research indicating the importance of land management are numerous. "

Interactive comment on "The Land Use Model Intercomparison Project (LUMIP): Rationale and experimental design" by David M. Lawrence et al.

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General comments:
Realizing this is primarily a "documentation" paper and not a "results" paper, my comments are mainly regarding clarity and completeness of description.

The NCAR Last Millennium Ensemble (LME) is not mentioned anywhere in this manuscript, but it is a natural antecedent to much of what is described here and it seems to me it would be handy to reference (e.g., ca. line 122; Otto-Bliesner et al. 2016).

We are familiar with the LME work and we looked through the LME paper again. It's not fully clear to us that the LME is directly relevant. Certainly, for the LME a historical land use reconstruction was generated, but it was kind of a mishmash of different datasets. For CMIP6, the LUH2 dataset will extend back to 850AD for the purpose of running last millennium simulations in PMIP. This is a positive development and will be discussed in the LUH2 document, but it seems tangential to what we are discussing in this paper. So, we have elected not to include mention of the LME here so as to avoid any confusion that LUMIP is really addressing the Last Millenium land use change topic.

Specific comments:
L3: "...large to..." - It appears one or more words are missing.

Corrected to "large changes to"

L19: "...respect to-." - Likewise, seems words are missing.

Corrected to with "respect to LULCC."

L41-43: Clarify: effect on global MEAN air temperature is small.

Corrected.

L98-102: Expand acronyms.

Done.

L200: Good to cite previous recent works regarding climate impacts of global deforestation (e.g., Davin and Noblet-Ducoudré 2010) and remote climate impacts of tropical deforestation (e.g., Snyder 2010, Badger and Dirmeyer 2016).

Later in the text, in Section 2.2.1 we cite several papers that have looked at global or regional deforestation. We add the suggested references there along with a phrase summarizing the results.

L228: Apparently more missing words, "...level if."

Corrected. Removed the word "if".

L263: I well understand and appreciate the issues of providing guidance to the execution of model runs in MIPs, but wouldn't it be good to declare an avenue for consultation - a wiki or something - to assist the groups "to make their own decisions..."?

Definitely, and this has always been the plan. We noted higher up in the paper that a forum will be available, but repeat that here, since initialization and defining constant land use for each model is likely to be among the more complex aspects of setting up the LUMIP simulations.

L314: "Figure X" needs a number.

Apologies. All figure captions have been corrected. Not sure how that error slipped through into the submitted version.

L321: Also cite Badger and Dirmeyer (2015) in this regard.

Done.

L409: Change "i.e.," to "e.g.,"

Done.

L476: Should cite the most recent effort at land model benchmarking – PLUMBER (Best et al. 2015).

Good point. Also added the Randerson et al. paper on carbon cycle metrics.

L544-46: There have been investigations of the effect of land-atmosphere coupling on land use change responses. In particular, Kumar et al. (2013) developed a clever method to extract the land use change impact in CMIP5 simulations where multiple climate change factors were convolved in each RCP.

We went back and reread the Kumar et al. (2013) paper and it doesn't seem to us that the role of land-atmosphere interactions is a primary focus of that study. We do cite the Kumar et al. (2013) paper earlier in the paper for it's argument that the LULCC impacts are uncertain. So, we elect not to add reference to the paper in the discussion of land-atmosphere interactions.

Sec 4.2: The existence variable output lists is mentioned then glossed over – please give a direct link to a list of (what is the "LUMIP CMIP6 variable request"?) or list them in supplemental tables in this paper. This is an important detail.

We have added a list of variables and noted that the list is subject to change. It's not clear to us at this stage how the CMIP6 variable request documents will be maintained/distributed so it is difficult to be clearer than that. However, there is a process that will/is being communicated to all modeling groups. "A list of requested land-use tile variables is shown in Table 5. However, this list is subject to change. Modelers should refer to the CMIP6 output request documents for the final variable list. "

Figure 9 is not cited in text.

Corrected.

Interactive comment on "The Land Use Model Intercomparison Project (LUMIP): Rationale and experimental design" by David M. Lawrence et al.
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We thank Dr. Di Vittorio for his very thorough and constructive review.

The authors present the rationale and experimental protocol for the upcoming LUMIP. It appears that they intend this to be the primary reference document for the modeling groups participating in LUMIP. They first provide a comprehensive background and context with respect to CMIP6, and then describe an idealized experiment, a set of historical land-only experiments, and a set of future experiments. They then introduce a plan to develop metric, discuss challenges to analyses, and describe linkages to other MIPs that will enable studies relating LULCC to land-coupling strength and extremes. The paper concludes with a description and examples of subgrid data reporting for LUMIP.

The introduction and context are thorough and compelling, and the set of experiments is quite comprehensive and ambitious. I am impressed by this expression of the tremendous effort put forth by the LUMIP team (and others who may have contributed). I have reviewed this text as if I were a modeler expecting to participate in LUMIP. For the most part, the authors have done a good job explaining what is expected of the LUMIP participants. Apart from some clarification and additional detail, there is only one potentially major issue, and a few minor ones, that should be addressed prior to publication. I have summarized the main points here, with additional detail found in the specific suggestions and comments section below:

1) The experiments and the required simulations need to be presented in full, so that modeling teams can use this document for direct guidance. This means that the parent/ control simulations shared with other MIPs need to be described with the relevant land configurations so that the experiments using LUMIP-specific simulations can be clearly presented or inferred. The tables 1-3 need to include all relevant sims, with the MIP-shared ones clearly marked, and the tier clearly marked. These tables will be an important reference. Please note that a simulation is not an experiment, and in most cases multiple simulations (at least on plus a control) are required to constitute an experiment. Of course, every little detail and contingency cannot be included here, and the authors do thankfully provide an online venue for further clarifications, updates, and details.

In the Tables, we already reference the 'parent/control' simulations including names and the relevant MIP. Though LUMIP has been in consultation with these other MIPs during their experimental design,

LUMIP does not control how those simulations are setup or executed. In our opinion, the tables are clear as is and adding the names of additional experiments that are not in the LUMIP request is more likely to confuse rather than clarify. All modeling centers that participate in CMIP6 should be able to clearly reference these tables in combination with the other MIP documentation papers to execute the required simulations. We did add information on the Tier of the parent / control simulation. In all cases, LUMIP intentionally built off of Tier 1 simulations from other MIPs.

2) The potentially major issue involves the default land configuration for LUMIP and the rest of CMIP6. There are several aspects that should be addressed, but the one I am most concerned about is the use of gross (intra-annual) LULCC transitions as the default in models with this capacity. To make the most robust comparison across models, gross transitions should not be used, except as part of LUMIP to examine the consequences of including them. It is acknowledged that including gross transitions can have a large impact on the carbon cycle, CMIP5 has already shown how including gross transitions can create carbon cycle outliers, the biogeophysical impacts of including gross transitions in models are not well established, and the gross transitions are probably the most uncertain component of the land use/cover data. Furthermore, I expect that still only a minority of models will be able to use the gross transitions.

We acknowledge that the impact of gross transitions is uncertain, but we would also argue that including gross transitions in some fashion is more defensible that leaving it out completely. In any case, LUMIP / CMIP6 cannot and does not control decisions on model configurations. Those decisions are left to the modeling centers. In the case of LUMIP, we hope that the additional data layers in the LUH2 dataset will spur groups to include additional relevant processes, but that remains up to each modeling center as they balance many competing research needs and foci. That said, we have explicitly included a simulation in the set of land-only experiments (land-netTrans) that will allow LUMIP to assess the impact of gross versus net transitions in a multi-model context.

These are related notes that I don't expect to be dealt with here or in CMIP6, but should be thought about for future model comparisons: Irrigation and fertilization and other land management activities also raise red flags in this regard, but these may have smaller and more local effects than gross transitions, and so may be of less concern when comparing against models that do not have crop or management components. But gridded nitrogen application data are also very uncertain, as are nitrogen model components in general. Prognostic biogeography is another capacity that should be turned off for general model comparison (until most models have it, anyway), and turned on (in something like LUMIP) for examining the differences it generates (I understand that this would pose challenges for teams to do additional, separate model spin-ups for the two configs, but one may ask what the utility is of additional model comparisons in which the models continue to diverge in basic capacity and initial state).

Our response to this is similar to that stated above. LUMIP cannot specify the configuration that each modeling center elects to utilize in CMIP simulations. The potentially considerable differences in configuration across models will certainly complicate analysis, but there is no practical solution to this problem. We agree that specific questions about specific aspects of land use on climate will require more targeted MIP efforts. Clever use of the data can still be informative. A main intent of the realistic historical or projection experiments is not to understand model differences but to understand the potential impact of land-use on current and future climate. In this context, the structural differences across models is simply an element of uncertainty that cannot be reduced at this point. Other simulations within LUMIP will be more useful in terms of assessing models relative to each other. In particular, the idealized deforestation experiment is designed to allow direct comparison across models of the impact of deforestation. Furthermore, the land-only land use experiments are designed for a multi-model assessment/comparison of the impact on surface fluxes of various aspects of land use over the historical period.

3) The experiment to explore the effects of fertilization is not complete. This might have been a practical consideration, but it does not independently address both primary fertilization causes of differences in crop growth: area and application rate. Questions regarding nitrogen application rates loom just as large as questions regarding fertilized area, and it would be useful to include the other two complementary sims: constant area with changing rate, and constant rate with changing area. Irrigation could be subjected to a similar set of sims, but it is less clear what it would mean to impose a constant irrigation rate because it varies year to year, usually based on environmental conditions and need.

Almost every one of the simulations listed in Table 2 could be expanded into several different experiments to tease out the relative contribution of specific aspects of land use/management. The list that we have included is already very long and is likely to tax groups considerably to get them all done. Others have proposed additional simulations and at this point, our plan is not to expand this any further, but as the project moves forward over the next several years, we reserve the right to add additional optional experiments, which we will request/advertise through the LUMIP website and mailing lists.

4) What is the recommended protocol for using the new forest/non-forest area data in the non-idealiized sims and the rest of cmip6? You describe how different types of models (i.e. different initial forest area, different definitions of forest area, (non-)prognostic biogeography) should deal with forest in the idealized sim, but give no guidance on how different types of models should deal with the new forest area input. Just having the forest area input without guidance could still cause considerable divergence in land cover across models. I suggest presenting a recommended protocol for using the forest area data so as to minimize such divergence.

There will be another paper on the land use datasets themselves where guidance will be given. Preliminary guidance is also available through the LUMIP website. We now note both avenues for guidance in the text.

5) Please discuss the role of uncertainty in the LULCC data. There is a short section on uncertainty in atmospheric forcing data, and uncertainty in LULCC data is just as relevant, yet less understood. Addressing such uncertainty is beyond the scope of LUMIP, but the topic needs attention called to it because it will have to be addressed in the future.

After discussing further with the LUMIP team, we have elected to add 2 additional simulations in the land-only set of simulations to provide a preliminary sensitivity analysis of uncertainty in historical land-use. We added the following text as well as ammendments to Table 2.
"To help address the issue of sensitivity to uncertainty in historical land-use forcing, two alternative historical land-use reconstructions have also been developed. These alternatives are based on same data sources, use same algorithms, and are provided in same format as the reference LUH2 product, but span range of uncertainty in the key historical input datasets for agriculture and wood harvest. Specifically, the 'high' reconstruction, assumes high historical estimates for crop and pasture and wood harvest, and the 'low' reference assumes low estimates for each of these terms, relative to the reference. "

specific suggestions and comments:

abstract

line 1: ". . .large [?changes?] to the. . ."

Corrected.

lines 12-13: not sure what you mean by "relative to fossil fuel emissions." see comment for line 677 below.

See answer below.

line 19: unfinished sentence ". . .with respect to ???"

Corrected.

line 20: How does this relate to the previous sentence? Are you only presenting activity (2)?

We modified the text to : "In this manuscript, we describe the LUMIP activity (2), i.e., the LUMIP simulations …"

lines 18-21: I suggest expanding/explaining the acronyms here.

Unless we get guidance from GMD that this is required, we prefer the succinctness as stated in the abstract.

line 27: what is "a new subgrid land-use tile data request?" Does this mean you are also presenting activity (1)?

This is explained in detail in the body of the text. We amend the sentence slightly to increase clarity "describes a new subgrid land-use tile data request for selected variables (reporting data separately for primary and secondary land, crops, pasture, urban).

introduction
line 38: ". . .climate are relatively. . ."

Corrected.

line 68: ". . .expansion have likely. . ."

Corrected.

line 71: NEE is also a surface flux, albeit a net one - maybe use "seasonality of mass and energy surface fluxes" or something similar

Corrected.

line 80: ". . .climate has led to open. . ."

Corrected.

line 93-102: expand these acronyms on first time use

Done.

lumip activities

line 111: I suggest you separate out this third question, which takes additional work beyond what is required for question 2.

Done.

line 115: not sure what you mean by “relative to fossil fuel emissions.” see comment for line 677 below.

See answer below.

line 124: It would be useful to define a protocol for using the forest/non-forest data in the non-idealized experiments. The protocol could be similar to that outlined for the idealized deforestation experiments, which acknowledges differences between prognostic and non-prognostic biogeography models and differences in initial forest cover among models. For example, the protocol could focus on matching annual changes in forest cover, with all the prognostic biogeography models including biogeographical changes for matching in the historical period, but not including them for matching in the future period (because the IAMs do not incorporate biogeographical effects on land cover in their scenarios). It would make sense for all the models to do the lumip sims without the prognostic biogeography (and then add sims to explore the effects of biogeography), but this would require additional sims to replicate those shared by other mips. this is something to think about for future mips.

The protocol for use of the forest/non-forest data will be provided in the LUH2 paper and associated documentation on the LUMIP website. We agree that it would be good to try to isolate the impact of dynamic biogeography, but we deem this outside the scope of the current LUMIP effort, which is already very extensive.

lines 138-142: are the luh2 wood harvest data by volume/mass, or by area? or are both provided? can all the LUMIP participants deal with wood harvest mass? if both are provided, you may want to recommend (or request) that groups use the volume/mass data.

Both are provided, but this is a topic for the LUH2 paper.

line 166: suggestion: “. . .variables on [individual] land-use tiles [within grid cells]. . .,” or maybe ‘distinct’ or ‘separate,’ “multiple” is unclear

Text amended to “or selected key variables on separate land-use tiles within each grid cell (primary …”

line 176: you may want to include a citation here as well, as evidence for this may not be widely acknowledged.

Not sure what the reviewer wants here. In this section, we are only noting what WCRP Grand Challenges that LUMIP will be able to contribute to. This isn’t the place to include references to work that shows whether or not LULCC has an impact in these areas. Those references are included elsewhere. The Trenberth and Asrar reference actually just refers to the document where that Grand Challenge is introduced. It probably makes more sense to remove it, so as not to be confusing.

line 186: this example sounds more like land management (mowing vs not). Maybe a better example of land use is whether forest is harvested or not (and rather than wood harvest be a management type, forest management options would include plantation vs tree selection vs clear cut). another land use example is whether grassland or shrubland is used for grazing/pasture or not, or whether cropland is annuals, perennials, orchard, or fallow (or whether there is cropland at all).
line 188: wood harvest is more like a land use, in that it describes the purpose (wood) for which humans exploit forest (or other land cover types). as mentioned above, there are several land management strategies that can be employed to achieve the land use of harvesting wood.

These are good points. There are grey areas, but the definition can certainly be better stated:

“Land cover refers to “the attributes of the Earth’s land surface and immediate subsurface, including biota, soil, topography, surface and groundwater, and human (mainly built-up) structures”, and is represented in land models by categories like forest, grassland, cropland or urban areas. Land use is the “purpose for which humans exploit the land cover”; e.g., a grassland may be left in its natural state, mowed, or utiilzed as rangeland for livestock. Land management refers to ways in which humans treat vegetation, soil, and water, and is captured in land models by processes such as irrigation, use of fertilizers and pesticides, crop species selection, or methods of wood harvesting (selective logging versus clear cutting).”

line 193: You may want to be clear that in this manuscript LULCC refers to ALCC only. I am not sure that this is generally the case, nor that it should generally be the case. experimental design and description

Good point. We have modified sentence to make this more clear.

lines 196-198: please revise and/or split this sentence to clarify it. also, expand DECK, as i think it is a first time use of the acronym

Done.

lines 198-199: awkward: “. . .coupled model idealized deforestation experiments. . .”

Rewritten to: “Phase one features a coupled model simulation with an idealized deforestation scenario that is designed to advance process-level understanding and to quantify model sensitivity to land-cover change impacts on climate and biogeochemical stocks and fluxes.”

lines 201-202: “. . .the forced response of land-atmosphere fluxes to land cover change. . .”

Done.

lines 207-209: This information is incongruous and unclear. What does “request” mean? What do “tier 1” and “tier 2” mean? You also refer to tier 3 in table 3. What is tier 3?

We have modified the text to try to make this more clear. The Tier 3 experiment was a typo and has been removed.
“Details of the model experiments are described below. The full set of LUMIP experiments include:
- **Tier 1 (high priority): 500 years GCM/ESM; 650 years land-only**
- **Tier 2 (medium priority): 500 years GCM/ESM; up to 1500 years land-only**

Note that these totals only represent the LUMIP-sponsored simulations. LUMIP analysis requires control simulations from other MIPs, e.g., a pre-industrial control DECK simulation or a CMIP6 historical simulation. We note the required ‘parent’ simulation and responsible MIP, where applicable.”

line 210: what about section 2.1? lines 119-215 focus on the lumip experiments, and then you jump immediately, and unexpectedly, to a non-lumip discussion

We changed the text to make this clearer.
“In this section, we begin with a discussion and recommendations on the specification of land use in CMIP6 Diagnostic, Evaluation and Characterization of Klima (DECK) and historical experiments and other MIP experiments (Section 2.1). Also in this section, we outline the full set of requested LUMIP experiments (Sections 2.2 and 2.3). LUMIP includes a two phase, tiered, model experiment plan.”

lines 225-249: suggestion: separate paragraphs for general guidelines, 1850-specific guidelines, and >2100-specific guidelines also, rather than use “relevant year” and “constant land use year,” pick a single, descriptive term to refer to the year that defines the “constant land use,” such as “constant land use reference year,” or something better

We couldn’t find a clean way to separate the paragraphs, but we did take the suggestion of referring to the constant land use year as the constant land use reference year.

line 251: “. . .differences among CMIP6. . .”

Corrected.

line 255: need definition of “PI-control” - this can be done at first use, which may be line 221-220

We think that the phrase already included in the text explains the pre-industrial control simulation sufficiently. Details, as with all the parent simulations, should be obtained within the CMIP6 paper by Eyring et al. (2016).

phase 1 experiments

lines 268-270: it sounds like there is only one experiment also, table 1 includes only one simulation. it should also include the comparison/control simulation for the experiment, which appears to be the DECK picontrol.

That is correct. We had been considering some regional deforestation experiments to go along with this experiment, but decided in the end not to include them. We have corrected the text to make it clear that there is only one idealized deforestation simulation. In Table 1, we add text to make it clear that the idealized deforestation simulation should be setup identically to the piControl simulation.

line 276: is Fig X a supplemental figure? or should it be figure 2?

Apologies, we mistakenly didn’t get the numbering right for this figure. It has been corrected.

line 276: this should be included in table 1 also, it should be made clear that picontrol needs to be in equilibrium for several years prior to the branch, and how you intend to us picontrol as the control sim for the experiment. I am guessing that you intend to use an average of pre-branch picontrol years as the control for comparing the deforestation and post-deforestation years of the lumip sim (assuming that the picontrol isn’t continuing in parallel, which would also work). however, 30 years of constant forest may not be enough time for the land carbon cycle to equilibrate, so comparison with pre-deforestation may not be robust. I suggest adding another 30 years to the post-deforestation part of the sim to ensure some stability for comparison with picontrol.

We have now noted in text that the run should be branched from at least 80 years prior to the end of the piControl and that is should be branched from a point of stability. We have not added 30 years to the end of the simulation, in the interest of keeping the number of simulated years as low as possible. We acknowledge that the carbon stocks will not necessarily be in equilibrium, but full equilibrium is not required in this case where we will mainly be evaluating relative changes across models.

line 285: you may want to state “by the end of year t,” which clearly includes models that change forest area throughout the year and models that make a single area change during the year.

Done.

lines 288-296: It should be made clear that t=1850 is the initial state (i.e. t=0). Especially in equation 2, where the t limits are not shown (maybe they should be).

Corrected as suggested.

lines 291 and 296: do you mean Ftot? and in line 296, this should be less than or equal to 20 M km^2.

Yes. We have corrected.

lines 292-293: shouldn't this be equation (2)? and it is currently duplicate.

Yes. Corrected.

lines 303-306: It should be requested that modeling teams report the annual spatial land type data (for diagnostics such as figure 2), and the global area of forest removed, so as to know which models were able to remove 20 M km^2 of forest, and which ones were not able to do so.

We have amended the text to reflect this. Annual data on forest fraction is in the data request.

line 305: "the examples shown in figure 2" should probably be in parentheses, as this phrase muddles the sentence a bit

Done

line 332-335: land-hist is missing from the tier 1 list. it is still tier 1 even though this sim is also required for another cmip6 mip, which should be made more clear here and in table 2.

We have attempted to make this clearer and included mention that the land-hist simulation is required, even if LS3MIP is not completed by a particular modeling center.

line 333: what is "X?" 13? and it looks like the period can be either 165 or 315

Yes, it is 13, now included I text.

lines 334-335: the land-hist sims need to be described in detail, as it is the basis for all the other sims. for example, is the prognostic crop model part of this sim? are gross (intra-annual) lulcc transitions standard here?

We add some text to make it clear that the land-hist simulation should have the same land configuration as in the coupled CMIP6 historical simulation. We also note that additional land-hist configurations are possible if a group has more advanced land model and that groups can utilize that configuration additionally.

lines 342-346: This is redundant, and as such, confusing. It sounds like something additional, but it isn't. It can be removed.

We don't think that this text is redundant. This text covers the situation where a modeling group may wish to utilize their more advanced land model version, in addition to their coupled model version, for the full set of factorial experiments.

line 349: what do you mean by the "TRENDY" simulations? there is only one climate related sim listed, and it is not indicated as a TRENDY simulation. Besides, these are LUMIP simulations, and it seems unnecessary to complicate things by calling one simulation a TRENDY simulation.

Agreed. We have removed reference to TRENDY here.

lines 350-351: not sure what “clean comparison” means. yes, the climate forcings will be the same, but there will still be land cover, land use, and land management differences among the models. And probably resolution differences as well. Different initial years and land states and how they came about will also introduce differences among the model outputs.

We take your point, they are relatively clean, but there will be the usual challenges. We remove the sentence.

lines 372-377: this paragraph is evidence that the default for all cmip6 models should be either gross or net transitions. given that only some models can represent gross transitions, the high uncertainty of the gross transition data, and the accompanying uncertainty due to land cover translation (particularly non-forest), the default across all cmip6 should be net annual transitions. otherwise some models will have grossly different carbon estimates in all simulations and experiments. this means that the LUMIP simulation here should be land-grossTrans, where the gross transitions are enabled to explore their effects on surface mass and energy exchange.

As noted above, we cannot dictate within CMIP6 what the default configuration for each model is. We include the experiments to look at gross versus net in the land-only simulations to help us identify what impact the assumptions about whether or not to include gross (and how it is included) has. You could probably identify problems with all sorts of assumptions that go into the treatment of land use in these models.

lines 378-380: need to reference section 2.3.1 to tell reader that the appropriate GCM simulations will be available.
Done.

lines 381-389: Uncertainty in the driving land use/cover data poses the same challenge for comparison to observations. This needs to be acknowledged here as well, and I would expect it to be discussed more thoroughly in the LUH2 paper. Related to the uncertainty in the driving land use/cover data is the remaining uncertainty due to the translation of land use to land cover, which includes differences between land cover classes and plant functional types, the changes in non-forest land cover (which are not harmonized), and differences between the definition of forest in the LUH2 data and in the models, and how different models will implement the forest cover changes (e.g. prognostic vs. non-prognostic biogeography models). I don’t think it is possible to explore the model sensitivity to land use/cover uncertainty in cmip6, but this exploration should be noted as a target for future cmips and land mips, with the potential for using additional land use/cover data sets to drive the models.

This topic will be covered in more detail in the LUH2 paper, but the point is well taken. We have elected to include a couple of additional experiments in the set of land-only simulations with alternative plausible land-use reconstructions. These simulations will allow for sensitivity analysis of the impact of different land-use histories.

phase 2 experiments

line 395: “Historical” seems like an extra word here

It’s actually not an extra word. Somewhat awkwardly, the CMIP6 Historical simulation is not part of the DECK or a satellite MIP so it is in it’s own category. We reworded slightly to try to make sentence clearer.

line 399: describe all the relevant aspects of the cmip6 historical concentration-driven simulation. for example, what land use/management processes are included?

As above, we can't specify this. Each modeling group will make their own decisions about what to include in their CMIP6 historical simulations. All we can do is ask for information about what aspects of land use were included.

line 416: you may want to move your parenthetical note about ssp scenarios from line 420 to here. You should also include the relevant details of the parent sims here. e.g., what land use and land management activities are active.

Done. Same as above with respect to what land use and land management activities are active. It is up to each group to decide.

line 422: land management isn't isolated in these experiments. the changes will be a combination of differences in land use, cover, and management (same issue in figure 3 caption). there may be individual pixels that can be extracted that have only land management/use/cover differences, but there will also be dependencies on the surrounding land what the total effects are for a given pixel. At the subgrid level this may work out for the crop data, but only if there are comparable crop areas between sims within the given pixels and only the management options are different (e.g. irrigation and fertilizer).

We reword to downplay how much we can do with respect to providing input on land policy, but we still keep this sentiment since we think that, although the results will not be directly relevant to policy (i.e., not policy prescriptive), with careful analysis one should be able at least infer the impacts of different land use and land management decisions on future climate.

line 434: again, land management isn't isolated in these sims. and there will effects of surrounding land on a given pixel.

See above.

land use metrics and analysis plans

line 491: paired simulation analyses means that you need to ensure that your main control sims (which are shared with other mips) are well described in this paper as well the lumip specific ones, so that your lumip experiments are clear.

As we have noted before, we feel that the descriptions for the LUMIP experiments are as clear as we can make them and that we should not describe the experiments from the other MIPs in detail since it is those MIPs that have the responsibility to fully define them. By pointing the user to the relevant simulation in the other MIPs, we can ensure that groups complete the simulation as requested by that MIP. If we reproduce the description in the LUMIP paper, there is a significant probability that the descriptions will be out of sync and/or incorrect.

lines 527-531: redundant sentences

Fixed. Thanks.

line 533: rfmip - another acronym needing expanding

Done.

lines 535-540: i suggest briefly describing the rfmip land experiment and how it complements lumip to make this paragraph more relevant.

Looking at the simulations in RFMIP, it is actually not easy to simply explain the experiment that isolates land-use ERF because it actually involves three experiments. Providing enough detail for a reader to be able to understand what was done would make the paragraph too cumbersome, in our opinion. The main point is the result and readers can refer to either the RFMIP paper or the Andrews et al. paper for details.

lines 543-558: this is a good idea, and differences in land coupling strength among models may (or may not) also help identify where land use/cover/management may be different among models.

We think you mean where land use /cover/management impacts may be different among models. We make that point in the text.

lines 592-594: This is a good idea, but I think that the forest and non-forest areas need to be separated out to replace the primary/secondary land category, to the extent possible (i expect that not all requested variables are kept track of at the forest/nonforest level, but some of them, such as carbon, are kept track of at the pft level in some models). for variables and models that do not distinguish between forest and nonforest, the primary/secondary value can be placed in one category with a flag in the other signifying that land cover is not segregated. This may not be practically feasible due to how the models store and write outputs, however, so it is something to consider for future comparisons, and maybe with more land cover types distinguished from each other.

We acknowledge that there are many ways to try to condense the vast amount of data that land models can potentially produce. After many discussions, we elected to go with the four listed land use types. We believe that this set of land use types will produce the most information for the smallest amount of additional data. Each model is likely going to need to aggregate their subgrid output in different ways to conform with the request. We accept that the request for archival of subgrid land use information is to a certain degree experimental and we anticipate that there will be problems encountered along the way. One of our goals, though, is to push the community to at least start thinking about archiving and utilizing subgrid data. We believe that our request will do that and that the experience gained through the process will provide the basis for modifications for future MIPs whether they be CMIP or other.

lines 601-604: figures 6 and 7 don't seem to help much here, as they are not complete and clear about the variables (e.g., only biogeochemistry is shown, and fig 7 shows processes rather than variables). A table of all the requested variables, with the subgrid ones noted, would be more useful. please provide a link or a supplemental table of the full list of variables requested.

We removed Figure 6 and have redrawn Figure 7. In addition, we have added a list of variables, with the caveat that the list is subject to change. "A list of requested land-use tile variables is shown in Table 5. However, this list is subject to change. Modelers should refer to the CMIP6 output request documents for the final variable list. "

lines 651-654: please reference figure 9 if you want to include it.

Done.

line 674: for the future runs, land management isn't isolated (or will be extremely difficult to isolate, even at the subgrid level). you can get information about this from the historical land-only experiments, however.

We agree, and have reworded to note that these experiments will be useful to provide preliminary assessment of how land use and land management could be utilized to mitigate climate.

line 677: not sure what you mean by "relative to fossil fuel emissions." It seems that the experiments are designed to quantify the effects of lulcc, in a more absolute sense, which can then be compared to the total emissions effects. I don't see quantification of fossil fuel effects only, nor outputs that would be lulcc effects relative to fossil fuel effects.

The impact of LULCC change emissions relative to fossil fuel emissions should be able to be inferred through the no LULCC experiments, but we take your point that we do not have the experiments to explicitly assess this. We change to "effects on climate of LULCC relative to all forcings."

Tables and Figures

Table 1 please include other simulation required for the experiment it should be more clear that this is a tier 1 experiment

We refer to the piControl experiment in the comments.

Table 2 it should be more clear which tier the experiments are in, and this should be noted in the same column for all. I suggest stating the tier at the beginning of each description or notes column, for each experiment. Or adding a narrow "tier" column on the right, with the appropriate number indicated. land-hist needs to be clearly marked as a sim that is shared by another mip. land-crop-nomanage: is all crop area constrained to 1850? so this is like a constant crop sim, and the pasture area and harvest can change over time? can irrigation amounts change? what about fertilization area?

We prefer not to add a column. Priority is listed in Table caption. Added text indicating that land-hist is shared. Crop area is transient (now noted). This simulation in combination with lnd-crop-noIrrig and lnd-crop-noFert helps isolate the impact of crop management through irrigation and fertilization. Irrigation amounts are not specified by LUH2, only irrigated-equipped area.

what is a "prognostic crop model" and how does it differ from what is used in the control sim? The description needs to be more complete as to what is different from the land-hist sim land-crop-nofert: i suggest two more sims to ask questions about the effects of changing area vs changing amounts: one with constant area and changing rate, and one with constant rate and changing area. land-netTrans: unclear what it means to maintain gross transitions in excess of net transitions also, the degree to which spatially gross transitions are included at coarser resolution depends on the upscaling process; the finer grid cells can be summed to get a net change for a coarser grid cell.

We agree that the term prognostic crop model is confusing and have removed the term prognostic. We only mean to distinguish between the treatment of croplands as unmanaged grasslands versus with crops with some form of management, especially including explicit planting and harvesting. The suggestion for additional simulations that would more effectively isolate specific aspects of fertilization are good ones, but we have elected not to include them because the list of experiments is already long. Our hope/intention is that once these experiments are underway, individual modeling groups or several groups together can elect to conduct additional factorial simulations to probe even further where appropriate for their model. At some stage, insightful additional simulations could potentially be added to the overall protocol through the forum/email list.

Regarding the land-netTrans, we have reconsidered the land-netTrans experiment and decided that it would be clearer if we simply specify this as a no shifting cultivation simulation. Both the language and the concept is now clearer. We have added a figure that explains what we mean by shifting cultivation.

Table 3 the tier of each simulation needs to be clearly marked. i suggest adding rows for the control cmip6 sim, and the tier 2 and 3 ensemble members. tier 3 needs to be explained in the text. see comments above.

We now more clearly demarcate the Tiers for each experiment.

Table 4 This does not seem necessary, as this information, plus more, is directly available in the text.

We prefer to retain Table 4, even though it is relatively simple, for readers who want to quickly scan the document to see how we have defined the land use tiles.

Figure 3 Why note only 1 of the 3 additional lumip sims in the caption? note all or none.
maybe state that the brown text are the additional sims.

Text has been removed. We think it is clear that the brown text represents the LUMIP sims so have not added anything.

Figure 4 I would classify wood harvest as land use, with various types of silviculture/harvest (e.g. tree selection, clear cut, plantation, coppice) as land management.
see the definitions you invoke in section 1.3.

Corrected.

Figure 5 This figure and its caption is not consistent with the section on net lulcc emissions.

We have rewritten the caption and the net LULCC emission section to make it clearer and remove inconsistencies.

LULCC emissions are also "seen" by vegetation in prescribed transient CO2 sims also because the historical atmosphere data include all emissions (LULCC occurred historically) and the IAM projected CO2 emissions include their respective estimates of LULCC emissions. Furthermore, figure 5c also has LASC, even with constant CO2, because different land covers have different potential rates of carbon uptake.

We have revised the text in both the main paper and the figure caption to improve clarity of the discussion here: "The loss of additional sink capacity (LASC) is a factor when environmental conditions change transiently, which is the case when historical CO_2 concentrations, which implicitly include increases in CO_2 due to fossil-fuel burning (FFB) and LULCC, are prescribed from observations. Prognostic LULCC emissions are directly "seen" by the terrestrial vegetation (natural and anthropogenic) only in the ESM setup, where CO_2 is interactive. In this case, a fraction of the LULCC emissions is taken up again by the vegetation ("land-use carbon feedback")."

Agreed that technically the amount of CO2 that could be taken up can change even in a constant CO2 run, but the concept of a sink typically refers to a situation where CO2 is evolving. In any case, we believe that the main point of this section is to note that care needs to be taken when assessing LULCC carbon fluxes across different model configurations. Discussion within the research community is ongoing about this topic and LUMIP will certainly be involved in those discussions.

Figure 9 not referenced by text

Fixed.

Interactive comment on "The Land Use Model Intercomparison Project (LUMIP): Rationale and experimental design" by David M. Lawrence et al.
R. J. Stouffer

Ronald.Stouffer@noaa.gov
Received and published: 21 May 2016

1. Page 2, Abstract, 1st line – Missing word. I think "changes" should go just after "large" and before "to the Earth surface"

Corrected.

2. Page 2, lines 29-30 – Should mention need for documentation of what the groups did to run the experiment. These details are at least as important to trying to follow the experimental design.

Added request for documentation to the abstract.

3.page 3, line 59 – 40% of radiative forcing – What is time period? When to when: : :

Modified text to say "…accounts for ~45% of the total historic (1850 to 2010) changes in radiative forcing (Ward et al. 2014)."

4. Page 6, line 142 – "industrial roundwood" – What is this? Please define.

We amended the sentence to: "… fuelwood and industrial roundwood (i.e., timber that is cut for uses other than for fuel)."

5. Page 8, section 2 – I think there should be multiple mentions of the need for documentation of what was done and how by the modeling groups. Each group's land model is quite different from the others. The details will be very important if we are going to be able to figure out the results after the experiments are completed.

Agreed. We have attempted to make this clearer and will be communicating with all the groups explicitly and frequently to make this request. Google group is already setup for communication.

6. Page 10 – Several references to Figure X – line 276, 282, 299. Please insert correct figure number. 6B. Page 11, lines 314, 333
Corrected.

7. Page 13, top – This discussion is confusing to me. Cleanly discuss the various types of errors: model, forcing, observations.

We have rewritten the paragraph to improve clarity.

The Land Use Model Intercomparison Project (LUMIP) contribution to CMIP6: Rationale and experimental design

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Abstract

Human land-use activities have resulted in large changes to the Earth surface, with resulting implications for climate. In the future, land-use activities are likely to expand and intensify further to meet growing demands for food, fiber, and energy. The Land Use Model Intercomparison Project (LUMIP) aims to further advance understanding of the impacts of land-use and land-cover change (LULCC) on climate, specifically addressing the questions: (1) What are the effects of LULCC on climate and biogeochemical cycling (past-future)? (2) What are the impacts of land management on surface fluxes of carbon, water, and energy and are there regional land-management strategies with promise to help mitigate against climate change? In addressing these questions, LUMIP will also address a range of more detailed science questions to get at process-level attribution, uncertainty, data requirements, and other related issues in more depth and sophistication than possible in a multi-model context to date. There will be particular focus on the separation and quantification of the effects on climate from LULCC relative to all forcings, separation of biogeochemical from biogeophysical effects of land-use, the unique impacts of land-cover change versus land management change, modulation of land-use impact on climate by land-atmosphere coupling strength, and the extent that impacts of enhanced CO_2 concentrations on plant photosynthesis are modulated by past and future land use.

LUMIP involves three major sets of science activities: (1) development of an updated and expanded historical and future land-use dataset, (2) an experimental protocol for specific LUMIP experiments for CMIP6, and (3) definition of metrics and diagnostic protocols that quantify model performance, and related sensitivities, with respect to LULCC. In this manuscript, we describe the LUMIP activity (2), i.e., the LUMIP simulations that will formally be part of CMIP6. These experiments are explicitly designed to be complementary to simulations requested in the CMIP6 DECK and historical simulations and other CMIP6 MIPs including ScenarioMIP, C4MIP, LS3MIP, and DAMIP. LUMIP includes a two-phase experimental design. Phase one features idealized coupled and land-only model simulations designed to advance process-level understanding of LULCC impacts on climate, as well as to quantify model sensitivity to potential land-cover and land-use change. Phase two experiments focus on quantification of the historic impact of land use and the potential for future land management decisions to aid in mitigation of climate change. This paper documents these simulations in detail, explains their rationale, outlines plans for analysis, and describes a new subgrid land-use tile data request for selected variables (reporting model output data separately for primary and secondary land, crops, pasture, and urban land-use types). It is essential that modeling groups participating in LUMIP adhere to the experimental design as closely as possible and clearly report how the model experiments were executed.

Keywords: Land-use change, climate and Earth system modeling, CMIP6

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1. Introduction

Historic land-cover and land-use change has dramatically altered the character of the Earth's surface, directly impacting climate and perturbing natural biogeochemical cycles. Land-use activities are expected to expand and/or intensify in the future to meet increasing human demands for food, fiber, and energy. From a broad perspective, the biogeophysical impacts of land-use and land-cover change (LULCC) on climate are relatively well-understood with observational and modeling studies tending to agree that deforestation has and will lead to cooling in high latitudes and warming in the tropics with more uncertain changes in the mid-latitudes (e.g., Bonan 2008; Davin and de Noblet-Ducoudré 2010; Lee et al. 2011; Li et al. 2016; Pielke et al. 2011; Swann et al. 2012). The impact of land-cover change on, for example global mean surface air temperature, has been and is projected to continue to be relatively small (Brovkin et al. 2013; Lawrence et al. 2012), but, regionally, climate change due to deforestation can be as large or larger than that resulting from increases in greenhouse gas emissions (de Noblet-Ducoudré et al. 2012). Nonetheless, substantial disagreement exists across models in terms of their simulated regional climate response to LULCC (Kumar et al. 2013; Pitman et al. 2009), and some observed effects do not appear to be captured by models (Lejeune et al. 2016), contributing to a lack of confidence in model projections of regional climate change. Variation among future scenarios of land-use change, which could depart significantly from historical trends due to large-scale adoption of either afforestation or biofuel policies, introduces another source of uncertainty that has not been examined in a systematic fashion (Jones et al. 2013b).

The biogeochemical impact of LULCC relates to emissions of greenhouse gases (GHGs) such as CO_2, CH_4, and N_2O in response to LULCC (e.g., Canadell et al. 2007; Houghton 2003; Pongratz et al. 2009; Shevliakova et al. 2009). Models estimate that the net LULCC carbon flux - the CO_2 exchange between vegetation and atmosphere due to LULCC such as emissions due to forest clearing and carbon uptake in regrowth of harvested forest - has accounted for ~25% of the historic increase in atmospheric carbon dioxide concentration (Ciais et al. 2014), but the LULCC flux remains one of the most uncertain terms in the global carbon budget (Houghton et al. 2012). As on the biogeophysical side, models show a wide range of estimates for historic and future emissions due to LULCC (Arora and Boer 2010; Boysen et al. 2014; Brovkin et al. 2013). When emissions of all GHG species due to LULCC are considered, the forcing due to LULCC accounts for ~45% of the total historic (1850 to 2010) changes in radiative forcing (Ward et al. 2014).

At the same time, there is growing awareness that the details of land use matter and that land management or land-use intensification can have as much of an impact on climate as land-cover change itself. Luyssaert et al. (2014) emphasize that while humans have instigated land-cover change over about 18-29% of the ice-free land surface, a much larger fraction of the planet (42-58%) has not experienced land-cover change per se, but is nonetheless managed, sometimes intensively, to satisfy human demands for food and fiber. Furthermore, the temperature impacts, assessed through remote sensing and paired tower sites, are roughly equivalent for land-management change and land-cover change. Other examples of research indicating the importance of specific

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aspects of land management are numerous. For example, irrigation, which has increased substantially over the 20th century (Jensen et al. 1990), can directly impact local and regional climate (Boucher et al. 2004; Sacks et al. 2009; Wei et al. 2013). In some regions, cooling trends associated with irrigation area expansion have likely offset warming due to greenhouse gas increases (Lobell et al. 2008a). Explicit representation of the crop life cycle also appears to be important; Levis et al. (2012) showed that including an interactive crop model into a global climate model (GCM) can improve the seasonality of surface turbulent fluxes and net ecosystem exchange and thereby directly impact weather and climate and the carbon cycle. In another study, Pugh et al. (2015) found that accounting for harvest, grazing, and tillage resulted in cumulative post-1850 land-use related carbon loss that was 70% greater than in simulations ignoring these processes. There is a hypothesis that increasing crop production over the 20th century could account for ~25% of the observed increase in the amplitude of the CO_2 annual cycle (Gray et al. 2014; Zeng et al. 2014). Furthermore, agricultural practices can mitigate heat extremes through the cooling effects of irrigation (Lobell et al. 2008b), due to enhanced evapotranspiration associated with cropland intensification (Mueller et al. 2015), or by increasing surface albedo by transitioning to no-till farming (Davin et al. 2014). Forest management and the harvesting of trees for wood products or fuel is also important and has substantial carbon cycle consequences (Hurtt et al. 2011) with the carbon flux due to wood harvest amounting to an equivalent of up to 15% of the forest net primary production in strongly managed regions such as Europe (Luyssaert et al. 2010). Awareness that land management can impact climate has led to open questions about whether or not there is potential for implementation of specific land management as a tool for local or global climate mitigation (e.g., Canadell and Raupach 2008; Marland et al. 2003).

Due to the predicted increases in global population and affluence as well as the increasing importance of bioenergy, demand for food and fiber is likely to surge during the coming decades. Expansion of active management into relatively untouched regions could satisfy a portion of the growing demand for food and fiber but intensification is likely to play a stronger role in strategies for global sustainability (Foley et al. 2011; Reid et al. 2010). Therefore, we can anticipate a growing contribution from land-management change to the overall impacts of LULCC on the climate system. The requirement of negative emissions to achieve low radiative forcing targets highlights the need for more comprehensive understanding of the impacts (e.g., on land use, water, nutrients, albedo) and sustainability of carbon removal strategies such as bioenergy carbon capture and storage (BECCS, Smith et al. 2016).

Clearly, the impacts of land cover and land use on climate are myriad and diverse and, while uncertain, are sufficiently large and complex to warrant an expanded activity focused on land-use within CMIP6. The Land Use Model Intercomparison Project (LUMIP, https://cmip.ucar.edu/lumip) addresses this topic in the context of CMIP6 (Eyring et al. 2015). The goal of LUMIP is to enable, coordinate, and ultimately address the most important science questions related to the effects of land-use on climate. LUMIP scientific priorities and model experiments have been developed in consultation with several existing model intercomparison activities and research programs that focus on the role of land use in climate including the Land-Use and Climate, IDentification of robust impacts project

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(LUCID, de Noblet-Ducoudré et al. 2012; Pitman et al. 2009), the Land-use change: assessing the net climate forcing, and options for climate change mitigation and adaptation project (LUC4C, http://luc4c.eu/), the trends in net land carbon exchange project (TRENDY, http://dgvm.ceh.ac.uk/node/9), and the Global Soil Wetness Project (GSWP3). In addition, the LUMIP experimental design is complementary with and in some cases requires simulations from several other CMIP6 MIPs including ScenarioMIP (O'Neill 2016), C4MIP (Jones et al. 2016), LS3MIP (Van den Hurk et al. 2016), DAMIP (Gillett 2016), and RFMIP (Pincus 2016). In all cases, the LUMIP experiments are complementary and not duplicative with experiments requested in these other MIPs. We will reference these cross-MIP interactions throughout this manuscript, where applicable.

1.1 LUMIP Activities

The main science questions that will be addressed by LUMIP, in the context of CMIP6 are:

- What are the global and regional effects of land-use and land-cover change on climate and biogeochemical cycling (past-future)?
- What are the impacts of land management on surface fluxes of carbon, water, and energy
- Are there regional land-use or land-management strategies with promise to help mitigate against climate change?

In addressing these questions, LUMIP will also address a range of more detailed science questions to get at process level attribution, uncertainty, data requirements, and other related issues in more depth and sophistication than possible in a multi-model context to date. There will be particular focus on (1) the separation and quantification of the effects on climate from LULCC relative to all forcings, (2) separation of biogeochemical from biogeophysical effects of land-use, (3) the unique impacts of land-cover change versus land-use change, (4) modulation of land-use impact on climate by land-atmosphere coupling strength, and (5) the extent that the direct effects of higher CO_2 concentrations on increases in global plant productivity are modulated by past and future land use.

Three major sets of science activities are planned within LUMIP. First, a new set of global gridded land-use forcing datasets has been developed to link historical land-use data and future projections in a standard format required by climate models (Figure 1). This new generation of "land-use harmonization" (LUH2) builds upon past work from CMIP5 (Hurtt et al. 2011), and includes updated inputs, higher spatial resolution, more detailed land-use transitions, and the addition of important agricultural management layers. The new dataset includes annual land-use states, transitions, and management layers for the years 850 to 2100 at 0.25° spatial resolution. Note that land-cover data and forest/non-forest data, as well as land-use transitions, will be provided in the new dataset in order to help minimize misinterpretation of the land-use dataset that occurred in CMIP5 where, for example, the strong afforestation in RCP4.5 was not captured in Community Earth System Model (CESM) simulations because of differing assumptions embedded within the CESM land use translator (a software package that translates the LUH

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data into CESM land-cover datasets) and the LUH dataset (Di Vittorio et al. 2014). Several harmonized future land-use trajectories will be processed for the period 2016-2100 in support of the ScenarioMIP Shared Socioeconomic Pathway scenarios (see Section 2.3.2). Cropland is disaggregated into five crop functional types based on input data from FAO and Monfreda et al. (2008). Crop rotations are also included. Grazing lands are disaggregated into managed pastures and rangelands based on input data from the updated HYDE3.2 dataset (updated from HYDE3.1, Klein Goldewijk et al. 2011), which also provides inputs for gridded cropland, urban, and irrigated area. The modeling process includes new underlying maps of potential biomass density and biomass recovery rate, which are used to disaggregate both primary and secondary natural vegetation into forested and non-forested land. It also includes a new representation of shifting cultivation rates and extent, constrains forest loss between the years 2000-2012 with Landsat-based forest loss data from Hansen et al. (2013), and uses a new historical wood harvest reconstruction based on updated FAO data, new HYDE population data, and other sources. The LUH2 dataset will include several new agricultural management layers such as gridded nitrogen fertilizer usage based on Zhang et al. (2015), gridded irrigated areas (based on HYDE3.2), and gridded areas flooded for rice (also based on HYDE3.2), as well as the disaggregation of wood harvest into fuelwood and industrial roundwood (i.e., timber that is cut for uses other than for fuel). Future scenarios (years 2016-2100) will also include biofuel management layers. To help address the issue of sensitivity to uncertainty in historical land-use forcing, two alternative historical land-use reconstructions have also been developed. These alternatives are based on same data sources, use same algorithms, and are provided in same format as the reference LUH2 product, but span range of uncertainty in the key historical input datasets for agriculture and wood harvest. Specifically, the 'high' reconstruction, assumes high historical estimates for crop and pasture and wood harvest, and the 'low' reference assumes low estimates for each of these terms, relative to the reference.

The LUH2 dataset is available through the LUMIP website (https://cmip.ucar.edu/lumip) and will be described in a separate publication in this CMIP6 Special Issue. Guidance on use of the data will be provided in the LUH2 dataset paper and through the LUMIP website.

Second, an efficient model experiment design, including both idealized and scenario-based cases, is defined that will enable isolation and quantification of land-use effects on climate and the carbon cycle (see Section 2). The LUMIP experimental protocol enables integrated analysis of coupled and land-only (forced with observed meteorology) models which will support understanding and assessment of the forced response and climate feedbacks associated with land use and the relationship of these responses to land and atmosphere model biases.

Third, a set of metrics and diagnostic protocols will be developed to quantify model performance, and related sensitivities, with respect to land use (see Section 3). De Noblet-Ducoudré et al (2012) identified the lack of consistent evaluation of a land model's ability to represent a response to a perturbation such as land-use change as a key contributor to the large spread in simulated land-cover change responses seen in LUCID. As part of this activity, benchmarking data products will be identified to help constrain models. Where applicable, these metrics

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will be incorporated into land model metrics packages such as the International Land Model Benchmarking (ILAMB, http://www.ilamb.org/) system.

New output data standardization will also enrich and expand analysis of model experiment results. Particular emphasis within LUMIP is on archival of subgrid land information in CMIP6 experiments (including LUMIP experiments and other relevant experiments from ScenarioMIP, C4MIP, and the CMIP historical simulation). In most land models, physical, ecological, and biogeochemical land state and surface flux variables are calculated separately for several different land surface type or land management 'tiles' (e.g., natural and secondary vegetation, crops, pasture, urban, lake, glacier). Frequently, including in the CMIP5 archive, tile-specific quantities are averaged and only grid-cell mean values are reported. Consequently, a large amount of valuable information is lost with respect to how each land-use type responds to and interacts with climate change and direct anthropogenic modifications of the land surface. LUMIP has developed a protocol and associated data request for CMIP6 for selected key variables on separate land-use tiles within each grid cell (primary and secondary land, crops, pastureland, urban; see Section 4).

1.2 Relevance of LUMIP to CMIP6 questions and WCRP Grand Challenges

Land-use change is an essential forcing of the Earth System, and as such LUMIP is directly relevant and necessary for CMIP6 Question 1 (Eyring et al. 2015): "How does the Earth System respond to forcing?". LUMIP will also play a strong role in addressing the WCRP Grand Challenges (GC), particularly with respect to GC7 "determining how biogeochemical cycles and feedbacks control greenhouse gas concentrations and climate change," GC3 "understanding the factors that control water availability over land", and GC4 "assessing climate extremes, what controls them, how they have changed in the past and how they might change in the future." Due to the broad range of effects of land-use change and the major activities proposed, LUMIP is also of cross-cutting relevance to CMIP6 science questions 2 "What are the origins and consequences of systematic model biases?" and 3 "How can we assess future climate change given climate variability, climate predictability, and uncertainties in scenarios?"

1.3 Definitions of land cover, land use, and land management

Within LUMIP, we rely on prior definitions of land cover, land use, and land management (Lambin et al. 2006). Land cover refers to "the attributes of the Earth's land surface and immediate subsurface, including biota, soil, topography, surface and groundwater, and human (mainly built-up) structures", and is represented in land models by categories like forest, grassland, cropland or urban areas. Land use is the "purpose for which humans exploit the land cover"; e.g., a grassland may be left in its natural state, mowed, or utilized as rangeland for livestock. Land management refers to ways in which humans treat vegetation, soil, and water, and is captured in land models by processes such as irrigation, use of fertilizers and pesticides, crop species selection, or methods of wood harvesting (selective logging versus clear cutting). Thus, within the same land-cover category several land uses can occur, and

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within the same land-use category, management practices can differ. Land-cover change usually goes in hand with land-use change, but the opposite is not true. Land-cover change can also be driven by natural processes such as a change of the biogeographic vegetation distribution due to climate shifts or natural disturbance (Davies-Barnard et al. 2015; Schneck et al. 2013). For the purposes of LUMIP, the term "LULCC" includes anthropogenically-driven land-cover change only.

2. Experimental design and description

In this section, we begin with a discussion and recommendations on the specification of land use in CMIP6 Diagnostic, Evaluation and Characterization of Klima (DECK) and historical experiments and other MIP experiments (Section 2.1). Also in this section, we outline the full set of requested LUMIP experiments (Sections 2.2 and 2.3). LUMIP includes a two phase, tiered, model experiment plan. Phase one features a coupled model simulation with an idealized deforestation scenario that is designed to advance process-level understanding and to quantify model sensitivity to land-cover change impacts on climate and biogeochemical stocks and fluxes. Phase one also includes a factorial set of land-only model simulations that allow assessment of the forced-response of land-atmosphere fluxes to land-cover change as well as examination of the impacts of various land use and land-management practices. Phase two experiments will focus on the quantification of the historic impact of land use and the potential for future land management decisions to aid in the mitigation of climate change. A forum for discussion of the experiments and for distribution of minor updates or clarifications to the experimental design will be hosted at the LUMIP website (https://cmip.ucar.edu/lumip).

Details of the model experiments are described below. The full set of LUMIP experiments include:

- Tier 1 (high priority): 500 years GCM/ESM; ~650 years land-only
- Tier 2 (medium priority): 500 years GCM/ESM; up to 1500 to 3000 years land-only

Note that these totals only represent the LUMIP-sponsored simulations. LUMIP analysis requires control simulations from other MIPs, e.g., a pre-industrial control DECK simulation or a CMIP6 historical simulation. We note the required 'parent' simulation and responsible MIP, where applicable.

In Sections 2.2 and 2.3, we describe each experiment in detail. Also included is the scientific rationale for the particular experiment or set of experiments. The heading for each experiment includes several relevant pieces of information according to the following format - **Short description** (*CMIP6 experiment ID*, model configuration, Tier X, # years) - where the model configuration is either land-only (offline land simulations forced with observed meteorology), GCM (fully coupled simulation, concentration-driven), or ESM (fully coupled simulation, emissions-driven).

2.1 Land-use treatment in the CMIP6 DECK, historical experiments, and other MIP experiments

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There exists a large diversity in representation of LULCC among different land models, and therefore it is typically non-trivial to define what is meant by the terms land use and in particular the term "constant land use." Several CMIP6 simulations both within LUMIP and in other CMIP6 MIPs require land use to be held constant in time including (1) DECK experiments including CO_2 concentration and CO_2 emission driven pre-industrial control simulations (*piControl*), abrupt quadrupling of CO_2 (*abrupt-4×CO2*) and 1%yr^{-1} CO_2 increase (*1pctCO2*) simulations, (2) LUMIP no land-use change simulations (Section 2.3.1), (3) C4MIP idealized simulations including biogeochemically-coupled 1%yr^{-1} CO_2 increase (*1pctCO2-bgc*) and other C4MIP Tier 2 idealized simulations, and (4) ScenarioMIP extension simulations for the period 2100-2300 (*ssp126-ext, ssp585-ext*) for which land-use data will not be provided.

LUMIP provides the following recommendations to clarify treatment of constant land use. Land cover and land use should be fixed according to the LUH2 specifications for the constant land use reference year (e.g., year 1850 for the DECK pre-industrial control simulation, year 2100 for ScenarioMIP extension simulations). The fraction of cropland and pastureland, as well as the crop type distribution should be held constant. Any land management (e.g., irrigation, fertilization) that exists for the constant land use year should be maintained at the same level. Wood harvesting for timber and shifting cultivation, specified by the LUH2 land-use reconstructions (i.e., through transition matrices or the mass of harvested wood), should be implemented if a model's land-use component permits these processes to be maintained through time at a specified level. If the fire model utilizes population density or other anthropogenic forcings to determine fire ignition and/or suppression rates, then this forcing should also be held constant. We recognize that the diversity of model approaches means that the definition and requirements for constant land management may differ across models. Groups will need to make their own decisions with respect to the treatment of land management in constant land-use scenarios, for example with respect to specification of harvesting on croplands, grazing on pastureland, application of fertilizers, level of irrigation, and wood harvest. Wood harvest, in particular, may require model-specific treatment since turning off wood harvest in the ScenarioMIP 2100-2300 extension runs is likely to result in unrealistic carbon stock trends, while maintaining wood harvest at year 2100 levels for an additional 200 years could unrealistically decimate the forests where the LUH2 datasets indicate wood harvest is happening in 2100. We stress that the individual modeling group decisions should be made within the context of achieving an equilibrated biogeophysical and biogeochemical (e.g., carbon, nitrogen) land state for the pre-industrial 1850 control configurations and to minimize any discontinuities in the shift between a constant land-use simulation and a subsequent transient land-use simulation (see next paragraph for further clarification and discussion). Furthermore, the treatment of constant land use and land management should be clearly documented for each model and experiment. Because some land models are driven by annual maps of land use and others require transition rates between different land-use categories, LUMIP will provide two different 1850 constant land-use datasets – fraction of pastures and crops in 1850 and a one-time set of gross transitions from potential vegetation to the 1850 land-use state.

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LUMIP acknowledges and endorses the need for flexible strategies to initialize CMIP6 historical simulations and DECK AMIP simulations. This flexibility is necessitated by (1) considerable structural differences among CMIP6-participating land models, especially with respect to land use (e.g., models with and without wood harvest) and vegetation dynamics (e.g., prescribed versus prognostic vegetation type and age distributions), (2) different spin-up strategies for land-only models versus coupled GCMs and ESMs (e.g., spin-up for potential vegetation versus constant 1850 land use), and (3) uncertainties in PI-Control experiments due to omission of documented secular multi-century trend in vegetation and soil carbon storage and land-use carbon emissions prior to 1850 (Houghton et al 2010). There are several strategies that have been used in the past and discussed by the modeling groups at present time, including:

- a "seamless" transition from the PI-control to historical as suggested by C4MIP (Jones et al. 2016);
- a "bridge" experiment from an equilibrated ESM spin-up with potential vegetation and subsequent application of land-use scenario applied at a year prior to 1850 (Sentman et al. 2011; Shevliakova et al. 2013).

Consequently, LUMIP does not provide any recommendation on land initialization but requests that all modeling groups document their initialization procedure for their CMIP6 historical simulations and report any differences in biogeophysical and biogeochemical land states between the 1850 pre-industrial control and the beginning of the CMIP6 historical simulations in 1851. As noted above, a forum for discussion along with additional recommendations and clarifications with respect to initialization, the configuration of 'constant land use', use of the LUH2 data, and other topics will be maintained through the LUMIP website (https://cmip.ucar.edu/lumip).

2.2. Phase 1 experiments

Phase 1 consists of two sets of experiments: (a) idealized coupled deforestation experiment that enables analysis of the biogeophysical and biogeochemical response to land-cover change and the associated changes in climate in a controlled and consistent set of simulations (Table 1) and (b) a series of offline land-only simulations to assess how the representation of land cover and land management affects the carbon, water, and energy cycle response to land-use change (Table 2).

2.2.1 Global deforestation (*deforest-glob*, GCM, Tier 1, 80 years)

Description: Idealized deforestation experiment in which 20 million km^2 of forest area (covered by trees) is converted to natural grassland over a period of 50 years with a linear rate of 400,000 $km^2\ yr^{-1}$, followed by 30 years of constant forest cover (Figure 2A). This simulation should be branched from an 1850 control simulation (*piControl*); all pre-industrial forcings including CO_2 concentration and land-use maps and land-management should be maintained as in the *piControl* and discussed in Section 2.1. The branch should occur at least 80 years prior to the end of the piControl simulation so that *deforest-glob* and *piControl* can be directly compared. In order to concentrate the deforestation from grid cells with predominant forest cover, deforestation should be restricted to

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the top 30% of land grid cells in terms of their area of tree cover. Effectively, this concentrates the deforestation in the tropical rainforest and boreal forest regions (Figure 3). To do this:

1. Sort land grid cells by forest area and select the top 30% (*gcdef*, Figure 2B).
2. Calculate tree plant type loss for each year at each grid cell by attributing the 400,000 km^2 yr^{-1} forest loss proportionally to their forest cover fraction across the *gcdef* grid cells.

Step 2 is formalized as follows. Let *f(x,y,t)* be the forest fraction in grid cell (*x,y*) at the end of year *t* ($0 \leq t \leq 80$), *A(x,y)* is the area of the grid cell (million km^2). At t=0 (initialization of *deforest-glob*), forest fraction should be equal to that of the year 1850 in the *piControl*. The total forest area, F_{tot} (million km^2), within the grid cells identified for deforestation (*gcdef*) in Step 1 is:

$$F_{tot} = \sum_{gcdef} f(x,y,t=0)A(x,y) \quad (1)$$

If F_{tot} is more than 20 million km^2, then the scaling coefficient k_{gcdef} is

$$k_{gcdef} = \frac{20}{F_{tot}} \leq 1 \quad (2)$$

and temporal development of forest fraction in deforested grid cells is calculated as follows:

$$f(x,y,t) = \begin{cases} f(x,y,t=0)(1-\frac{k_{gcdef}t}{50}) & 0 < t \leq 50 \\ f(x,y,t=0)(1-k_{gcdef}) & t > 50 \end{cases} \quad (3)$$

If F_{tot} is less than or equal to 20 million km^2, then the scaling coefficient k_{cgef} is taken as 1.

Trees should be replaced with natural unmanaged grasslands. Land use and land management should be maintained at 1850 levels as in the *piControl* experiment. All above ground biomass (cWood, cLeaf, cMisc) should be removed and below ground biomass (cRoot) transferred to appropriate litter pools (Figure 2C). If there is no separation of above and below ground biomass in the model, then the whole vegetation biomass pool (cVeg) should be removed. The replacement of forest with natural grasslands should be done in such a way that the carbon (and nitrogen if applicable) from the forested soil is maintained and allowed to evolve according to natural model processes. If initial forest cover in the *gcdef* grid cells is less than 20 million km^2 then should linearly remove all the forested area from the *gcdef* grid cells over 50 years and report the total area of forest removed. Note that even with substantially different initial forest cover in CCSM4 versus MPI-ESM-P (the examples shown in Figure 3), the prescribed land-cover change is quite similar for both models when using this deforestation protocol and that modelling groups should strive to produce similar deforestation patterns.

Note that implementation of the deforestation is likely to differ for models with and without vegetation dynamics. Applying deforestation for models without dynamic vegetation should be straightforward as the deforestation can be applied through a time series of land-cover maps that each group can generate. For models with dynamic vegetation, if possible, vegetation dynamics should be turned off in areas where deforestation is being applied.

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Outside the deforested areas, vegetation dynamics can be maintained since the tree cover response to the climate change induced by deforestation is expected to be small over the 80-year simulation time scale.

We recognize that each participating land model has its own unique structures that may or may not be adequately covered in the above description sketched on the Figure 2. Each modelling group should implement the deforestation in a manner that makes the most sense for their particular modelling system. It is important, however, that all groups strive to produce a spatial and latitudinal deforestation signal that replicates that shown in Figure 3 as closely as possible. The goal of this experiment is to impose deforestation patterns that are as similar as possible across models so as to limit the impact of across-model differences in deforestation patterns on the multi-model evaluation of deforestation impacts on climate and carbon fluxes.

Rationale: This experiment is designed to be conceptually analogous to the 1% per year CO_2 simulation in the DECK. Prior idealized global or regional deforestation simulations (Badger and Dirmeyer 2015, 2016; Bala et al. 2007; Bathiany et al. 2010; Davin and de Noblet-Ducoudré 2010; Lorenz et al. 2016; Snyder 2010) have proven informative and highlighted how both biogeophysical and biogeochemical forcings due to land-use change contribute to temperature changes, how the ocean can modulate the response, and how remote effects of LULCC can be detected in some situations. However, differences in implementation of realistic historic or projected land-cover change across different models is a problem that has plagued prior land-cover change model intercomparison projects, with a third to a half - depending on season and variable - of the differences in climate response attributable to differences in imposed land cover (Boisier et al. 2012). The relatively simple LUMIP idealized deforestation protocol will enhance uniformity in the prescribed deforestation and therefore enable more direct and meaningful comparison of model responses to deforestation. The gradual deforestation allows a comparison across models with respect to what amplitude of forest loss is needed before a detectable signal emerges at the local and global level, and will provide insight into detection and attribution of land-cover change impacts at regional scales.

2.2.2 Land-only land-cover and land-use simulations (*land-xxxx*, land-only; *land-hist*, *land-hist-altStartYear* and *land-noLu* are Tier 1, all others Tier 2, up to 13 simulations, 165 to 315 years each).

Description: A set of land-only simulations that are identical to the LS3MIP (Van den Hurk et al. 2016) historical land-only (*land-hist*; Table 2) simulation except with each simulation differing from the *land-hist* simulation in terms of the specific treatment of land use or land management, or in terms of prescribed climate. Note that all simulations should be forced with the default reanalysis dataset provided through LS3MIP (GSWP3 at time of writing). The primary control experiment is *land-hist* this is defined in LS3MIP. This experiment is required (Tier 1), even if the modeling group is not contributing to the full set of LS3MIP experiments. The *land-hist* simulation should include land cover, land use, and land management that is identical to that used in the coupled CMIP6 historical simulation (see next paragraph for more discussion). Two of the LUMIP simulations - *land-hist-*

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altStartYear and *land-hist-noLu* - are Tier 1. The remaining experiments are Tier 2. Detailed descriptions of the factorial set of simulations are listed in Table 2.

We anticipate that only a limited number of participating land models will be able to perform all the experiments, but the experimental design allows for models to submit the subset of experiments that are relevant for their model. In some instances, groups may also have a more advanced land model in terms of its representation of land-use-related processes than that which is used in the coupled CMIP6 historical simulation. In these cases, we request that models submit the LUMIP Tier 1 land-only experiments with the configuration of the land model used in the coupled model CMIP6 historical simulation, but groups are encouraged to provide an additional set of land-only simulations with their more advanced model configuration.

Rationale: This factorial series of experiments serves several purposes and is designed to provide a detailed assessment of how the specification of land-cover change and land management affects the carbon, water, and energy cycle response to land-use change. This set of experiments utilizes state-of-the-art land model developments that are planned across several contacted modeling centers and will contribute to the setting of priorities for land use for future CMIP activities. The potential analyses that will be possible through this set of experiments is vast. We highlight several particular analysis foci here:

(a) The *land-hist* and *land-noLu* simulations will provide context for the global coupled CMIP6 historical simulations, enabling the disentanglement of the LULCC forcing (changes in water, energy and carbon fluxes due to land-use change) from the response (changes in climate variables such as temperature and precipitation that are driven by LULCC-induced surface flux changes), though differences in the coupled model and observed climate forcing will need to be taken into account. The land-only simulations also allow more detailed quantification of the net LULCC flux.

(b) Relative influence of various aspects of land management on the overall impact of land use on water, energy, and carbon fluxes. For example, comparing the *land-hist* experiment to the experiment with no irrigation (*land-crop-noirrig*) will allow a multi-model assessment of whether or not the increasing use of irrigation during the 20th century is likely to have significantly altered trends of regional water and energy fluxes (and therefore climate) or crop yield/carbon storage in agricultural regions.

(c) Pre-industrial land conversion for agriculture was substantial (Pongratz et al. 2008) and has long term and non-negligible legacy effects on the carbon cycle that last well beyond the standard 1850 starting year of CMIP6 historical simulations (Pongratz and Caldeira 2012). By comparing *land-hist* with *land-hist-altStartYear* across a range of models, we can further establish how important pre-1850 land use is for the historical (1850-2005) land carbon stock trajectory.

(d) Gross land-use transitions, especially due to shifting cultivation, can exceed net transitions by a factor of two or more (Hurtt et al. 2011). Accounting for gross transitions instead of just net transitions results in 15-40% higher simulated net land-use carbon fluxes (Hansis et al. 2015; Stocker et al. 2014; Wilkenskjeld et

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al. 2014). For models that can represent shifting cultivation, a parallel experiment (*lnd-hist-noShiftcultivate*) in which shifting cultivation is turned off (net transition) through an alternative set of provided land-use transitions will allow evaluation of the impact of shifting cultivation across a range of models and assumptions (Figure 4).

(e) Comparison of effects of LULCC on surface climate and carbon fluxes (which can be calculated by comparing historical and no-LULCC simulations) between the land-only simulations and the global coupled model simulations (Section 2.3.1) allows assessment of consequences of model climate biases on LULCC effects.

(f) Uncertainty in the land-use history reconstruction is itself a source of uncertainty in the impacts of historic LULCC. The alternative land-use history simulations (*land-hist-altLu1* and *land-hist-altLu2*) in combination with the default land-use history simulation (land-hist) provide information on the sensitivity of the models to a range of plausible reconstructions of land-use history.

Impact of historic meteorological forcing datasets: It is critical to acknowledge that all observed historic forcing datasets are subject to considerable errors and uncertainty and that the weather and climate variability and trends represented in these datasets may not accurately reflect reality, especially in remote regions where limited data went into either the underlying reanalysis or the gridded products. These limitations pose a challenge when comparing the model outputs (like latent heat flux, for example) to observed estimates because biases may actually be a function of biases in the meteorological forcing dataset rather than deficiencies in the model. While the land-only LUMIP simulations will only be driven with a single atmospheric forcing dataset (the reference dataset used in the *land-hist* experiment of LS3MIP), the sensitivity of land model output to uncertainty in atmospheric forcing will be assessed in more depth within LS3MIP, which can inform the assessment of the land-only LUMIP simulations.

2.3. Phase 2 experiments

The Phase 2 LUMIP experiments are designed to provide a multi-model quantification of the impact of historic LULCC on climate and carbon cycling and to assess the extent to which land management could be utilized as a climate change mitigation tool. This set of experiments includes land-only and coupled historical and future simulations that are derivatives of historical or future simulations within LS3MIP, ScenarioMIP, C4MIP as well as the CMIP6 Historical simulation with land use held constant or modified to an alternative land-use scenario (Table 3). These simulations will be used to assess the role of land use on climate from the perspective of both the biogeophysical and biogeochemical impacts and are likely to be of interest to DAMIP, C4MIP, ScenarioMIP, and LS3MIP.

2.3.1 Historical no land-use change experiment (*hist-noLu*; concentration-driven, Tier 1, 165 years)

Description: Historical simulation that is identical to CMIP6 historical concentration-driven simulation except that land use is held constant. All land use and management (irrigation, fertilization, wood harvest, gross transitions

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exceeding net transitions) is maintained at 1850 levels, in exactly the same way as done for the CMIP6 pre-industrial control simulation (*piControl*).

Rationale: This simulation, when compared to the CMIP6 historical simulation, isolates the biogeophysical impact of land-use change on climate and addresses the CMIP6 science question "How does the Earth system respond to forcing?" For models that are run with a diagnostic land carbon cycle, the difference in carbon stocks between *hist-noLu* and the *CMIP6 historical* simulation represents the integrated net LULCC flux. Note that the parallel set of land-only simulations (LS3MIP *land-hist* experiment and LUMIP *land-noLu* experiment, see Sect. 2.1.3) will enable groups to disentangle the contributions of land-use-change induced effects on surface fluxes from atmospheric feedbacks and response (e.g., Chen and Dirmeyer 2016), though the influence of differences in land forcing in coupled versus land-only simulations will need to be taken into account during the analysis. This experiment is directly relevant for detection and attribution studies (DAMIP).

2.3.2 Future land-use policy sensitivity experiments (*ssp370-ssp126Lu* and *ssp126-ssp370Lu*, GCM concentration-driven, Tier 1, 2015-2100; *esm-ssp585-ssp126Lu*, ESM emission-driven, Tier 1, 2015-2100)

Description: These experiments are derivatives of ScenarioMIP (*ssp370* and *ssp126*, see below for short description of the Shared Socioeconomic Pathways (SSP) land-use scenarios) and C4MIP (*esm-ssp85*) simulations (Figure 5). In each case, the LUMIP experiment is identical to the 'parent' simulation except that an alternative land-use dataset is used. All other forcings are maintained from the parent simulation.

Rationale: Both concentration-driven and emission-driven LUMIP alternative land-use simulations are requested. Concentration-driven variants of ScenarioMIP *ssp370* and *ssp126* are required but each using the land-use scenario from the other: i.e., LUMIP simulation *ssp370-ssp126Lu* will run with all forcings identical to *ssp370* except for land use which is to be taken from *ssp126*. These simulations permit analysis of the biogeophysical climate impacts of projected land use and enable preliminary assessment of land use and land management as a regional climate mitigation tool (green arrows on Figure 5). Note that these simulations should be considered sensitivity simulations since they will include a set of forcings that are inconsistent with each other (e.g., land use from SSP1-2.6 in a simulation that in all other respects is equivalent to SSP3-7). This particular set of simulations was selected because the projected land-use trends in SSP3-7 and SSP1-2.6 diverge strongly with SSP3-7 representing a reasonably strong deforestation scenario and SSP1-2.6 including significant afforestation (see Figure 6). These experiments will provide a direct test of an assumption underlying the SSP framework, namely that a particular radiative forcing level can be achieved by multiple socioeconomic scenarios with negligible effect on the resulting climate (Van Vuuren et al. 2014), an assumption that may not hold if patterns of land-use change associated with alternative SSPs diverge significantly enough from one another (Jones et al. 2013b). Furthermore, including experiments in both low and medium/high radiative forcing scenarios allows examination of the extent to which the impact of land-use change differs at different levels of climate change and at different levels of CO_2 concentration (red arrows on Figure 5). These sets of experiments can be utilized to provide partial guidance on

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the utility of careful land management as a climate mitigation strategy (Canadell and Raupach 2008; Marland et al. 2003).

Emission-driven simulations allow assessment of the full feedback (biogeophysical + biogeochemical) due to land-use change onto climate. In these simulations the ESMs simulate the concentration of atmospheric CO_2 in response to prescribed boundary conditions of anthropogenic emissions. Biogeophysical effects operate in the same way as in concentration-driven simulations but in addition, the carbon released or absorbed due to land-use change will affect how the CO_2 concentration of the atmosphere evolves in time. Additionally, emission-driven simulations permit assessment of consistency between Integrated Assessment Model predictions (which typically include the biogeochemical effect of land use as a carbon source, but neglect the biophysical effects) about land use and land-use change carbon fluxes with ESM modeled land-use emissions. C4MIP has requested an emission-driven variant to *ssp585,* which will be performed in concentration-driven mode for ScenarioMIP. This will allow quantification of the effects of the climate-carbon cycle feedback on future CO2 and climate change (brown arrow on Figure 5). In LUMIP we request a further SSP5-8.5 simulation: emission-driven but with land use taken from SSP1-2.6. This experiment (*esm-ssp585-ssp126Lu)* will therefore parallel the C4MIP emission-driven experiment (*esm-ssp585)* but will allow us to quantify the full effects of a different land-use scenario through both biophysical and biogeochemical processes (blue arrow on Figure 5).

Land-use scenarios in SSPs: The scenarios chosen for use in CMIP6 were developed as part of the Shared Socioeconomic Pathways (SSP) effort (Van Vuuren et al. 2014). Five SSPs were designed to span a range of challenges to mitigation and challenges to adaptation. These SSPs can be combined with RCPs to provide a set of scenarios that span a range of socioeconomic assumptions and radiative forcing levels (Riahi et al. 2016). ScenarioMIP selected eight scenarios from this suite for use in CMIP6. Within LUMIP, we focus on three of these scenarios in our experimental design, chosen because they span a range of future land-use projection (see Popp et al. 2016 for more comprehensive discussion of land-use trajectories). The SSP5-8.5 is a high radiative forcing scenario, reaching 8.5 W m^{-2} in 2100, with relatively little land-use change over the coming century. The increase in radiative forcing is driven by increased use of fossil fuels; however, the combination of a relatively small population and high agricultural yields leads to little expansion of cropland area (Kriegler et al. 2016). In contrast, the SSP3-7 is a world with a large population and limited technological progress, resulting in expanded cropland area (Fujimori et al. 2016). In the SSP1-2.6, efforts are made to limit radiative forcing to 2.6 W m^{-2}. These mitigation efforts include reduced deforestation as well as reforestation and afforestation, leading to a scenario where forest cover increases over the coming century (Van Vuuren et al. 2016). Figure 6 shows global time series of forest area, cropland area, pastureland area, wood harvest, area equipped for irrigation, and nitrogen fertilization amounts in the SSP scenarios, highlighting those scenarios selected by ScenarioMIP and LUMIP.

3. Land-use metrics and analysis plans

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3.1 Land-use metrics

A goal of LUMIP is to establish a useful set of model diagnostics that enable a systematic assessment of land use-climate feedbacks and improved attribution of the roles of both land and atmosphere in terms of generating these feedbacks. The need for more systematic assessment of the terrestrial and atmospheric response to land-cover change is one of the major conclusions of the LUCID studies. Boisier et al. (2012) and de Noblet-Ducoudré *et al* (2012) argue that the different land use-climate relationships displayed across the LUCID models highlights the need to improve diagnostics and metrics for land surface model evaluation in general and the simulated response to LULCC in particular. These sentiments are consistent with recent efforts to improve and systematize land model assessment (e.g., Abramowitz 2012; Best et al. 2015; Kumar et al. 2012; Luo et al. 2012; Randerson et al. 2009). LUMIP will promote a coordinated effort to develop biogeophysical and biogeochemical metrics of model performance with respect to land-use change that will help constrain model dynamics. These efforts dovetail with expanding emphasis in CMIP6 on model performance metrics. Several recent studies have utilized various methodologies to infer observationally-based historical change in land surface variables impacted by LULCC or divergences in surface response between different land-cover types (Boisier et al. 2013, 2014; Lee et al. 2011; Lejeune et al. 2016; Li et al. 2015; Teuling et al. 2010; Williams et al. 2012).

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The availability of both land-only and coupled historic simulations enables a more systematic assessment of the roles of land and atmosphere in the simulated response to land-use change. With both coupled and uncoupled experiments with and without land-use change, we can systematically disentangle the simulated LULCC forcing (changes in land surface water, energy and carbon fluxes due to land-use change) from the response (changes in climate variables such as T and P that are driven by LULCC-driven changes in surface fluxes).

LUMIP also proposes to develop a set of analysis metrics that succinctly quantify a model response to land use across a range of spatial scales and temporal scales that can then be used to quantitatively compare model response across different models, regions, and land management scenarios. For a given variable, say surface air temperature, diagnostic calculations will be completed for a pair of simulations (offline or coupled) with and without land-use change. Across a range of spatial scales, spanning from a single grid cell up to regional, continental, and global, seasonal mean differences between control and land-use change simulations will be examined. Differences will be expressed, for example, both in terms of seasonal mean differences and in terms of signal to noise (where 'noise' refers to the natural interannual climate variability simulated in the model). Lorenz et al. (2016) emphasize the importance of testing for field significance, especially in the context of evaluating the statistical significance of remote responses to LULCC.

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3.2 Net LULCC carbon flux: loss of additional sink capacity and the net land-use feedback

To quantify the climatic and carbon cycle consequences of LULCC and land management consistently across models, care has to be taken that the same conceptual framework is applied. Pongratz et al. (2014) have highlighted this issue for the net LULCC carbon flux. The large spread in published estimates of the net LULCC flux can be substantially attributed to differing definitions that arise from different model and simulation setups. These definitions differ in particular with respect to the inclusion of two processes, the loss of additional sink capacity (LASC) and the land use carbon feedback. The LASC, which is an indirect LULCC flux, occurs when conversion of land from natural lands (forests) to managed lands (crops or pasture) reduces the capacity of the land biosphere to take up anthropogenic carbon dioxide in the future (e.g., Gitz and Ciais 2003). While small historically it may be of the same order as the net LULCC flux without LASC for future scenarios of strong CO_2 increase (Gerber et al. 2013; Mahowald et al. 2016; Pongratz et al. 2014). The land-use carbon feedback can be assessed in emission-driven simulations where LULCC carbon fluxes alter the atmospheric CO_2 concentration and the land-use changes also affect the climate through biogeophysical responses, both of which can then feed back onto the productivity of both natural and managed vegetation. Over the historical period, a substantial fraction of the LULCC emissions have been offset with increased vegetation growth. Calculating the net LULCC flux by differencing carbon stocks from a pair of simulations with and without LULCC will lead to net LULCC flux estimates that are about 20-50% lower when calculated from a pair of emission-driven simulations (which include the land use carbon feedback) compared to a pair of land-only simulations (Pongratz et al. 2014; Stocker and Joos 2015).

Within LUMIP, several different model configurations are used that include the LASC and the land use carbon feedback to different extents (Figure 7). Note that to isolate the effect of LULCC emissions from those of fossil-fuel emissions, a reference simulation is needed, which may be a no-LULCC simulation or a simulation with an alternative LULCC scenario. In the case of the idealized deforestation experiments, where CO_2 is kept constant over time, all changes in carbon stocks can be directly attributed to LULCC. The net LULCC flux, as quantified from the land-only simulation, will differ slightly from that calculated in GCM simulations since the GCM simulations include biogeophysical climate feedbacks from LULCC. The difference in net LULCC flux between two LULCC scenarios as derived from the ESM setup follows a different definition, as the land-use carbon feedback is included and its effects cancel only partly by difference of the two simulations.

3.3 Radiative Forcing

A recognized limitation within CMIP5 was the difficulty in diagnosis of the radiative forcing due to different forcing mechanisms such as well-mixed GHGs, aerosols or land-use change. In addition, the regionally concentrated nature of biophysical land-use forcing limits the insight gained from quantifying it in terms of a global mean metric (or more strictly the Effective Radiative Forcing, ERF; Davin et al. 2007; Jones et al. 2013a; Myhre et al. 2013). Experiments were performed within CMIP5 to explore different model responses to individual forcings but were not designed to distinguish how each forcing led to a radiative forcing of the climate system versus how the climate system responded to that forcing. For CMIP6, RFMIP is designed to address this gap by including a factorial set of atmosphere-only simulations to diagnose the ERF due to each forcing mechanism individually. Andrews et al. (2016) performed the Radiative Forcing MIP (RFMIP) land use experiment to diagnose the historical ERF from land use in HadGEM2-ES and found a forcing of -0.4 W m^{-2} or about 17% of the total present-day anthropogenic

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radiative forcing. Other studies indicate that the combined radiative forcing effect of land-use change may be as large as ~40% of total present-day anthropogenic radiative forcing, when accounting for emissions of all GHG species due to LULCC (Ward et al. 2014). LUMIP will benefit from groups performing the RFMIP land-use experiment in addition to the LUMIP simulations.

3.4 Modulation of land-use change signal by land-atmosphere coupling strength

An axis of analysis that has not been investigated in great detail is how a particular model's regional land-atmosphere coupling strength signature (Guo et al. 2006; Koster et al. 2004; Seneviratne et al. 2010; Seneviratne et al. 2013) affects simulations of the climate impact of land-use change. One can hypothesize that LULCC in a region where the land is tightly coupled to the atmosphere, generally due to the presence of a soil moisture-limited evapotranspiration regime (Koster et al. 2004; Seneviratne et al. 2010), will result in a stronger climate response than the same LULCC in a region where the atmosphere is not sensitive to land conditions. In a single model study of Amazonian deforestation, Lorenz and Pitman (2014) find that this is indeed the case – small amounts of deforestation in a part of the Amazon domain where the model simulates strong land-atmosphere coupling has a larger impact on temperature than extensive deforestation in a weakly coupled region. Similarly, Hirsch et al. (2015) show that different planetary boundary layer schemes, which lead to different land-atmosphere coupling strengths, can modulate the impact of land-use change on regional climate extremes. LUMIP will collaborate with LS3MIP to systematically investigate the inter-relationships between land-atmosphere coupling strength, which can be diagnosed in any coupled simulation (e.g., Dirmeyer et al. 2014; Seneviratne et al. 2010), and LULCC impacts on climate and establish to what extent differences in land-atmosphere coupling strength across models (Koster et al. 2004) contribute to differences in modeled LULCC impacts.

3.5 Extremes

There is evidence that land surface processes strongly affect hot extremes, as well as drought development and heavy precipitation events, in several regions (Davin et al. 2014; Greve et al. 2014; Seneviratne et al. 2010; Seneviratne et al. 2013), and that these relationships could also change with increasing greenhouse gas forcing (Seneviratne et al. 2006; Wilhelm et al. 2015). Therefore, the role of LULCC needs to be better investigated, both in the context of the detection and attribution of past changes in extremes (Christidis et al. 2013) – in coordination with DAMIP – and in assessing its impact on projected changes in climate extremes. In particular, recent studies show that LULCC could affect temperature extremes more strongly than mean temperature, through a combination of changes in albedo (Davin et al. 2014) and accumulated changes in soil moisture content (Wilhelm et al. 2015). Careful assessment will be necessary to validate the inferred relationships between LULCC and extremes, given partly contradicting results with respect to the effects of LULCC on climate extremes in models and observations (Lejeune et al. 2016; Teuling et al. 2010).

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4. Subgrid data reporting

To address challenges of analyzing effects of LULCC on physical and biogeochemical state of land and its interactions with the atmosphere (e.g., analyses proposed in Section 3.2-3.5), LUMIP is including a Tier 1 data request of sub-grid information *for four sub-grid categories* (i.e., tiles) to permit more detailed analysis of land-use induced surface heterogeneity. The rationale for this request is that relevant and interesting sub-grid scale data that represents the heterogeneity of the land surface is available from current land models, but is not being used since sub-grid scale quantities are typically averaged to grid cell means prior to delivery to the CMIP database. Several recent studies have demonstrated that valuable insight can be gained through analysis of subgrid information. For example, Fischer et al. (2012) used sub-grid output to show that not only is heat stress higher in urban areas compared to rural areas in the present-day climate, but also that heat stress is projected to increase more rapidly in urban areas under climate change. Malyshev et al. (2015) found a much stronger signature of the climate impact of LULCC at the subgrid level (i.e., comparing simulated surface temperatures across different land-use tiles within a grid cell) than is apparent at the grid cell level. Subgrid analysis can also lead to improved understanding of how models operate. For example, Schultz et al. (2016) showed, through subgrid analysis of the Community Land Model, that the assumption that plants share a soil column and therefore compete for water and nutrients has the side effect of an effective soil heat transfer between vegetation types which can alias into individual vegetation type surface fluxes. Furthermore, reporting carbon pools and fluxes by tiles will enable assessment of land-use carbon fluxes not only with the standard method of differencing land-use and no land-use experiments (e.g., as described in Section 3.2) but also within a single land-use experiment, utilizing bookkeeping approaches (Houghton et al. 2012) which allow a more direct comparison of observed and modeled carbon inventory

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4.1 Types of land-use tiles

Four land-use categories are requested for selected key variables: (1) primary and secondary land (including bare ground and vegetated wetlands), (2) cropland, (3) pastureland, and (4) urban (Table 4). Other sub-grid categories such as lakes, rivers and glaciers are excluded from this request. The proposed set of land-use sub-grid reporting units closely corresponds to land-use categories to be used in the CMIP6 historical land-use reconstructions and future scenarios. Primary (i.e., natural vegetation never affected by LULCC activity) and secondary land (i.e., natural vegetation that has previously been harvested or abandoned agricultural land with potential to regrow) are combined because most land components of ESMs models do not yet distinguish between these two land types.

4.2 Requested variables and rules for reporting

Overall, there are 5 classes of variables that are requested. These variables describe (a) the subgrid structure and how it evolves through time, (b) biogeochemical fluxes, (c) biogeophysical variables, (d) LULCC fluxes and carbon transfers (Figure 8), and (e) carbon stocks on land-use tiles. A list of requested land-use tile variables is shown in

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Table 5. However, this list is subject to change. Modelers should refer to the CMIP6 output request documents for the final variable list.

Subgrid tile variables should be submitted according to the following structure, using Leaf Area Index (LAI) as an example: laiLut (lon, lat, time, landusetype4) – where the landusetype4 dimension has an explicit order of psl, crp, pst, urb where "psl" = primary and secondary land, "crp" = cropland, "pst" = pastureland, and "urb" = urban.

It is recognized that different models have very different implementation of LULCC processes and may only be able to report a subset of variables/land-use tiles, but models are requested to report according to the following rules:

- The sum of the fractional areas for psl + crp + pst + urb may not add up to 1 for grid cells with lakes, glaciers or other land sub-grid categories.
- If a model does not represent one of the requested land-use tiles, then it should report for these tiles with missing values.
- In cases where more than one land-use tile shares information then duplicate information should be provided on each tile (e.g., if pastureland and cropland share the same soil then duplicate information for soil variables should be provided on the pst and crp tiles).
- If a model does not represent one of the requested variables for any of the subgrid land-use tiles, then this variable should be omitted.
- Note that for variables where for a particular model the concept of a tiled quantity is not appropriate, that quantity should only be reported at the grid-cell level. An example is Anthropogenic Product Pools (APP). Many models do not track APP at the subgrid tile level, instead aggregating all sources of APP into a single grid-cell level APP variable. In this case, APP should only be reported at the grid cell level as per the CMIP request.

4.3 Land-use tile-reporting/aggregation for example models

Community Land Model (CLM) example

CLM captures a variety of ecological and hydrological sub-grid characteristics (Figure 9, Lawrence et al. 2011; Oleson et al. 2013). Spatial land surface heterogeneity in CLM is represented as a nested subgrid hierarchy in which grid cells are composed of multiple land units, snow/soil columns, and PFTs. Each grid cell can have a different number of land units, each land unit can have a different number of columns, and each column can have multiple PFTs. The first subgrid level, the land unit, is intended to capture the broadest spatial patterns of subgrid heterogeneity. The CLM land units are glacier, lake, urban, vegetated, and crop. The land unit level can be used to further delineate these patterns. For example, the urban land unit is divided into density classes representing the tall building district, high density, and medium density urban areas. The second subgrid level, the column, is intended to capture potential variability in the soil and snow state variables within a single land unit. For example, the vegetated land unit could contain several columns with independently evolving vertical profiles of soil water and temperature. Similarly, the crop land unit is divided into multiple columns, two columns for each crop type (irrigated and non-irrigated). The central characteristic of the column subgrid level is that this is where the state variables for water and energy in the soil and snow are defined, as well as the fluxes of these components within the soil and snow. Regardless of the number and type of plant function types (PFTs) occupying space on the column, the column physics operates with a single set of upper boundary fluxes, as well as a single set of transpiration fluxes from multiple soil levels. These boundary fluxes are weighted averages over all PFTs. Currently, for glacier, lake, and vegetated land units, a single column is assigned to each land unit.

In order to meet requirements of the LUMIP sub-grid reporting request, the following aggregation would be required for CLM:

- Primary and secondary land (psl): vegetated land unit includes all primary and secondary land which includes all natural vegetation and bare soil
- Crops (crp): crop land unit including all non-irrigated and irrigated crops
- Pastureland: not explicitly treated in CLM, reported as missing value
- Urban (urb): urban land unit including tall building, high density, and medium density areas
- Lakes and glaciers are not included in any of the LUMIP subgrid categories, so are not reported

GFDL LM3 example

The GFDL CMIP5 land component LM3 (Shevliakova et al. 2009) resolves sub-grid land heterogeneity with respect to different land-use activities: each grid cell includes up to 15 different tiles (including a bare soil tile) to represent differences in above- and below-ground hydrological and carbon states (Figure 10). A grid cell could have one cropland tile, one pasture tile, one natural tile, and up to 12 secondary land tiles as well as lake and glacier tiles. Secondary tiles refer to lands that were harvested (i.e., prior primary or secondary) or abandoned agricultural lands, pastures and croplands. The tiling structure of LM3 and ESM2 was designed to work with the CMIP5 LUH dataset (Hurtt et al. 2011). Changes in the area and type of tiles occur annually based on gross transitions from the LUH dataset. Similarly to the scenario design, secondary or agricultural lands are never allowed to return to primary lands. The physical and ecological states and properties of each of the tiles are different, and the physical and biogeochemical fluxes between land and the atmosphere are calculated separately for every tile. Each cropland, pasture and secondary tile has three anthropogenic pools with three different residence times (1 year, 10 years, and 100 years. For LUMIP sub-grid tile reporting, all secondary and natural tiles will be aggregated into the primary and secondary tile (PSL). For each requested land-use tile the three different residence-time anthropogenic pools will be aggregated into one.

5. Summary

Here, we have outlined the rationale for the Land Use Model Intercomparison Project (LUMIP) of CMIP6. We provided detailed descriptions of the experimental design along with analysis plans and instructions for subgrid land-use tile data archiving. The efficient, yet comprehensive, experimental design, which has been developed through workshops and discussions among the land-use modeling and related communities over the past two years, includes idealized and realistic experiments in coupled and land-only model configurations. These experiments are designed to advance process-level understanding of land-cover and land-use impacts on climate, to quantify model sensitivity to potential land-cover and land-use change, to assess the historic impact of land use, and to provide preliminary evaluation of the potential for targeted land use and management as a method to contribute to the mitigation of climate change. In addressing these topics, LUMIP will also study more detailed land-use science questions in more depth and sophistication than possible in a multi-model context to date. Analyses will focus on the separation and quantification of the effects on climate from LULCC relative to all forcings, separation of biogeochemical from biogeophysical effects of land use, the unique impacts of land-cover change versus land-use change, modulation of land-use impact on climate by land-atmosphere coupling strength, the role of land-use change on climate extremes, and the extent that impacts of enhanced CO_2 concentrations on plant photosynthesis are modulated by past and future land use.

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Data availability

As with all CMIP6-endorsed MIPs the model output from the LUMIP simulations described in this paper will be distributed through the Earth System Grid Federation (ESGF). The natural and anthropogenic forcing datasets required for the simulations will be described in separate invited contributions to this Special Issue and made available through the ESGF with version control and digital object identifiers (DOI's) assigned. Links to all forcings datasets will be made available via the CMIP Panel website.

Author contribution

DML and GCH are co-leads of LUMIP. DML wrote the document with contributions from all other authors.

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Table 1: Idealized deforestation experiment designed to gain process understanding and to assess biogeophysical role of land-cover change on climate and inter-compare modeled biogeochemical response to deforestation (concentration-driven).

Experiment ID	**Experiment Name**	**Experiment Description**	**Years**
deforest-glob	Idealized transient global deforestation	Idealized deforestation experiment, 20 million km^2 forest removed linearly over a period of 50 years, with an additional 30 years with no specified change in forest cover (Tier 1). This simulation should be branched from an 1850 control simulation (***piControl***); all pre-industrial forcings including CO_2 concentration and land-use maps and land management should be maintained as in the ***piControl*** as discussed in Section 2.1	80 years

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Table 2. **Land-only** land-cover, land-use, and land-management change simulations. Assess relative impact of land-cover, land-use, and land-management change on fluxes of water, energy, and carbon; forced with historical observed climate. The simulations *land-hist*, *land-hist-altStartYear* and *land-noLu* are Tier 1, all other simulations are Tier 2. All simulations should be pre-industrial to 2015 where pre-industrial start can be either 1850 or 1700 depending on model.

Experiment ID	Description	Notes
land-hist	Same land model configuration, including representation of land cover, land use, and land management, as used in coupled CMIP6 historical simulation with all applicable land-use features active. Start year either 1850 or 1700 depending on standard practice for particular model. All forcings transient including CO_2, N-deposition, aerosol deposition, etc. Shared simulation with LS3MIP.	This simulation can and likely will be a different configuration across models due to different representations of land use for each model. See LS3MIP protocol for full details including details on forcing dataset and spinup.
land-hist-altStartYear	Same as ***land-hist*** except starting from either 1700 (for models that typically start in 1850) or 1850 (for models that typically start in 1700).	Comparison to ***land-hist*** indicates impact of pre-1850 land-use change.
land-noLu	Same as ***land-hist*** except no land-use change (see Section 2.1 for explanation of no land use).	
land-hist-altLu1 **land-hist-altLu2**	Same as ***land-hist*** except with two alternative land-use history reconstructions, that span uncertainty in agriculture and wood harvest. Specifically, the ***altLu1*** is a 'high' reconstruction, assumes high historical estimates for crop and pasture and wood harvest and ***altLu2*** is a 'low' reference assumes low estimates for each of these terms, relative to the reference dataset.	In combination with ***land-hist***, allows assessment of model sensitivity to different assumptions about land-use history reconstructions. Note that land use in 1700 and 1850 will be different to that in ***land-hist*** so model will need to be spunup again for both alternative datasets. Note that these reconstructions do not span the entire range of uncertainty and the simulations should be considered sensitivity simulations.
land-cCO2	Same as ***land-hist*** except with CO_2 held constant	
land-cClim	Same as ***land-hist*** except with climate held constant	Continue with spinup forcing looping over first 20 years of meteorological forcing data.
land-crop-grass	Same as ***land-hist*** but with all new crop and pastureland treated as unmanaged grassland	For this simulation, treat cropland like natural grassland without any crop management in terms of biophysical properties but is treated as agricultural land for dynamic vegetation (i.e. no competition with natural vegetation areas).
land-crop-noIrrigFert	Same as ***land-hist*** except with plants in cropland area utilizing at least some form of crop management (e.g., planting and harvesting) rather than simulating cropland vegetation as a natural grassland. Irrigated area and fertilizer area/use should be held constant.	Maintain 1850 irrigated area and fertilizer area/amount and without any additional crop management except planting and harvesting. Irrigation amounts with irrigated area allowed to change.
land-crop-noIrrig	Same as ***land-hist*** but with irrigated area held at 1850 levels; only relevant if ***land-hist*** utilizes at least some form of crop management (e.g., planting and harvesting)	Maintain 1850 irrigated area. Irrigation amounts within the 1850 irrigated area allowed to change
land-crop-noFert	Same as ***land-hist*** but with fertilization rates and area held at 1850 levels/distribution; only	

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	relevant if ***land-hist*** utilizes at least some form of crop management (e.g., planting and harvesting)	
land-noPasture	Same as ***land-hist*** but with grazing and other management on pastureland held at 1850 levels/distribution, i.e. all new pastureland is treated as unmanaged grassland (as in ***land-crop-grass***).	
land-noWoodHarv	Same as ***land-hist*** but with wood harvest maintained at 1850 amounts/areas	Wood harvest due to land deforestation for agriculture should continue yielding non-zero anthropogenic product pools
land-noShiftcultivate	Same as ***land-hist*** except shifting cultivation turned off. Only relevant for models where default model treats shifting cultivation (see Figure 4)	An additional LUC transitions dataset will be provided as a data layer within LUMIP LUH2 dataset with shifting cultivation deactivated.
land-noFire	Same as ***land-hist*** but with anthropogenic ignition and suppression held to 1850 levels	For example, if ignitions are based on population density, maintain constant population density through simulation

Table 3: **Coupled Model** Phase 2 simulations, all Tier 1.

Experiment ID	Experiment Name	Experiment Description	Years
hist-noLu	Historical with no land-use change	Same as concentration-driven ***CMIP6 historical*** (Tier 1) except with LULCC held constant. See section 2.1 for explanation of no land use. Two additional ensemble members requested in Tier 2.	1850-2014
ssp370-ssp126Lu	SSP3-7 with SSP1-2.6 land use	Same as ScenarioMIP ***ssp370*** (SSP3-7 deforestation scenario, Tier 1) except use land use from ***ssp126*** (SSP1-2.6 afforestation scenario); concentration-driven. Two additional ensemble members requested (Tier 2) contingent on ScenarioMIP ***ssp370*** large ensemble (Tier 2) being completed	2015-2100
ssp126-ssp370Lu	SSP1-2.6 with SSP3-7 land use	Same as ScenarioMIP ***ssp126*** (SSP1-2.6 afforestation scenario, Tier 1) except use land use from ***ssp370*** (SSP3-7 deforestation scenario); concentration-driven.	2015-2100
esm-ssp585-	Emissions-driven	Same as C4MIP ***esm-ssp585*** (Tier 1) except use SSP1-2.6 land	2015-

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ssp126Lu	SSP5-8.5 with SSP1-2.6 land use	use (afforestation scenario); emission driven	2100

Table 4. Land-use tile types and abbreviations.

Land-use Tile Type	Land-Use Tile Abbreviation	Comment
Primary and secondary land	psl	Forest, grasslands, and bare ground
Cropland	crp	
Pastureland	pst	Includes managed pastureland and rangeland
Urban settlement	urb	

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Table 5. List of requested variables on land-use tiles. Note that this list may be updated. Modelers should refer to the CMIP6 variable request lists for the final list.

Variable short name	Variable Long Name	Comments
Biogeochemical and ecological variables		
gppLut	gross primary productivity on land use tile	
raLut	plant respiration on land use tile	
nppLut	net primary productivity on land use tile	
cTotFireLut	total carbon loss from natural and managed fire on land use tile, including deforestation fires	Different from LMON this flux should include all fires occurring on the land use tile, including natural, man-made and deforestation fires
rhLut	soil heterotrophic respiration on land use tile	
necbLut	net rate of C accumulation (or loss) on land use tile	Computed as npp minus heterotrophic respiration minus fire minus C leaching minus harvesting/clearing. Positive rate is into the land, negative rate is from the land. Do not include fluxes from anthropogenic pools to atmosphere
nwdFracLut	fraction of land use tile tile that is non-woody vegetation (e.g. herbaceous crops)	
Biogeophysical variables		
tasLut	near-surface air temperature (2m above displacement height, i.e. t_ref) on land use tile	
tslsiLut	surface 'skin' temperature on land use tile	temperature at which long-wave radiation emitted
hussLut	near-surface specific humidity on land use tile	Normally, the specific humidity should be reported at the 2 meter height
hflsLut	latent heat flux on land use tile	
hfssLut	sensible heat flux on land use tile	
rsusLut	surface upwelling shortwave on land use tile	
rlusLut	surface upwelling longwave on land use tile	
sweLut	snow water equivalent on land use tile	
laiLut	leaf area index on land use tile	Note that if tile does not model lai, for example, on the urban tile, then should be reported as missing value
mrsosLut	Moisture in Upper Portion of Soil Column of land use tile	the mass of water in all phases in a thin surface layer; integrate over uppermost 10cm
mrroLut	Total runoff from land use tile	the total runoff (including "drainage" through the base of the soil model) leaving the land use tile portion of the grid cell
mrsoLut	Total soil moisture	
irrLut	irrigation flux	
fahUrb	Anthropogenic heat flux	Anthropogenic heat flux due to human activities such as space heating and cooling or traffic or other energy consumption
LULCC fluxes and carbon transfers		
fProductDecompLut	flux from anthropogenic pools on land use tile into atmosphere	If a model has separate anthropogenic pools by land use tile
fLulccProductLut	carbon harvested due to land-use or land-cover change process that enters anthropogenic product pools on tile	This annual mean flux refers to the transfer of carbon primarily through harvesting land use into anthropogenic product pools, e.g.,deforestation or wood harvesting from primary or secondary lands, food harvesting on croplands, harvesting (grazing) by animals on pastures.
fLulccResidueLut	carbon transferred to soil or litter pools due to land-use or land-cover change processes on tile	This annual mean flux due refers to the transfer of carbon into soil or litter pools due to any land use or land-cover change activities
fLulccAtmLut	carbon transferred directly to atmosphere due to any land-use or land-cover change activities including deforestation or agricultural fire	This annual mean flux refers to the transfer of carbon directly to the atmosphere due to any land-use or land-cover change activities.
Carbon stock variables		
cSoilLut	carbon in soil pool on land use tiles	end of year values (not annual mean)

cVegLut	carbon in vegetation on land use tiles	end of year values (not annual mean)
cLitterLut	carbon in above and belowground litter pools on land use tiles	end of year values (not annual mean)
cAntLut	anthropogenic pools associated with land use tiles	anthropogenic pools associated with land use tiles into which harvests are deposited before release into atmosphere PLUS any remaining anthropogenic pools that may be associated with lands which were converted into land use tiles during reported period. Does NOT include residue which is deposited into soil or litter; end of year values (not annual mean)
LULCC fraction changes		
fracLut	fraction of grid cell for each land use tile	end of year values (not annual mean); note that fraction should be reported as fraction of land grid cell
fracOutLut	annual gross fraction of land use tile that was transferred into other land use tiles	cumulative annual fractional transitions out of each land use tile; for example, for primary and secondary land use tile, this would include all fractional transitions from primary and secondary land into cropland, pastureland, and urban for the year; note that fraction should be reported as fraction of land grid cell
fracInLut	annual gross fraction that was transferred into this tile from other land use tiles	cumulative annual fractional transitions into each land use tile; for example, for primary and secondary land use tile, this would include all fractional transitions from cropland, pastureland, and urban into primary and secondary land over the year; note that fraction should be reported as fraction of land grid cell

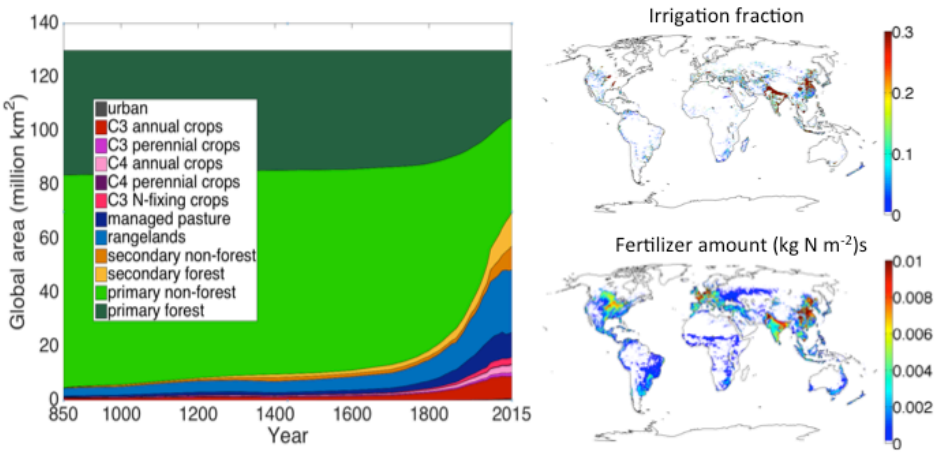

Figure 1. Time-series of global land area occupied by each LUH2 land-use state from 850 to 2015 (left). Note that extensions to 2100 for all of the ScenarioMIP SSPs will also be provided. Fraction of each 0.25° grid-cell that is irrigated in year 2015 (top right). Fertilizer applied in year 2015 (bottom right).

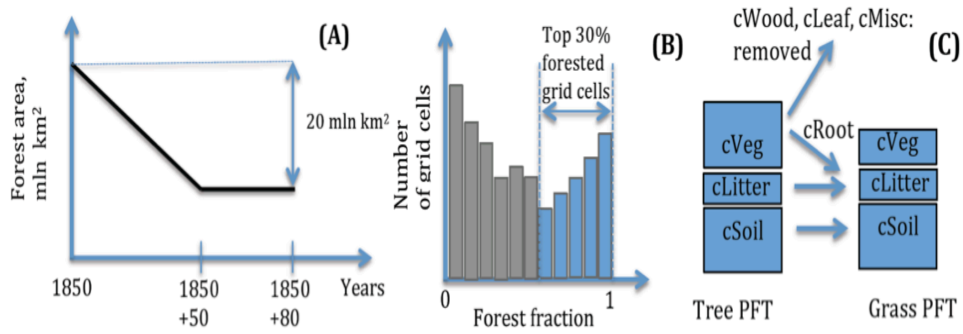

Figure 2. A schematic of experimental setup in the *deforest-glob* experiment. (A) Scenario of forced changes in the global forest area. (B) Sorting and selection of the grid cells that should be deforested. (C) Transition of carbon pools after deforestation.

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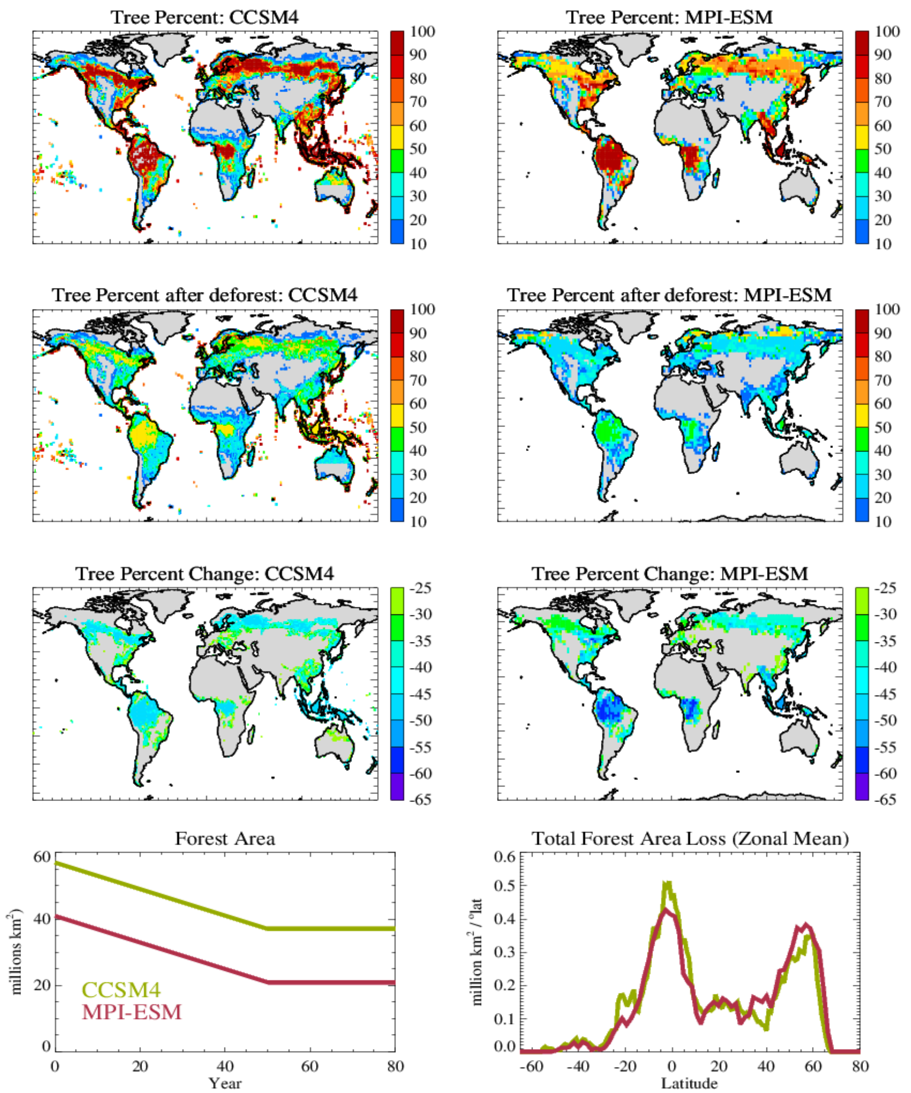

Figure 3: Sample maps of fraction of grid cell covered by trees at the start of the idealized deforestation simulation, after idealized deforestation (year 50), and the change in tree fraction by the end of the deforestation period. Time series of forest area and zonal mean forest area loss are also shown. Examples are shown for two typical CMIP5 models with strongly differing initial forest cover. Even with the different initial forest cover, the deforestation patterns and amounts are broadly equivalent across the two models.

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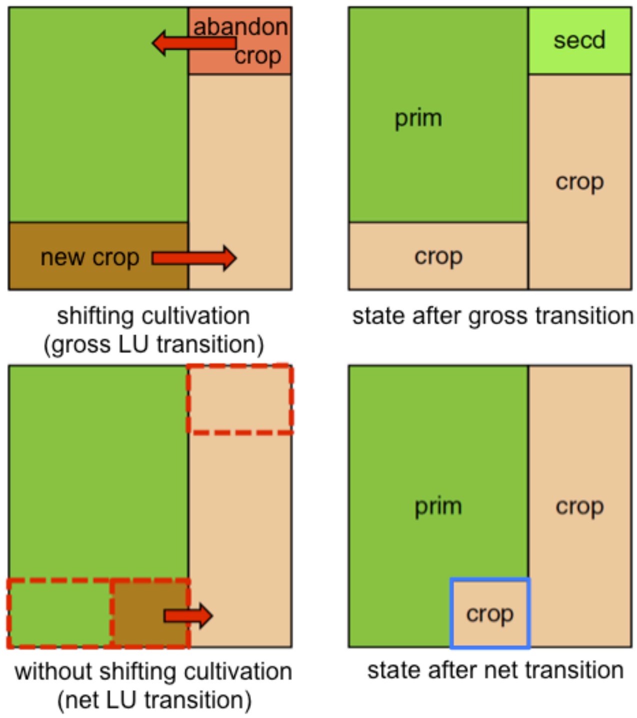

Figure 4. Schematic diagram showing difference between inclusion of shifting cultivation (gross transitions) versus exclusion of shifting cultivation (net transitions). Where shifting cultivation is included (upper row), new cropland (or pastureland) is taken (deforestation) from primary land ('prim') and abandoned to secondary land ('secd') in parallel within a grid cell. In this case carbon fluxes, for example, are captured for each transition. Where shifting cultivation is not represented (lower row), only the difference of new cropland minus abandoned cropland (represented by crop area outlined in blue in bottom right figure) undergoes a transition to cropland and no cropland is abandoned to form secondary land. In this case, a smaller grid cell area fraction is affected by LUC. Adapted from Figure 1 of Stocker et al. (2014).

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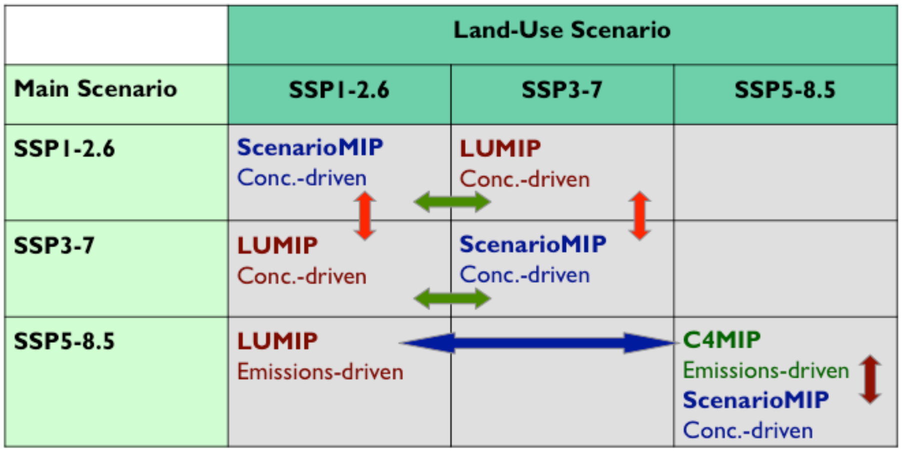

Figure 5: Schematic describing the future land-use policy sensitivity experiments. Green arrows indicate set of experiments that permit analysis of the biogeophysical climate impacts of projected land use and enable assessment of land management as a regional climate mitigation tool. Red arrows indicate set of experiments that allow study of how the impact of land-use change differs at different levels of climate change and at different levels of CO_2 concentration. Blue arrow indicates set of experiments that will enable quantification of the full effects of a different land-use scenario through both biophysical and biogeochemical processes. Brown arrows indicate set of experiments that allow quantification of the effects of the climate-carbon cycle feedback on future CO_2 and climate change.

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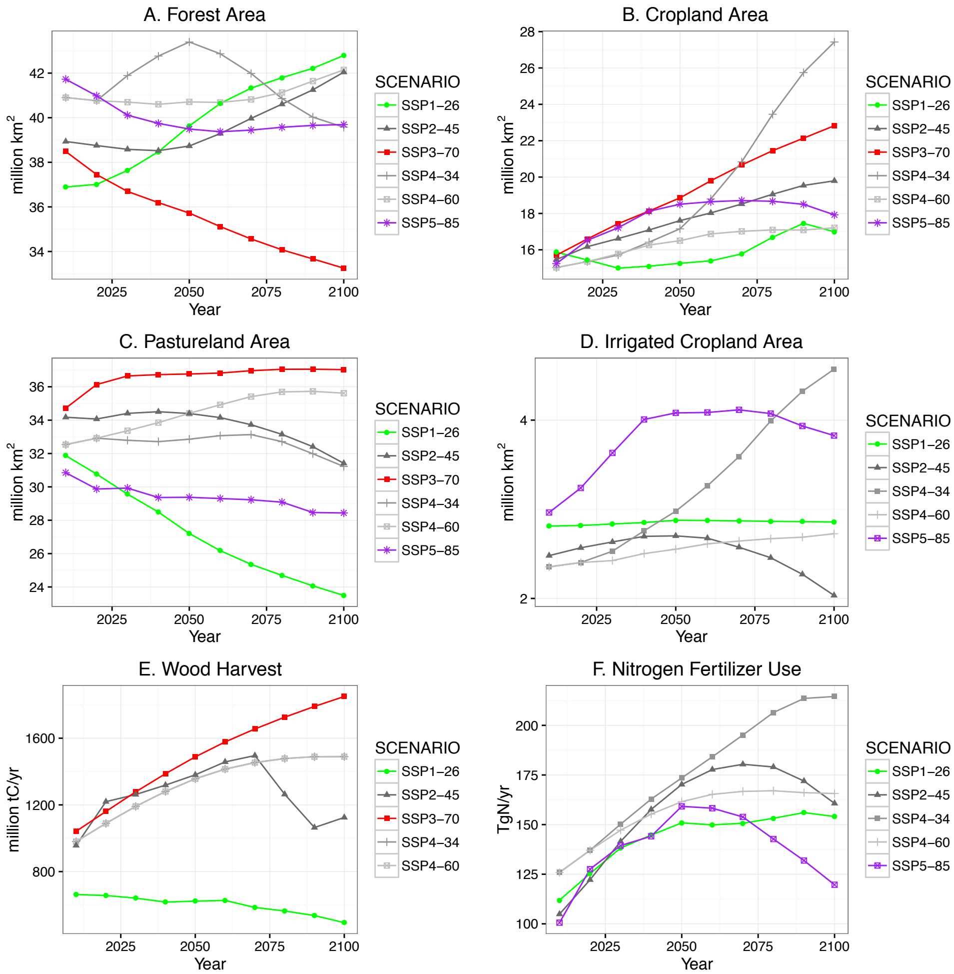

Figure 6: Global time series of land cover (A), land use (B, C, E), and land management (D, F) for the future simulations. Lines indicate SSP-RCP scenarios chosen for ScenarioMIP, with colored lines representing scenarios with specific LUMIP experiments. Data is provided by the IAM community (see Popp et al. 2016 for more details). Data will be harmonized to ensure consistency between the end of the historical period and the beginning of the projection period for each of the scenarios. Note that not all IAMs predict all the LUH2 land management quantities (e.g., wood harvest is missing for SSP5-8.5). The missing land management variables will be generated during the harmonization process in a manner that is consistent with the underlying scenario.

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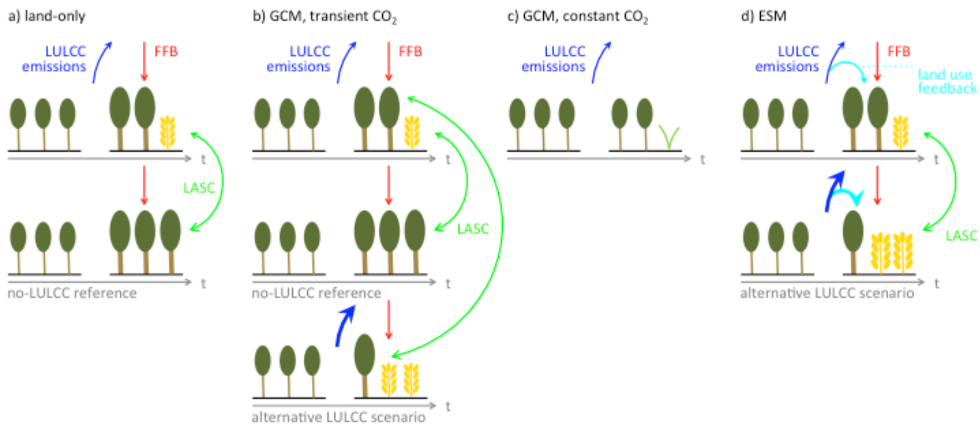

Figure 7: Illustration of the different setups used in the LUMIP experiments, using the example of forest replacement by cropland or grassland. The loss of additional sink capacity (LASC) is a factor when environmental conditions change transiently, which is the case when historical CO_2 concentrations, which implicitly include increases in CO_2 due to fossil-fuel burning (FFB) and LULCC, are prescribed from observations. Prognostic LULCC emissions are directly "seen" by the terrestrial vegetation (natural and anthropogenic) only in the ESM setup, where CO_2 is interactive. In this case, a fraction of the LULCC emissions is taken up again by the vegetation ("land-use carbon feedback"). Note that only atmospheric CO_2 is prescribed in a-c, while other environmental conditions feed back with LULCC's biogeophysical effects.

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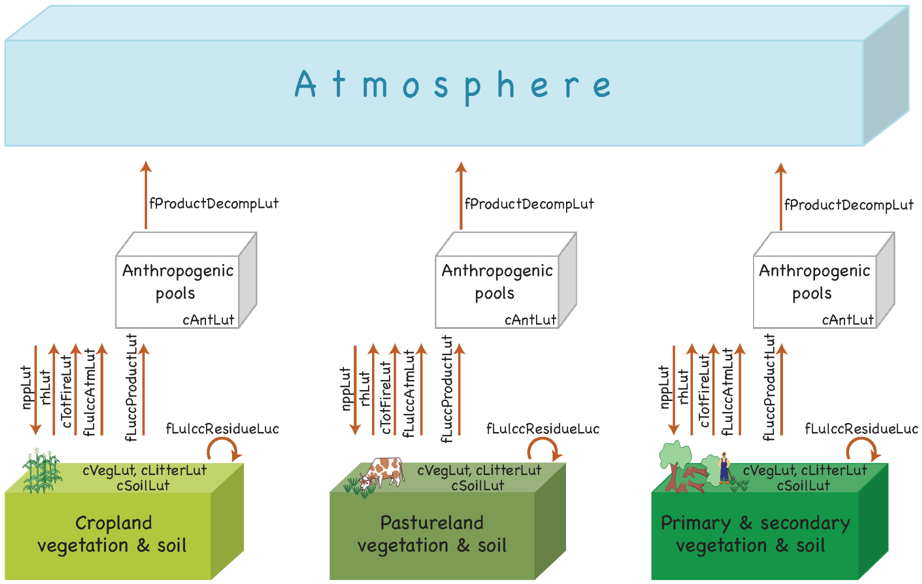

Figure 8. Exchanges and transfers affecting storage of biogeochemical constituents in land models under LULCC. Variable descriptions can be found in Table 5. Urban tile not shown, but if carbon fluxes are calculated on a particular model's urban tile, then these fluxes should be reported for urban tile as well.

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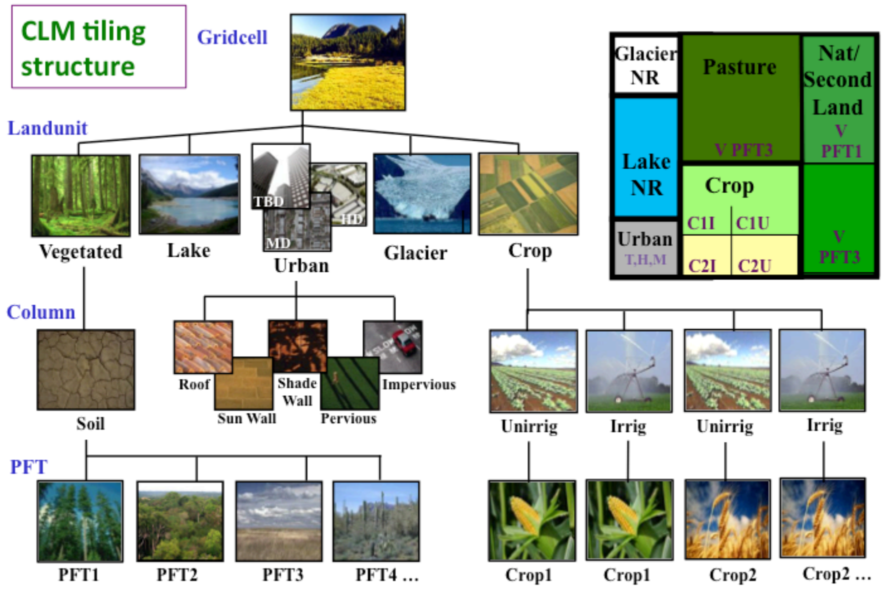

Figure 9. CLM tiling structure (Figure 8, Oleson et al. 2013). Subgrid aggregation: PSL = Vegetated land unit including all PFTs and bare soil; CRP = Crop land unit including all crop types irrigated (I) and non-irrigated (U); PST = not explicitly represented in CLM, report as missing value; URB = weighted average of Tall Building District, High Density, and Medium Density types in Urban landunit. Glacier and Lake are not reported.

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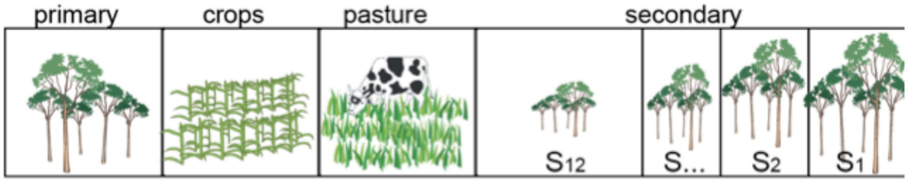

Figure 10. In the GFDL ESM2M and ESM2G CMIP5 simulations each grid cell has up to 15 land tiles, including lakes, glaciers, croplands, pasturelands, primary, and up to 10 secondary vegetation tiles. All GFDL models use gross transitions from the LULCC scenarios. The secondary vegetation tiles are generated by wood harvesting (primary to secondary and secondary to secondary transitions) as well as by agricultural abandonment (croplands to secondary and pastures to secondary transitions). Each land-use tile has its own C anthropogenic pool and separate above- and below-ground C stores. For LUMIP, all variables on primary and secondary tiles will be aggregated and reported under the PSL tile. Urban is not represented and will be reported as missing values. Glaciers and lakes are not reported.

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