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

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Geoscientific Model Development Discussions

Abstract

Human land-use activities have resulted in large 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 and/or adapt to 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 land-use change relative to fossil fuel emissions, 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-. In this paper, we describe the LUMIP simulations that will formally be part of CMIP6. These experiments are explicitly designed to be complementary to experiments from the CMIP core, ScenarioMIP, and C4MIP. LUMIP includes a two-phase experimental design. Phase one features idealized coupled and land-only model experiments 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 (primary and secondary land, crops, pasture, urban). It is essential that modeling groups participating in LUMIP adhere to the experimental design as closely as possible.

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 is 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 global impact of land-cover change on, for example 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 ~40% of the total 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 are numerous. 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) and cooling trends associated with irrigation area expansion has likely offset warming due to greenhouse gas increases in some regions (Lobell et al. 2008a). Levis et al. (2012) showed that including a prognostic crop model into a global climate model (GCM) can improve the seasonality of surface fluxes and net ecosystem exchange and thereby directly impact weather and climate and the carbon cycle. 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 (Pugh et al. 2015). There is also 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). The carbon flux due to wood harvest can amount to an equivalent of up to 15% of the forest net primary production in strongly managed regions such as Europe (Luyssaert et al. 2010). 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). Awareness that land management can impact climate has lead 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 LUCID (de Noblet-Ducoudré et al. 2012; Pitman et al. 2009), LUC4C (http://luc4c.eu/), TRENDY (http://dgvm.ceh.ac.uk/node/9), and 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 and are there regional land management strategies with promise to help mitigate and/or adapt to 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 land-use change relative to fossil fuel emissions, (2) separation of biogeochemical from biogeophysical effects of land-use, (3) the unique impacts of land-cover change versus land management change, (4) modulation of land-use impact on climate by land-atmosphere coupling strength, and (5) the extent that direct effects of enhanced CO_2 concentrations on plant photosynthesis (changes in water-use efficiency and/or plant growth) 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 RCP4.5 afforestation scenario did not translate as such in land-cover datasets applied in CESM simulations (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

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Manuscript under review for journal Geosci. Model Dev.
Published: 12 April 2016

Geoscientific Model Development Discussions

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. Future scenarios (years 2016-2100) will also include biofuel management layers. The LUH2 dataset will be available through the LUMIP website (https://cmip.ucar.edu/lumip) and PCMDI and will be described in a separate publication in this CMIP6 Special Issue.

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 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 multiple land-use tiles (primary and secondary land, crops, pastureland, urban; see Section 4).

Geosci. Model Dev. Discuss., doi:10.5194/gmd-2016-76, 2016
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Published: 12 April 2016

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" (Trenberth and Asrar 2014), 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, pastureland, or urban areas. Land use is the "purpose for which humans exploit the land cover"; e.g., a pastureland may be mowed or left in its natural state. 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 wood harvest. Thus, within the same land-cover category several land uses can occur, and 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. Further, land-cover change can also be driven by natural processes such as a change of the biogeographic vegetation distribution due to climate shifts, so that "climate-induced" and "anthropogenic" land-cover change (ALCC) can be distinguished (Davies-Barnard et al. 2015; Schneck et al. 2013). The term "LULCC" includes ALCC only.

2. Experimental design and description

In this section, we begin with a discussion and recommendations on the specification of land use in CMIP6 DECK ands historical experiments, and other MIP experiments and we outline the full set of requested LUMIP experiments. LUMIP includes a two phase, tiered, model experiment plan. Phase one features coupled model idealized deforestation experiments designed to advance process-level understanding and to quantify model sensitivity to land-cover change impacts on climate and biogeochemical cycles. Phase one also includes a factorial set of land-only model experiments that allow assessment of the forced-response of land-cover change on land-to-atmosphere fluxes as well as examination of the impacts of various land-management practices. Phase two

Geosci. Model Dev. Discuss., doi:10.5194/gmd-2016-76, 2016
Manuscript under review for journal Geosci. Model Dev.
Published: 12 April 2016

Geoscientific Model Development Discussions

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 included below. The total request includes:

- Tier 1: 520 years GCM/ESM; 650 years land-only
- Tier 2: 330 years GCM/ESM; up to 1500 years land-only

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

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 "constant land use", as is required in several CMIP6 simulations including (1) DECK experiments - 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*), (2) idealized LUMIP deforestation experiments (Section 2.2.1) and no land-use change experiments (Section 2.3.1), and (3) idealized C4MIP experiments - biogeochemically-coupled 1%yr^{-1} CO_2 increase (*1pctCO2-bgc*) and other C4MIP Tier 2 idealized experiments, and (4) extension experiments for ScenarioMIP 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 relevant year. The fraction of cropland and pastureland, as well as the crop type distribution should remain constant. Any land management (e.g., irrigation, fertilization) that exists for the constant land use year should be maintained at the same level if. 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 appropriate for 1850, level of irrigation,

Geosci. Model Dev. Discuss., doi:10.5194/gmd-2016-76, 2016
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Published: 12 April 2016

Geoscientific Model Development Discussions

wood harvest, and gross transitions exceeding net transitions. 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. 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.

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 in 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.

2.2. Phase 1 experiments

Phase 1 consists of two sets of experiments: (a) idealized coupled deforestation experiments that enable 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

Geosci. Model Dev. Discuss., doi:10.5194/gmd-2016-76, 2016
Manuscript under review for journal Geosci. Model Dev.
Published: 12 April 2016

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 (Fig X, A). 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. In order to concentrate the deforestation from grid cells with predominant forest cover, deforestation should be restricted to 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 2). To do this:

1. Sort land grid cells by forest area and select the top 30% (*gcdef*, Figure X, B).
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*) in the year *t* ($1 \le t \le 80$), *A(x,y)* is the area of the grid cell (million km^2). The total forest area, F_{tot} (million km^2) of the grid cells identified for deforestation (*gcdef*) in Step 1 is:

$$F_{tot} = \sum_{gcdef} f(x,y,1850) A(x,y) \qquad (1)$$

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

$$k_{gcdef} = \frac{20}{F_{tot}} \le 1 \; k_{gcdef} = \frac{20}{F_{tot}} \le 1$$

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

$$f(x,y,t) = \begin{cases} f(x,y,1850)(1 - \frac{k_{gcdef} t}{50}) & t \le 50 \\ f(x,y,1850)(1 - k_{gcdef}) & t > 50 \end{cases} \qquad (2)$$

If F_{max} is less than 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 X, C). 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 is less than 20 million km^2 then model should linearly remove all the forested area over 50 years. Note that even with substantially different initial forest cover in CCSM4 versus MPI-

Geosci. Model Dev. Discuss., doi:10.5194/gmd-2016-76, 2016
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Published: 12 April 2016

Geoscientific Model Development Discussions

ESM-P, the examples shown in Figure 2, the prescribed land-cover change is quite similar under this 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. 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 X. 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 2 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 deforestation simulations (Bala et al. 2007; Bathiany et al. 2010; Davin and de Noblet-Ducoudré 2010) have proven informative and highlighted how both biogeophysical and biogeochemical forcings due to land-use change contribute to temperature changes and how the ocean can modulate the response. 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-alt-start-year* and *land-NoLu* are Tier 1, all others Tier 2, up to X simulations, 165 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 experiment differing from the *land-hist* experiment in terms of the specific treatment of land use or land management, or in terms of prescribed climate. Note that all experiments should be performed with the GSWP3 forcing dataset provided through LS3MIP. Two of the experiments - *land-hist-alt-start-year* and *land-hist-NoLu* - are Tier 1. The remaining experiments are Tier 2.

Geosci. Model Dev. Discuss., doi:10.5194/gmd-2016-76, 2016
Manuscript under review for journal Geosci. Model Dev.
Published: 12 April 2016

Geoscientific Model Development Discussions

Detailed descriptions of the factorial set of experiments 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 have a more advanced 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. Note that all models and simulations, apart from the TRENDY simulations isolating effects of climate change, will be forced with the same historical climate, which enables clean comparison across models. 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 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. They further allow quantification of the net LULCC flux, in the definition used in TRENDY that excludes the land-use feedback but accounts for the loss of additional carbon sink capacity.

(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-1700* 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 including shifting cultivation 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 al. 2014). For models that can represent gross transitions by default, a parallel experiment in which only net transitions are included will allow evaluation of the impact of gross versus net transitions across a range of models and assumptions.

(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 GCM simulations allows assessment of consequences of model climate biases on LULCC effects.

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 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 errors may actually be a function of errors in the forcing dataset rather than the model. While the planned land-only LUMIP experiments will only be driven with a single forcing dataset (the reference dataset used in the *land-hist* experiment of LS3MIP), the sensitivity of the representation of land processes to such variations 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 and CMIP6 Historical 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 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 (i.e., 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 (*ssp37-ssp126Lu* and *ssp126-ssp37Lu*, GCM concentration-driven, Tier 1, 2015-2100; *esm-ssp585-ssp126Lu*, ESM emission-driven, Tier 1, 2015-2100)

Description: These experiments are derivatives of ScenarioMIP (*ssp37* and *ssp126*) and C4MIP (*esm-ssp85*) simulations (Figure 3). 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 *ssp37* and *ssp126* are required but each using the land-use scenario from the other: i.e., LUMIP simulation *ssp37-ssp126Lu* will run with all forcings identical to *ssp37* except for land use which is to be taken from *ssp126* (see below for short description of the SSP land-use scenarios). These simulations permit analysis of the biogeophysical climate impacts of projected land use and enable assessment of land management as a regional climate mitigation tool (green arrows on Figure 3). 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 4). 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 3). These sets of experiments can be utilized to further inform 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 3). 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 3).

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 4 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

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 for land surface model evaluation in general (sometimes referred to as benchmarking) 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; Kumar et al. 2012; Lejeune et al. 2016; Luo et al. 2012). 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).

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 both in terms of seasonal mean differences (and their statistical significance based on student-t tests) and in terms of signal to noise (where 'noise' refers to the natural interannual climate variability simulated in the model).

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

Geosci. Model Dev. Discuss., doi:10.5194/gmd-2016-76, 2016
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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 derived from emission-driven simulations (which include the land-use carbon feedback) compared to land-only simulations (Pongratz et al. 2014; Stocker and Joos 2015).

Within LUMIP, several different model configurations are used that include the LASC and land-use feedback to different extents (Figure 5). 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 experiment or one applying an alternative LULCC scenario. In the case of the idealized deforestation experiments, where CO_2 is kept constant over time, all changes since the beginning of the simulation are attributable to LULCC. The net LULCC flux as quantified from the land-only simulation will differ slightly from that calculated in GCM simulations in that they include biogeophysical feedbacks from land-use change, as only atmospheric CO_2 is prescribed, while all other environmental conditions are responding to 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 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; Myhre et al. 2013). 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 (Jones et al. 2013a). 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 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 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 benchmarking will be necessary to validate the inferred relationships, given partly contradicting results regarding the effects of LULCC on climate extremes in models and observations (Lejeune et al. 2016; Teuling et al. 2010).

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 requesting sub-grid information *for four sub-grid categories* (i.e., tiles) to permit more detailed analysis of land-use induced surface

Geosci. Model Dev. Discuss., doi:10.5194/gmd-2016-76, 2016
Manuscript under review for journal Geosci. Model Dev.
Published: 12 April 2016

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

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, and (e) carbon stocks on land-use tiles (Figures 6 and 7). The full list of requested land-use tile variables is found in the LUMIP CMIP6 variable request.

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.

Geosci. Model Dev. Discuss., doi:10.5194/gmd-2016-76, 2016
Manuscript under review for journal Geosci. Model Dev.
Published: 12 April 2016

Geoscientific Model Development Discussions

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 8, 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

Geosci. Model Dev. Discuss., doi:10.5194/gmd-2016-76, 2016
Manuscript under review for journal Geosci. Model Dev.
Published: 12 April 2016

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. 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 evaluate the potential of land 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 land-use change relative to fossil fuel emissions, 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, 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.

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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6. References

Abramowitz, G., 2012: Towards a public, standardized, diagnostic benchmarking system for land surface models. *Geosci. Mod. Dev.*, **5,** 819-827.

Andrews, T., R. Betts, B. Booth, C. D. Jones, and G. S. Jones, 2016: Effective radiative forcing from historical land use change. *Submitted to J. Clim.*

Arora, V., and G. Boer, 2010: Uncertainties in the 20th century carbon budget associated with land use change. *Glob. Change Biol.*, **16,** 3327-3348.

Bala, G., K. Caldeira, M. Wickett, T. Phillips, D. Lobell, C. Delire, and A. Mirin, 2007: Combined climate and carbon-cycle effects of large-scale deforestation. *Proceedings of the National Academy of Sciences*, **104,** 6550-6555.

Bathiany, S., M. Claussen, V. Brovkin, T. Raddatz, and V. Gayler, 2010: Combined biogeophysical and biogeochemical effects of large-scale forest cover changes in the MPI earth system model. *Biogeosciences*, **7,** 1383-1399.

Boisier, J., N. de Noblet-Ducoudré, and P. Ciais, 2013: Inferring past land use-induced changes in surface albedo from satellite observations: a useful tool to evaluate model simulations. *Biogeosciences*, **10,** 1501-1516.

——, 2014: Historical land-use-induced evapotranspiration changes estimated from present-day observations and reconstructed land-cover maps. *Hydrol. Earth Syst. Sci.*, **18,** 3571-3590.

Boisier, J., N. d. Noblet-Ducoudré, A. Pitman, F. Cruz, C. Delire, B. den Hurk, M. Molen, C. Müller, and A. Voldoire, 2012: Attributing the impacts of land-cover changes in temperate regions on surface temperature and heat fluxes to specific causes: results from the first LUCID set of simulations. *J. Geophys. Res.*, **117**.

Bonan, G. B., 2008: Forests and climate change: forcings, feedbacks, and the climate benefits of forests. *Science*, **320,** 1444-1449.

Boucher, O., G. Myhre, and A. Myhre, 2004: Direct human influence of irrigation on atmospheric water vapour and climate. *Clim. Dyn.*, **22,** 597-603.

Boysen, L., V. Brovkin, V. Arora, P. Cadule, N. de Noblet-Ducoudré, E. Kato, J. Pongratz, and V. Gayler, 2014: Global and regional effects of land-use change on climate in 21st century simulations with interactive carbon cycle. *Earth System Dynamics*, **5,** 309-319.

Brovkin, V., L. Boysen, V. Arora, J. Boisier, P. Cadule, L. Chini, M. Claussen, P. Friedlingstein, V. Gayler, and B. Van Den Hurk, 2013: Effect of anthropogenic land-use and land-cover changes on climate and land carbon storage in CMIP5 projections for the twenty-first century. *J. Clim.*, **26,** 6859-6881.

Canadell, J. G., and M. R. Raupach, 2008: Managing forests for climate change mitigation. *Science*, **320,** 1456-1457.

Canadell, J. G., C. Le Quéré, M. R. Raupach, C. B. Field, E. T. Buitenhuis, P. Ciais, T. J. Conway, N. P. Gillett, R. Houghton, and G. Marland, 2007: Contributions to accelerating atmospheric CO2 growth from economic activity, carbon intensity, and efficiency of natural sinks. *Proceedings of the national academy of sciences*, **104,** 18866-18870.

Chen, L., and P. A. Dirmeyer, 2016: Adapting observationally based metrics of biogeophysical feedbacks from land cover/land use change to climate modeling. *Environ. Res. Lett.*, **11,** 034002.

Christidis, N., P. A. Stott, G. C. Hegerl, and R. A. Betts, 2013: The role of land use change in the recent warming of daily extreme temperatures. *Geophys. Res. Lett.*, **40,** 589-594.

Ciais, P., C. Sabine, G. Bala, L. Bopp, V. Brovkin, J. Canadell, A. Chhabra, R. DeFries, J. Galloway, and M. Heimann, 2014: Carbon and other biogeochemical cycles. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, 465-570.

Davies-Barnard, T., P. Valdes, J. S. Singarayer, A. Wiltshire, and C. Jones, 2015: Quantifying the relative importance of land cover change from climate and land use in the representative concentration pathways. *Global Biogeochem. Cycles*, **29,** 842-853.

Davin, E., N. de Noblet-Ducoudré, and P. Friedlingstein, 2007: Impact of land cover change on surface climate: Relevance of the radiative forcing concept. *Geophys. Res. Lett.*, **34**.

Davin, E. L., and N. de Noblet-Ducoudré, 2010: Climatic impact of global-scale deforestation: Radiative versus nonradiative processes. *J. Clim.*, **23,** 97-112.

Davin, E. L., S. I. Seneviratne, P. Ciais, A. Olioso, and T. Wang, 2014: Preferential cooling of hot extremes from cropland albedo management. *Proceedings of the National Academy of Sciences*, **111,** 9757-9761.

de Noblet-Ducoudré, N., J.-P. Boisier, A. Pitman, G. Bonan, V. Brovkin, F. Cruz, C. Delire, V. Gayler, B. Van den Hurk, and P. Lawrence, 2012: Determining robust impacts of land-use-induced land cover changes on surface climate over North America and Eurasia: results from the first set of LUCID experiments. *J. Clim.*, **25,** 3261-3281.

Di Vittorio, A., L. Chini, B. Bond-Lamberty, J. Mao, X. Shi, J. Truesdale, A. Craig, K. Calvin, A. Jones, and W. D. Collins, 2014: From land use to land cover: restoring the afforestation signal in a coupled integrated assessment–earth system model and the implications for CMIP5 RCP simulations. *Biogeosciences*, **11,** 6435-6450.

Dirmeyer, P. A., Z. Wang, M. J. Mbuh, and H. E. Norton, 2014: Intensified land surface control on boundary layer growth in a changing climate. *Geophys. Res. Lett.*, **41,** 1290-1294.

Eyring, V., S. Bony, G. Meehl, C. Senior, B. Stevens, R. Stouffer, and K. Taylor, 2015: Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organisation. *Geosci. Mod. Dev.*

Fischer, E., K. Oleson, and D. Lawrence, 2012: Contrasting urban and rural heat stress responses to climate change. *Geophys. Res. Lett.*, **39**.

Foley, J. A., N. Ramankutty, K. A. Brauman, E. S. Cassidy, J. S. Gerber, M. Johnston, N. D. Mueller, C. O'Connell, D. K. Ray, and P. C. West, 2011: Solutions for a cultivated planet. *Nature*, **478,** 337-342.

Fujimori, S., T. Hasegawa, T. Masui, K. Takahashi, D. S. Herran, H. Dai, Y. Hijoka, and M. Kainuma, 2016: SSP3: AIM Implementation of Shared Socioeconomic Pathways. *Submitted to Global Environmental Change*.

Gerber, S., L. O. Hedin, S. G. Keel, S. W. Pacala, and E. Shevliakova, 2013: Land use change and nitrogen feedbacks constrain the trajectory of the land carbon sink. *Geophys. Res. Lett.*, **40,** 5218-5222.

Gillett, N. P., 2016: Detectation and attribution MIP documentation paper. *in prep for this CMIP special issue of GMD*.

Gitz, V., and P. Ciais, 2003: Amplifying effects of land-use change on future atmospheric CO2 levels. *Global Biogeochem. Cycles*, **17**.

Gray, J. M., S. Frolking, E. A. Kort, D. K. Ray, C. J. Kucharik, N. Ramankutty, and M. A. Friedl, 2014: Direct human influence on atmospheric CO2 seasonality from increased cropland productivity. *Nature*, **515,** 398-401.

Greve, P., B. Orlowsky, B. Mueller, J. Sheffield, M. Reichstein, and S. I. Seneviratne, 2014: Global assessment of trends in wetting and drying over land. *Nat. Geosci.*, **7,** 716-721.

Guo, Z., P. A. Dirmeyer, R. D. Koster, Y. Sud, G. Bonan, K. W. Oleson, E. Chan, D. Verseghy, P. Cox, and C. Gordon, 2006: GLACE: the global land-atmosphere coupling experiment. Part II: analysis. *J. Hydrometeorol.*, **7,** 611-625.

Hansen, M. C., P. V. Potapov, R. Moore, M. Hancher, S. Turubanova, A. Tyukavina, D. Thau, S. Stehman, S. Goetz, and T. Loveland, 2013: High-resolution global maps of 21st-century forest cover change. *Science*, **342,** 850-853.

Hansis, E., S. J. Davis, and J. Pongratz, 2015: Relevance of methodological choices for accounting of land use change carbon fluxes. *Global Biogeochem. Cycles*, **29,** 1230-1246.

Hirsch, A. L., A. Pitman, J. Kala, R. Lorenz, and M. Donat, 2015: Modulation of Land-Use Change Impacts on Temperature Extremes via Land–Atmosphere Coupling over Australia. *Earth Interact.*, **19,** 1-24.

Houghton, R. A., 2003: Revised estimates of the annual net flux of carbon to the atmosphere from changes in land use and land management 1850–2000. *Tellus B*, **55,** 378-390.

Houghton, R. A., J. House, J. Pongratz, G. Van der Werf, R. DeFries, M. Hansen, C. L. Quéré, and N. Ramankutty, 2012: Carbon emissions from land use and land-cover change. *Biogeosciences*, **9,** 5125-5142.

Hurtt, G., L. P. Chini, S. Frolking, R. Betts, J. Feddema, G. Fischer, J. Fisk, K. Hibbard, R. Houghton, and A. Janetos, 2011: Harmonization of land-use scenarios for the period 1500–2100: 600 years of global gridded annual land-use transitions, wood harvest, and resulting secondary lands. *Clim. Change*, **109,** 117-161.

Jensen, M., W. Rangeley, and P. Dieleman, 1990: Irrigation trends in world agriculture. *Agronomy***,** 31-67.

Jones, A. D., W. D. Collins, and M. S. Torn, 2013a: On the additivity of radiative forcing between land use change and greenhouse gases. *Geophys. Res. Lett.*, **40,** 4036-4041.

Jones, A. D., W. D. Collins, J. Edmonds, M. S. Torn, A. Janetos, K. V. Calvin, A. Thomson, L. P. Chini, J. Mao, and X. Shi, 2013b: Greenhouse gas policy influences climate via direct effects of land-use change. *J. Clim.*, **26,** 3657-3670.

Jones, C. D., V. Arora, P. Friedlingstein, L. Bopp, V. Brovkin, J. Dunne, H. Graven, F. Hoffman, T. Ilyina, J. G. John, M. Jung, M. Kawamiya, C. Koven, J. Pongratz, T. Raddatz, J. Randerson, and S. Zaehle, 2016: The C4MIP experimental protocol for CMIP6 *Submitted to GMD*.

Klein Goldewijk, K., A. Beusen, G. Van Drecht, and M. De Vos, 2011: The HYDE 3.1 spatially explicit database of human-induced global land-use change over the past 12,000 years. *Global Ecol. Biogeogr.*, **20,** 73-86.

Koster, R. D., P. A. Dirmeyer, Z. Guo, G. Bonan, E. Chan, P. Cox, C. Gordon, S. Kanae, E. Kowalczyk, and D. Lawrence, 2004: Regions of strong coupling between soil moisture and precipitation. *Science*, **305,** 1138-1140.

Kriegler et al., E., 2016: Fossil-fueled development (SSP5): an energy and resource intensive scenario for the 21st century. *Submitted to Global Environmental Change*.

Kumar, S., P. A. Dirmeyer, V. Merwade, T. DelSole, J. M. Adams, and D. Niyogi, 2013: Land use/cover change impacts in CMIP5 climate simulations: A new methodology and 21st century challenges. *J. Geophys. Res.*, **118,** 6337-6353.

Kumar, S. V., C. D. Peters-Lidard, J. Santanello, K. Harrison, Y. Liu, and M. Shaw, 2012: Land surface Verification Toolkit (LVT)–a generalized framework for land surface model evaluation. *Geosci. Mod. Dev.*, **5,** 869-886.

Lambin, E. F., H. Geist, and R. R. Rindfuss, 2006: Introduction: local processes with global impacts. *Land-use and land-cover change*, Springer, 1-8.

Lawrence, D. M., K. W. Oleson, M. G. Flanner, P. E. Thornton, S. C. Swenson, P. J. Lawrence, X. Zeng, Z. L. Yang, S. Levis, and K. Sakaguchi, 2011: Parameterization improvements and functional and structural advances in version 4 of the Community Land Model. *J. Adv. Mod. Earth Sys.*, **3**.

Lawrence, P. J., J. J. Feddema, G. B. Bonan, G. A. Meehl, B. C. O'Neill, K. W. Oleson, S. Levis, D. M. Lawrence, E. Kluzek, K. Lindsay, and P. E. Thornton, 2012: Simulating the Biogeochemical and Biogeophysical Impacts of Transient Land Cover Change and Wood Harvest in the Community Climate System Model (CCSM4) from 1850 to 2100. *J. Clim.*, **25,** 3071-3095, doi:10.1175/jcli-d-11-00256.1.

Lee, X., M. L. Goulden, D. Y. Hollinger, A. Barr, T. A. Black, G. Bohrer, R. Bracho, B. Drake, A. Goldstein, and L. Gu, 2011: Observed increase in local cooling effect of deforestation at higher latitudes. *Nature*, **479,** 384-387.

Lejeune, Q., S. I. Seneviratne, and E. L. Davin, 2016: Comparative assessment of mid-latitude land-cover change effects on temperature in historical LUCID and CMIP5 simulations. *Submitted to J.Climate*.

Levis, S., G. B. Bonan, E. Kluzek, P. E. Thornton, A. Jones, W. J. Sacks, and C. J. Kucharik, 2012: Interactive crop management in the Community Earth System Model (CESM1): Seasonal influences on land-atmosphere fluxes. *J. Clim.*, **25,** 4839-4859.

Li, Y., M. Zhao, S. Motesharrei, Q. Mu, E. Kalnay, and S. Li, 2015: Local cooling and warming effects of forests based on satellite observations. *Nature communications*, **6**.

Li, Y., N. De Noblet-Ducoudré, E. L. Davin, S. Motesharrei, N. Zeng, S. Li, and E. Kalnay, 2016: The role of spatial scale and background climate in the latitudinal temperature response to deforestation. *Earth Syst. Dynam.*, **7,** 167-181, doi:10.5194/esd-7-167-2016.

Lobell, D. B., C. Bonfils, and J.-M. Faurès, 2008a: The role of irrigation expansion in past and future temperature trends. *Earth Interact.*, **12,** 1-11.

Lobell, D. B., C. J. Bonfils, L. M. Kueppers, and M. A. Snyder, 2008b: Irrigation cooling effect on temperature and heat index extremes. *Geophys. Res. Lett.*, **35**.

Lorenz, R., and A. J. Pitman, 2014: Effect of land-atmosphere coupling strength on impacts from Amazonian deforestation. *Geophys. Res. Lett.*, **41,** 5987-5995.

Luo, Y. Q., J. T. Randerson, G. Abramowitz, C. Bacour, E. Blyth, N. Carvalhais, P. Ciais, D. Dalmonech, J. B. Fisher, R. Fisher, P. Friedlingstein, K. Hibbard, F. Hoffman, D. Huntzinger, C. D. Jones, C. Koven, D. Lawrence, D. J. Li, M. Mahecha, S. L. Niu, R. Norby, S. L. Piao, X. Qi, P. Peylin, I. C. Prentice, W. Riley, M. Reichstein, C. Schwalm, Y. P. Wang, J. Y. Xia, S. Zaehle, and X. H. Zhou, 2012: A framework for benchmarking land models. *Biogeosciences*, **9,** 3857-3874, doi:10.5194/bg-9-3857-2012.

Luyssaert, S., P. Ciais, S. Piao, E. D. SCHULZE, M. Jung, S. Zaehle, M. Schelhaas, M. Reichstein, G. Churkina, and D. Papale, 2010: The European carbon balance. Part 3: forests. *Glob. Change Biol.*, **16,** 1429-1450.

Luyssaert, S., M. Jammet, P. C. Stoy, S. Estel, J. Pongratz, E. Ceschia, G. Churkina, A. Don, K. Erb, and M. Ferlicoq, 2014: Land management and land-cover change have impacts of similar magnitude on surface temperature. *Nat. Clim. Change*, **4,** 389-393.

Mahowald, N., K. Lindsey, E. Munoz, S. C. Doney, P. J. Lawrence, S. Schlunegger, D. Ward, D. M. Lawrence, and F. Hoffman, 2016: Interactions between land use change and carbon cycle feedbacks. . *Submitted to GBC*.

Malyshev, S., E. Shevliakova, R. J. Stouffer, and S. W. Pacala, 2015: Contrasting Local versus Regional Effects of Land-Use-Change-Induced Heterogeneity on Historical Climate: Analysis with the GFDL Earth System Model. *J. Clim.*, **28,** 5448-5469.

Marland, G., R. A. Pielke Sr, M. Apps, R. Avissar, R. A. Betts, K. J. Davis, P. C. Frumhoff, S. T. Jackson, L. A. Joyce, and P. Kauppi, 2003: The climatic impacts of land surface change and carbon management, and the implications for climate-change mitigation policy. *Climate policy*, **3,** 149-157.

Monfreda, C., N. Ramankutty, and J. A. Foley, 2008: Farming the planet: 2. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000. *Global Biogeochem. Cycles*, **22**.

Mueller, N. D., E. E. Butler, K. A. McKinnon, A. Rhines, M. Tingley, N. M. Holbrook, and P. Huybers, 2015: Cooling of US Midwest summer temperature extremes from cropland intensification. *Nat. Clim. Change*.

Myhre, G., D. Shindell, F.-M. Bréon, W. Collins, J. Fuglestvedt, J. Huang, D. Koch, J.-F. Lamarque, D. Lee, B. Mendoza, T. Nakajima, A. Robock, G. Stephens, T. Takemura, and H. Zhang, 2013: Anthropogenic and Natural Radiative Forcing. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley, Ed.

O'Neill, B. O., 2016: ScenarioMIP documentation paper. *in prep for this CMIP special issue of GMD*.

Oleson, K. W., D. M. Lawrence, G. B. Bonan, B. Drewniak, M. Huang, C. D. KOven, S. Levis, F. Li, W. J. Riley, Z. M. Subin, S. C. Swenson, and P. E. Thornton, 2013: Technical Description of version 4.5 of the Community Land Model (CLM). Ncar Technical Note NCAR/TN-503+STR, National Center for Atmospheric Research, Boulder, CO, 422 pp., DOI: 10.5065/D6RR1W7M (http://www.cesm.ucar.edu/models/cesm1.2/clm/CLM45_Tech_Note.pdf).

Pielke, R. A., A. Pitman, D. Niyogi, R. Mahmood, C. McAlpine, F. Hossain, K. K. Goldewijk, U. Nair, R. Betts, and S. Fall, 2011: Land use/land cover changes and climate: modeling analysis and observational evidence. *Wiley Interdisciplinary Reviews: Climate Change*, **2,** 828-850.

Pincus, R., 2016: RFMIP documentation paper. *in prep for this CMIP special issue of GMD*.

Pitman, A., N. de Noblet-Ducoudré, F. Cruz, E. Davin, G. Bonan, V. Brovkin, M. Claussen, C. Delire, L. Ganzeveld, and V. Gayler, 2009: Uncertainties in climate responses to past land cover change: First results from the LUCID intercomparison study. *Geophys. Res. Lett.*, **36**.

Pongratz, J., and K. Caldeira, 2012: Attribution of atmospheric CO2 and temperature increases to regions: importance of preindustrial land use change. *Environ. Res. Lett.*, **7,** 034001.

Pongratz, J., C. Reick, T. Raddatz, and M. Claussen, 2008: A reconstruction of global agricultural areas and land cover for the last millennium. *Global Biogeochem. Cycles*, **22**.

Pongratz, J., C. Reick, T. Raddatz, and M. Claussen, 2009: Effects of anthropogenic land cover change on the carbon cycle of the last millennium. *Global Biogeochem. Cycles*, **23**.

Pongratz, J., C. Reick, R. Houghton, and J. House, 2014: Terminology as a key uncertainty in net land use and land cover change carbon flux estimates. *Earth System Dynamics*, **5,** 177-195.

Popp et al., D., 2016: Shared Socio-economic Pathways – a framework for assessing potential land use futures. *Submitted to Global Environmental Change*.

Pugh, T., A. Arneth, S. Olin, A. Ahlström, A. Bayer, K. K. Goldewijk, M. Lindeskog, and G. Schurgers, 2015: Simulated carbon emissions from land-use change are substantially enhanced by accounting for agricultural management. *Environ. Res. Lett.*, **10,** 124008.

Reid, W. V., D. Chen, L. Goldfarb, H. Hackmann, Y. Lee, K. Mokhele, E. Ostrom, K. Raivio, J. Rockström, and H. J. Schellnhuber, 2010: Earth system science for global sustainability: grand challenges. *Science(Washington)*, **330,** 916-917.

Riahi et al., K., 2016: The Shared Socioeconomic Pathways: An Overview. *Submitted to Global Environmental Change*.

Sacks, W. J., B. I. Cook, N. Buenning, S. Levis, and J. H. Helkowski, 2009: Effects of global irrigation on the near-surface climate. *Clim. Dyn.*, **33,** 159-175.

Schneck, R., C. H. Reick, and T. Raddatz, 2013: Land contribution to natural CO2 variability on time scales of centuries. *J. Adv. Mod. Earth Sys.*, **5,** 354-365.

Schultz, N., X. Lee, P. Lawrence, D. Lawrence, and L. Zhao, 2016: Assessing the use of sub-grid land model output to study impacts of land cover change *Submitted to JGR*.

Seneviratne, S. I., D. Lüthi, M. Litschi, and C. Schär, 2006: Land–atmosphere coupling and climate change in Europe. *Nature*, **443,** 205-209.

Seneviratne, S. I., T. Corti, E. L. Davin, M. Hirschi, E. B. Jaeger, I. Lehner, B. Orlowsky, and A. J. Teuling, 2010: Investigating soil moisture–climate interactions in a changing climate: A review. *Earth-Science Reviews*, **99,** 125-161.

Seneviratne, S. I., M. Wilhelm, T. Stanelle, B. Hurk, S. Hagemann, A. Berg, F. Cheruy, M. E. Higgins, A. Meier, and V. Brovkin, 2013: Impact of soil moisture-climate feedbacks on CMIP5 projections: First results from the GLACE-CMIP5 experiment. *Geophys. Res. Lett.*, **40,** 5212-5217.

Sentman, L. T., E. Shevliakova, R. J. Stouffer, and S. Malyshev, 2011: Time scales of terrestrial carbon response related to land-use application: Implications for initializing an Earth system model. *Earth Interact.*, **15,** 1-16.

Shevliakova, E., R. J. Stouffer, S. Malyshev, J. P. Krasting, G. C. Hurtt, and S. W. Pacala, 2013: Historical warming reduced due to enhanced land carbon uptake. *Proceedings of the National Academy of Sciences*, **110,** 16730-16735.

Shevliakova, E., S. W. Pacala, S. Malyshev, G. C. Hurtt, P. Milly, J. P. Caspersen, L. T. Sentman, J. P. Fisk, C. Wirth, and C. Crevoisier, 2009: Carbon cycling under 300 years of land use change: Importance of the secondary vegetation sink. *Global Biogeochem. Cycles*, **23**.

Smith, P., S. J. Davis, F. Creutzig, S. Fuss, J. Minx, B. Gabrielle, E. Kato, R. B. Jackson, A. Cowie, and E. Kriegler, 2016: Biophysical and economic limits to negative CO2 emissions. *Nat. Clim. Change*, **6,** 42-50.

Stocker, B., and F. Joos, 2015: Large differences in land use emission quantifications implied by definition discrepancies. *Earth System Dynamics Discussions*, **6**.

Stocker, B. D., F. Feissli, K. M. Strassmann, R. Spahni, and F. Joos, 2014: Past and future carbon fluxes from land use change, shifting cultivation and wood harvest. *Tellus B*, **66**.

Swann, A. L., I. Y. Fung, and J. C. Chiang, 2012: Mid-latitude afforestation shifts general circulation and tropical precipitation. *Proceedings of the National Academy of Sciences*, **109,** 712-716.

Teuling, A. J., S. I. Seneviratne, R. Stöckli, M. Reichstein, E. Moors, P. Ciais, S. Luyssaert, B. van den Hurk, C. Ammann, and C. Bernhofer, 2010: Contrasting response of European forest and grassland energy exchange to heatwaves. *Nat. Geosci.*, **3,** 722-727.

Trenberth, K. E., and G. R. Asrar, 2014: Challenges and opportunities in water cycle research: WCRP contributions. *Surv. Geophys.*, **35,** 515-532.

Van den Hurk, B., H. Kim, G. Krinner, S. I. Seneviratne, C. Derksen, T. Oki, H. Douville, A. Ducharne, F. Cheruy, M. Puma, W. Li, B. Jia, A. Alessandri, D. M. Lawrence, G. Weedon, R. Ellis, S. Hagemann, J. Mao, and M. G. Flanner, 2016: The Land Surface, Snow and Soil moisture Model Intercomparison Program (LS3MIP): aims, set-up and expected outcome. *in prep for this CMIP special issue of GMD*.

Van Vuuren, D. P., E. Kriegler, B. C. O'Neill, K. L. Ebi, K. Riahi, T. R. Carter, J. Edmonds, S. Hallegatte, T. Kram, and R. Mathur, 2014: A new scenario framework for climate change research: scenario matrix architecture. *Clim. Change*, **122,** 373-386.

Van Vuuren, D. P., E. Stehfest, D. Gernaat, J. Doelman, M. van Berg, M. Harmsen, H.-S. de Boer, L. Bouwman, V. Daiogolou, O. Edelenbosch, B. Girod, T. Kram, L. Lassaletta, P. Lucas, H. van Meijil, C. Muller, B. Rvan Ruijven, and A. Tabeau, 2016: Energy, land-use and greenhouse gas emissions trajectories under a green growth paradigm. *Submitted to Global Environmental Change*.

Ward, D., N. Mahowald, and S. Kloster, 2014: Potential climate forcing of land use and land cover change. *Atmos. Chem. Phys.*, **14,** 12701-12724.

Wei, J., P. A. Dirmeyer, D. Wisser, M. G. Bosilovich, and D. M. Mocko, 2013: Where does the irrigation water go? An estimate of the contribution of irrigation to precipitation using MERRA. *J. Hydrometeorol.*, **14,** 275-289.

Wilhelm, M., E. L. Davin, and S. I. Seneviratne, 2015: Climate engineering of vegetated land for hot extremes mitigation: An Earth system model sensitivity study. *J. Geophys. Res.*, **120,** 2612-2623.

Wilkenskjeld, S., S. Kloster, J. Pongratz, T. Raddatz, and C. Reick, 2014: Comparing the influence of net and gross anthropogenic land-use and land-cover changes on the carbon cycle in the MPI-ESM. *Biogeosciences*, **11,** 4817-4828.

Williams, C. A., M. Reichstein, N. Buchmann, D. Baldocchi, C. Beer, C. Schwalm, G. Wohlfahrt, N. Hasler, C. Bernhofer, and T. Foken, 2012: Climate and vegetation controls on the surface water balance: Synthesis of evapotranspiration measured across a global network of flux towers. *Water Resour. Res.*, **48**.

Geosci. Model Dev. Discuss., doi:10.5194/gmd-2016-76, 2016
Manuscript under review for journal Geosci. Model Dev.
Published: 12 April 2016

Geoscientific Model Development Discussions

Zeng, N., F. Zhao, G. J. Collatz, E. Kalnay, R. J. Salawitch, T. O. West, and L. Guanter, 2014: Agricultural Green Revolution as a driver of increasing atmospheric CO2 seasonal amplitude. *Nature*, **515,** 394-397.

Zhang, X., E. A. Davidson, D. L. Mauzerall, T. D. Searchinger, P. Dumas, and Y. Shen, 2015: Managing nitrogen for sustainable development. *Nature*, **528,** 51-59.

Geosci. Model Dev. Discuss., doi:10.5194/gmd-2016-76, 2016
Manuscript under review for journal Geosci. Model Dev.
Published: 12 April 2016

Geoscientific Model Development Discussions
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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)	80 years

Geosci. Model Dev. Discuss., doi:10.5194/gmd-2016-76, 2016
Manuscript under review for journal Geosci. Model Dev.
Published: 12 April 2016

Geoscientific Model Development Discussions
Open Access

Table 2. Land-only land-cover and land-management change experiments. Assess relative impact of land-cover and land-management change on fluxes of water, energy, and carbon; forced with historical observed climate. The simulations *land-hist*, *land-hist-alt-start-year* and *land-NoLu* are Tier 1, all other experiments 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 as used in CMIP6 coupled experiments 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-dep, aerosol dep, etc.	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 (Tier 1)
land-hist-alt-start-year	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). (Tier 1)	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, Tier 1).	
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 GSWP3 forcing data.
land-crop-grass	Same as ***land-hist*** but with all new crop and pastureland treated as unmanaged grassland	This grassland as crop is like natural grassland in terms of biophysical properties but is treated as agricultural land for dynamic vegetation (i.e. no competition with natural vegetation areas).
land-crop-nomanage	Same as ***land-hist*** except with crop area utilizing prognostic crop model	Maintain 1850 irrigated area and fertilizer use and without any additional crop management except planting and harvesting
land-crop-noirrig	Same as ***land-hist*** but with irrigated area held at 1850 levels	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	
land-nowoodharv	Same as ***land-hist*** but with wood harvest maintained at 1850 amounts/areas	Wood harvest due to land clearing for agriculture should continue yielding non-zero anthropogenic pools
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-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
land-netTrans	Same as ***land-hist*** except with net LUC transitions instead of gross LUC transitions. If gross transitions exceeding net transitions have been applied in 1850, they should be maintained.	Net LUC transitions provided as layer within LUMIP land-use dataset. The dataset's aim is to exclude small-scale shifting cultivation; gross transitions will still occur when upscaled to the ESM's coarser resolution.

Geosci. Model Dev. Discuss., doi:10.5194/gmd-2016-76, 2016
Manuscript under review for journal Geosci. Model Dev.
Published: 12 April 2016

Geoscientific Model Development Discussions

Table 3: Phase 2 experiments, all Tier 1.

Experiment ID	Experiment Name	Experiment Description	Years
hist-NoLu	Historical with no land-use change	Same as concentration-driven ***CMIP6 historical*** 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
ssp37-ssp126Lu	SSP3-7 with SSP1-2.6 land use	Same as ScenarioMIP ***ssp37*** (SSP3-7 deforestation scenario) except use land use from ***ssp126*** (SSP1-2.6 afforestation scenario); concentration-driven. Two additional ensemble members requested (Tier 3) contingent on ScenarioMIP ***ssp37*** large ensemble being completed	2015-2100
ssp126-ssp37Lu	SSP1-2.6 with SSP3-7 land use	Same as ScenarioMIP ***ssp126*** (SSP1-2.6 afforestation scenario) except use land use from ***ssp37*** (SSP3-7 deforestation scenario); concentration-driven.	2015-2100
esm-ssp585-ssp126Lu	Emissions-driven SSP5-8.5 with SSP1-2.6 land use	Same as C4MIP ***esm-ssp585*** except use SSP1-2.6 land use (afforestation scenario); emission driven	2015-2100

Geosci. Model Dev. Discuss., doi:10.5194/gmd-2016-76, 2016
Manuscript under review for journal Geosci. Model Dev.
Published: 12 April 2016

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	

Geosci. Model Dev. Discuss., doi:10.5194/gmd-2016-76, 2016
Manuscript under review for journal Geosci. Model Dev.
Published: 12 April 2016

Geoscientific Model Development Discussions

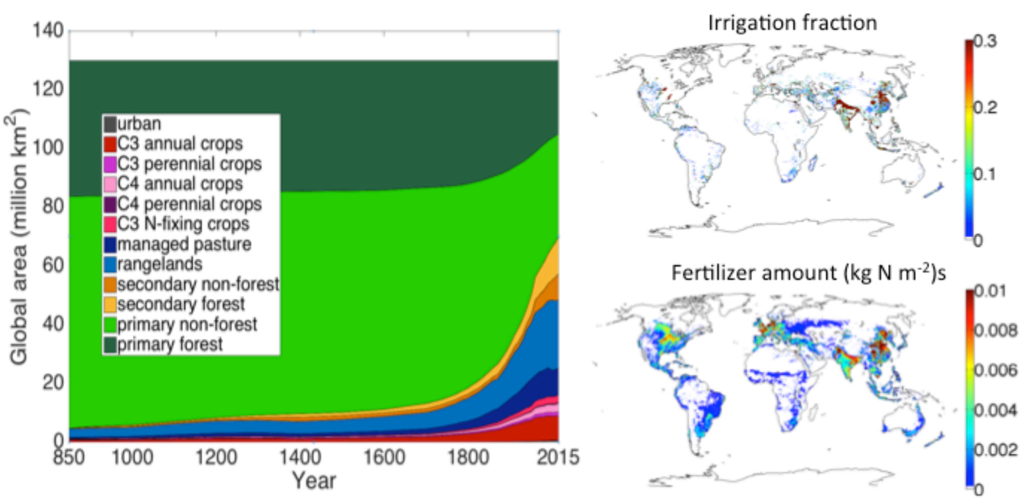

Figure 1. Time-series of global land area occupied by each LUH2 land-use state from 850 to 2015 (left). Note that extensions to 2100 for all of the ScenarioMIP SSPs will also be provided. Fraction of each 0.25° grid-cell that is irrigated in year 2015 (top right). Fertilizer applied in year 2015 (bottom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

Geosci. Model Dev. Discuss., doi:10.5194/gmd-2016-76, 2016
Manuscript under review for journal Geosci. Model Dev.
Published: 12 April 2016

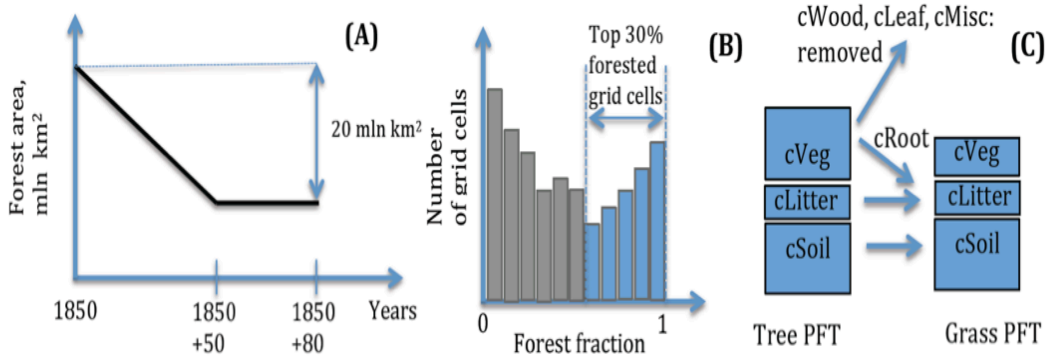

Fig. X. A schematic of experimental setup in the *deforest-glob* experiment. (A) Scenario of forced changes in the global forest area. (B) Sorting and selection of the grid cells that should be deforested. (C) Transition of carbon pools after deforestation.

Geosci. Model Dev. Discuss., doi:10.5194/gmd-2016-76, 2016
Manuscript under review for journal Geosci. Model Dev.
Published: 12 April 2016

Geoscientific Model Development Discussions

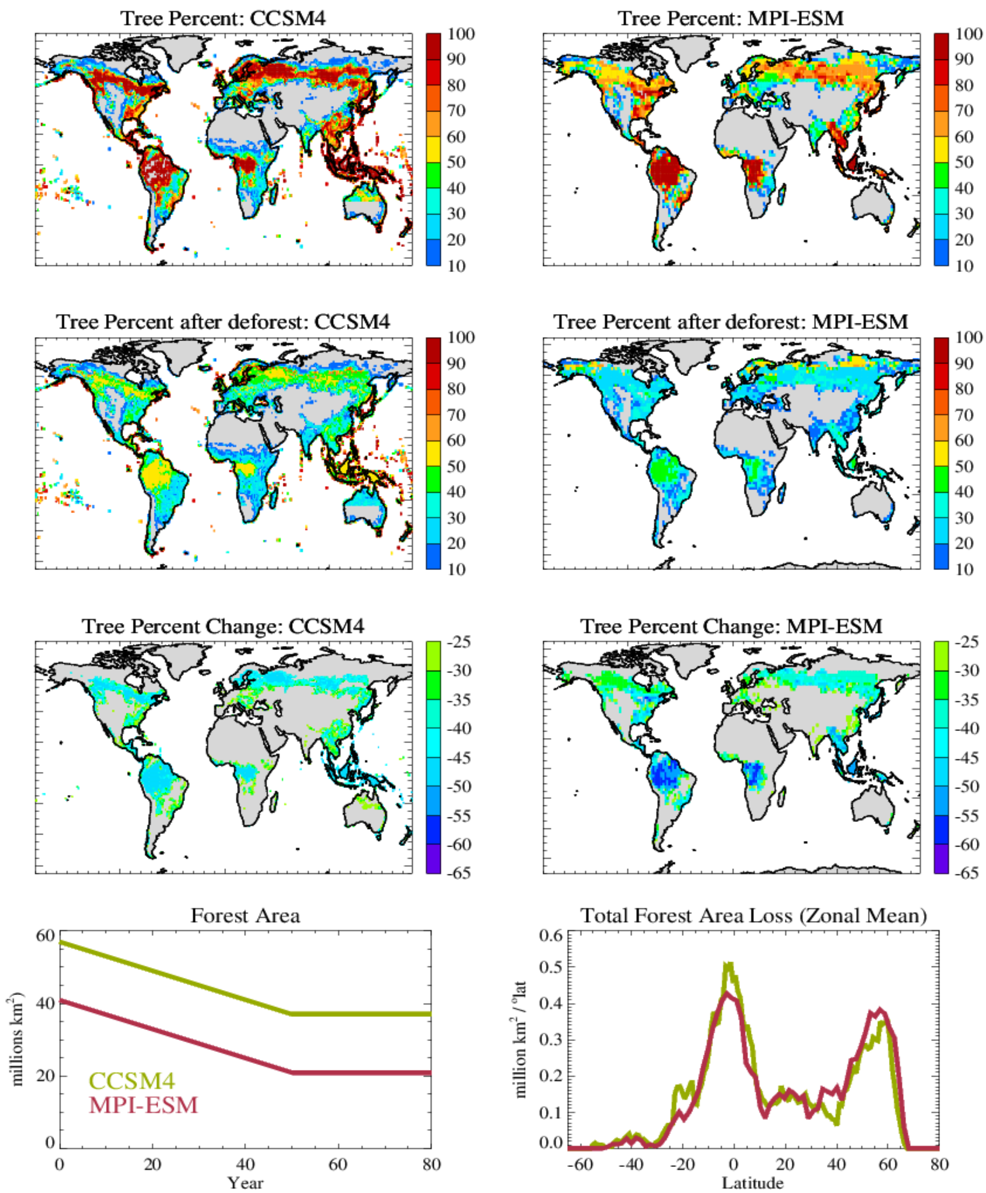

Figure 2: Sample maps of fraction of grid cell covered by trees at the start of the idealized deforestation simulation, after idealized deforestation (year 50), and the change in tree fraction by the end of the deforestation period. Time series of forest area and zonal mean forest area loss are also 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.

Geosci. Model Dev. Discuss., doi:10.5194/gmd-2016-76, 2016
Manuscript under review for journal Geosci. Model Dev.
Published: 12 April 2016

	Land-Use Scenario		
Main Scenario	**SSP1-2.6**	**SSP3-7**	**SSP5-8.5**
SSP1-2.6	**ScenarioMIP** Conc.-driven	**LUMIP** Conc.-driven	
SSP3-7	**LUMIP** Conc.-driven	**ScenarioMIP** Conc.-driven	
SSP5-8.5	**LUMIP** Emissions-driven		**C4MIP** Emissions-driven **ScenarioMIP** Conc.-driven

Figure 3: 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. In LUMIP we request a further SSP5-8.5 simulation: emission-driven but with land use taken from SSP1-2.6.

Geosci. Model Dev. Discuss., doi:10.5194/gmd-2016-76, 2016
Manuscript under review for journal Geosci. Model Dev.
Published: 12 April 2016

Geoscientific Model Development
Discussions
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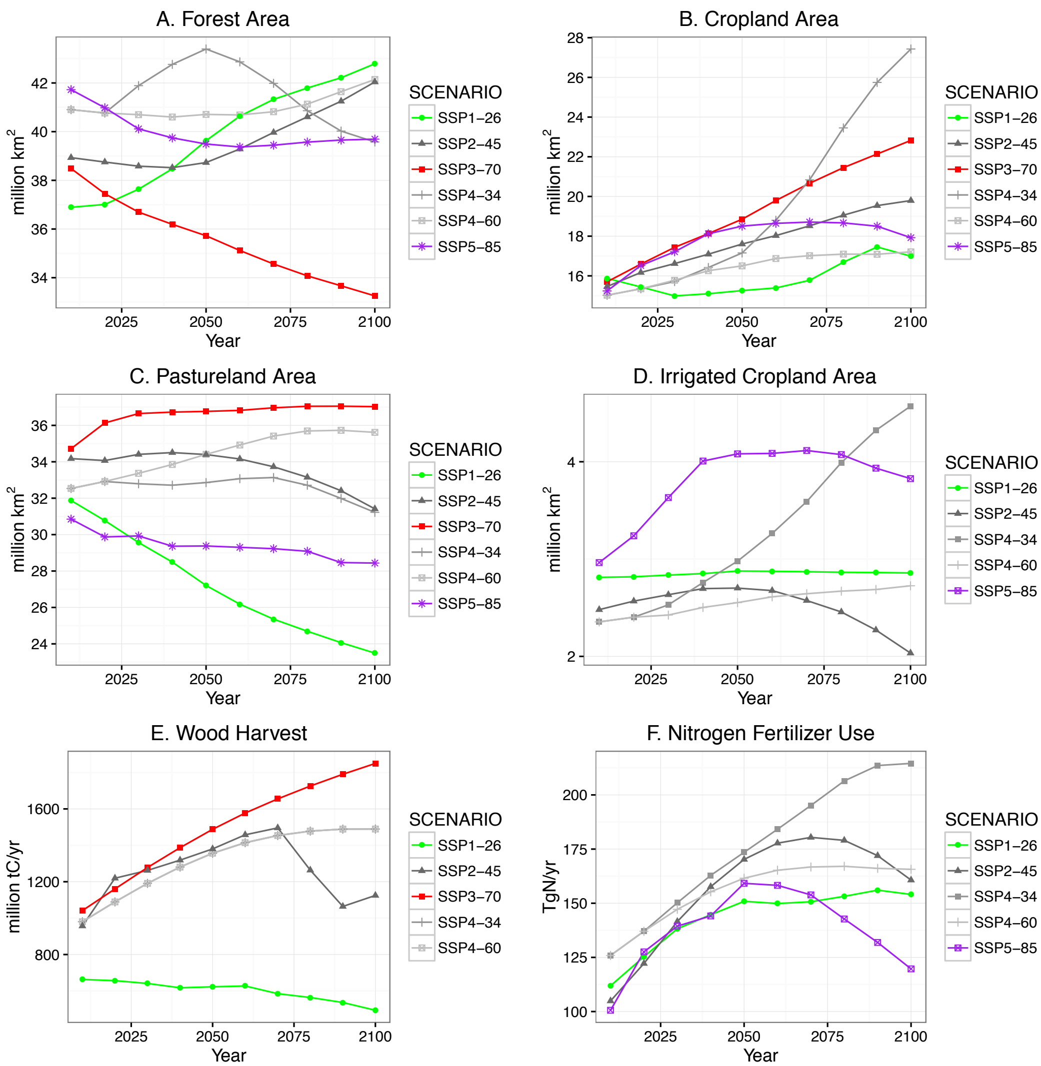

Figure 4: Global time series of land cover (A), land use (B, C), and land management (D-F) for the future simulations. Lines indicate SSP-RCP scenarios chosen for ScenarioMIP, with colored lines representing scenarios with specific LUMIP experiments. Data is provided by the IAM community (Figure 8, Oleson et al. 2013). 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, as described in (see Popp et al. 2016 for more details; Riahi et al. 2016 and). 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.

Geosci. Model Dev. Discuss., doi:10.5194/gmd-2016-76, 2016
Manuscript under review for journal Geosci. Model Dev.
Published: 12 April 2016

Geoscientific Model Development Discussions

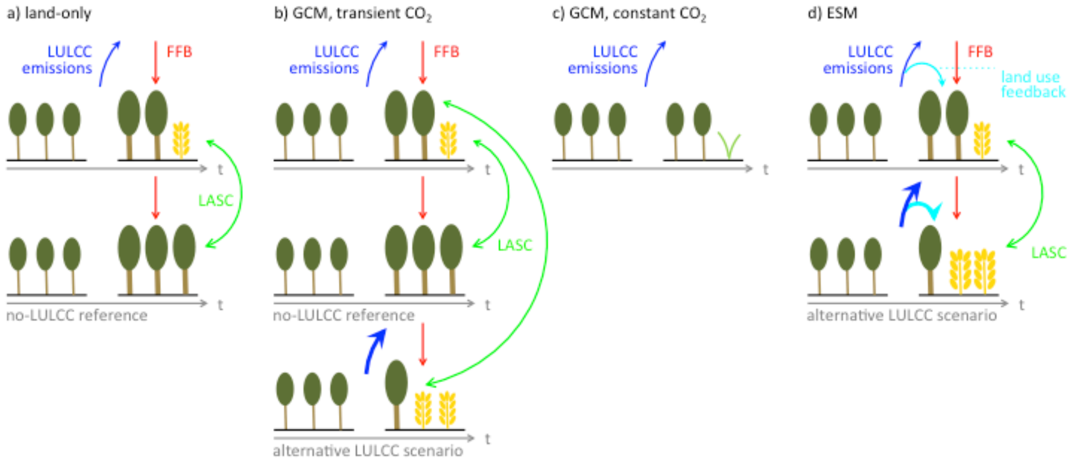

Figure 5: Illustration of the different setups used in the LUMIP experiments, using the example of forest replacement by cropland or grassland. The loss of additional sink capacity (LASC) occurs when environmental conditions change transiently, which is the case when CO_2 is prescribed from observations, which include fossil-fuel burning (FFB). LULCC emissions are "seen" by the terrestrial vegetation (natural and anthropogenic) only in the ESM setup, where CO2 is interactive. In this case, part of the emissions is taken up again by the vegetation ("land-use feedback"). Note that only atmospheric CO_2 is prescribed in a-c, while other environmental conditions feed back with LULCC's biogeophysical effects.

Geosci. Model Dev. Discuss., doi:10.5194/gmd-2016-76, 2016
Manuscript under review for journal Geosci. Model Dev.
Published: 12 April 2016

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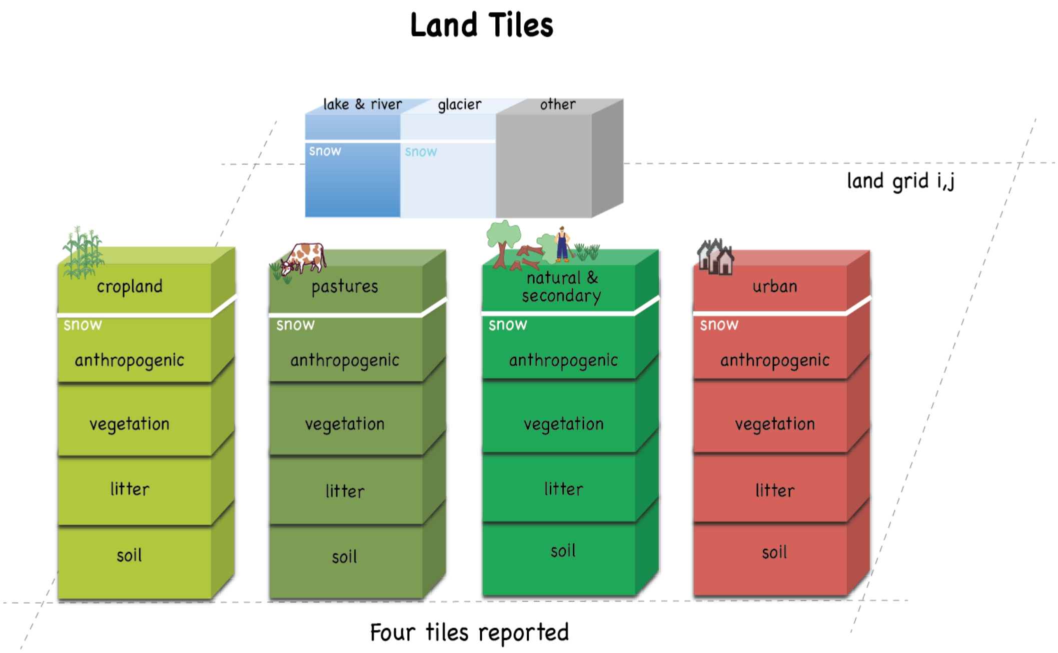

Figure 6. Four carbon (and nitrogen) stock variables are requested – vegetation, soil, litter, and anthropogenic product pool. Anthropogenic product pool is wood or food product pools.

Geosci. Model Dev. Discuss., doi:10.5194/gmd-2016-76, 2016
Manuscript under review for journal Geosci. Model Dev.
Published: 12 April 2016

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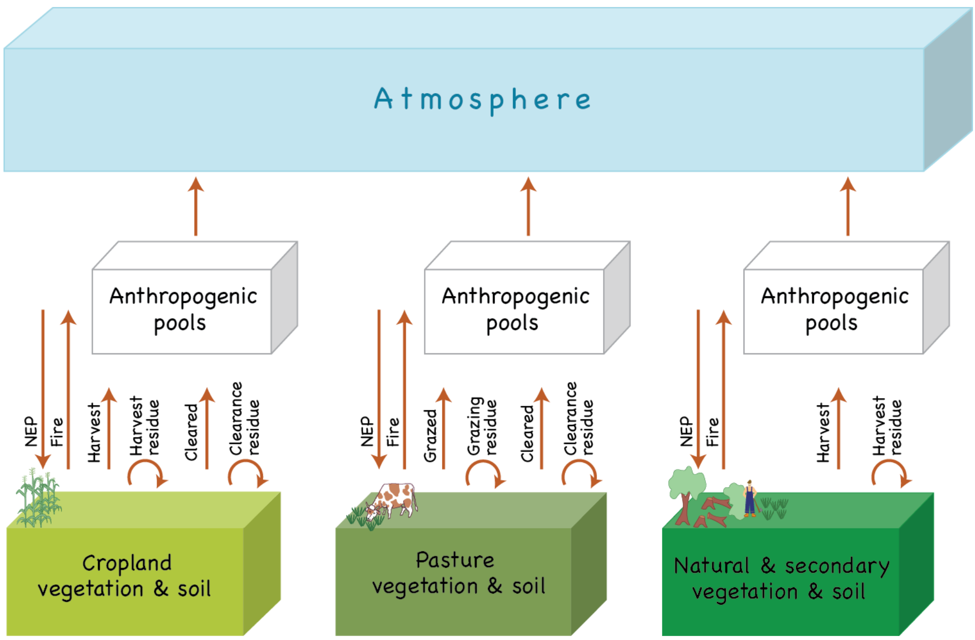

Figure 7. Exchanges and transfers affecting storage of biogeochemical constituents in land models under LULCC. NEP is Net Ecosystem Production.

Geosci. Model Dev. Discuss., doi:10.5194/gmd-2016-76, 2016
Manuscript under review for journal Geosci. Model Dev.
Published: 12 April 2016

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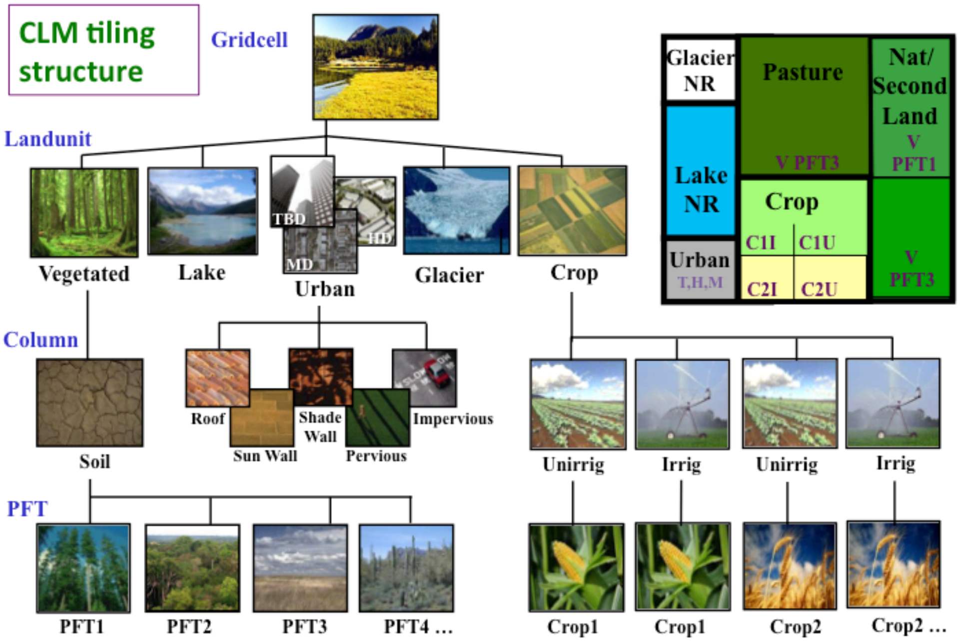

Figure 8. CLM tiling structure. Subgrid aggregation: PSL = Vegetated land unit including all PFTs and bare soil; CRP = Crop land unit including all crop types irrigated (I) and non-irrigated (U); PST = not explicitly represented in CLM, report as missing value; URB = weighted average of Tall Builidng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

Geosci. Model Dev. Discuss., doi:10.5194/gmd-2016-76, 2016
Manuscript under review for journal Geosci. Model Dev.
Published: 12 April 2016

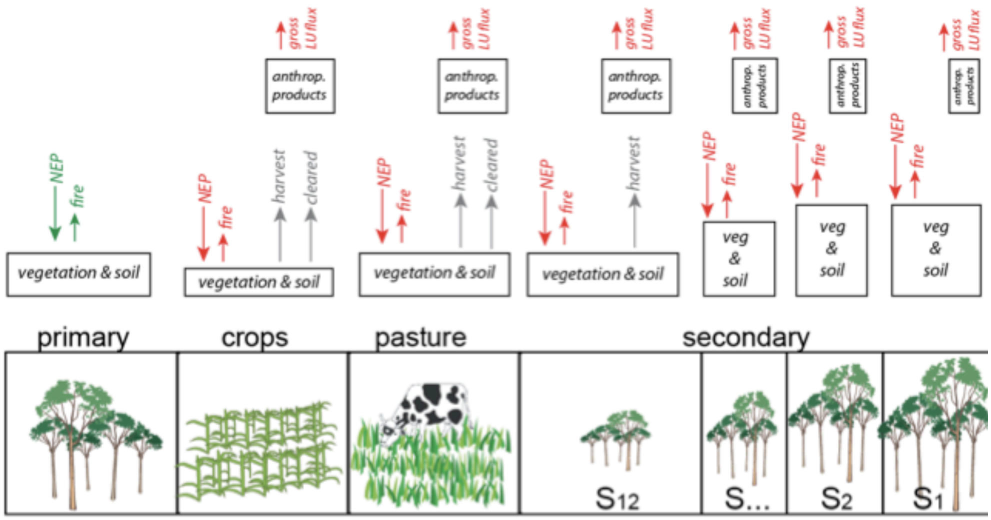

Figure 9. GFDL LM3 subgrid structure.