Application for CMIP6-Endorsed MIPs:
Land-Use Model Intercomparison Project (LUMIP)

Date: June 10, 2015

- **Name of MIP** *

Land-Use Model Intercomparison Project (LUMIP)

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- **Link to website (if available)** *

https://cmip.ucar.edu/lumip

- **Goal of the MIP and a brief overview** *

Human land-use activities have resulted in large changes to the biogeochemical and biophysical properties of the Earth surface, with resulting implications for climate. In the future, land-use activities are likely to expand and/or intensify further to meet growing demands for food, fiber, and energy. CMIP5 achieved a qualitative scientific advance in studying the effects of land-use on climate, for the first time explicitly accounting for the effects of global gridded land-use changes (past-future) in coupled carbon-climate model projections. Enabling this advance, the first consistent gridded land-use dataset (past-future) was developed, linking historical land-use data, to future projections from Integrated Assessment Models, in a standard format required by climate models. Results indicate that the effects of land-use on climate, while uncertain, are sufficiently large and complex to warrant an expanded activity focused on land-use for CMIP6. Land-use change is an essential forcing of the Earth System, and as such LUMIP is directly relevant and necessary for CMIP6 Question 1: “How does the Earth System respond to forcing?” LUMIP will also play a strong role in addressing the WCRP Grand Challenges, particularly with respect to the “AIMES theme for collaboration: biospheric forcings and feedbacks". 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 and 3, and to many of the WCRP Grand Challenges including Climate Extremes, Regional Climate Information, and Water Availability.

The goal of LUMIP is to take the next steps, and enable, coordinate, and ultimately address the most important science questions related to the effects of land-use on climate. The primary science questions of LUMIP are:

- What are the effects of land use and land-use change on climate and biogeochemical cycling (past-future)?
- Are there regional land management strategies with promise to help mitigate and/or adapt to climate change?
- What are the effects of climate change on land-use and land-use 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 for the community than possible to date. Of particular focus will be the separation and quantification of the effects on climate from fossil fuel emissions and land-use change, biogeochemical from biogeophysical effects, the unique impact of land cover change versus land management change, and modulation of land use impact on climate by land-atmosphere coupling strength.

Three major sets of science activities are envisioned. First, a set of metrics and diagnostic protocol will be developed to quantify model performance, and related sensitivities, with respect to land use. As part of this activity, benchmarking data products will be identified to help constrain models. These metrics will be incorporated into the International Land Model Benchmarking (ILAMB) system. This benchmarking/metrics emphasis in LUMIP dovetails with expanding emphasis in CMIP on metrics.

Second, data standardization efforts will build off the lessons learned and protocols in CMIP5, and work with new historical data, present data, IAMS, and ESMs to produce an enhanced standardized land-use data for CMIP6 model experiments passing the maximum amount of common information between these relevant domains. New output data standardization will also enrich and improve analysis of model experiment results. Particular emphasis is on promoting the archival of subgrid land information in CMIP6. 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, the 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 surface type responds to climate change and/or direct anthropogenic modifications. LUMIP is developing a proposal outlining the need and protocol for archival for selected key variables on multiple land tiles (see Appendix A for draft proposal).

Third, an efficient model experiment design including both idealized and scenario-based cases has been developed to isolate and quantify land-use effects. These experiments, described in greater detail below, include both idealized and realistic scenario simulations with and without transient land use. The experimental protocol enables integrated analysis of coupled and offline land models (forced with observed meteorology) 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.

[*] Note that experiments to address this question are not included in this proposal because our understanding is that very few Earth System Models have the capability to address this question yet. We maintain this question within LUMIP because it is a high priority land use change science question that LUMIP will promote through individual model efforts until enough models have the capability to do two-way climate-land use interactions.

LUMIP priorities and model experiments have been developed in close consultation with several existing model intercomparison activities and research programs that focus on the role of land use in climate including LUCID, GSWP3, LUC4C, TRENDY, and AgMIP. In addition, discussions have begun and are ongoing with other proposed CMIP MIPs to ensure that our proposed experiments are complementary and not duplicative. These proposed MIPs include ScenarioMIP, AerChemMIP, C4MIP, LS3MIP, DAMIP, and RFMIP.

- **An overview of the proposed experiments***

LUMIP proposes a two phase, tiered, model experiment plan. Phase one, which can start soon, will feature idealized coupled and land-only model experiments designed to improve process understanding and assess how models represent the impact of changes in land use on climate, as well as to quantify model sensitivity to potential land cover and land use changes. Phase two experiments will be based on historical land use and realistic scenarios identified by ScenarioMIP. Phase two experiments are designed to isolate the role of historical and projected future land-use changes on climate. As there are more possible experiments than are achievable with available resources by all groups, experiments are tiered in order of importance.

Details of the model experiments are included below. The total request includes (all at standard resolution):

Tier 1: 520 years GCM/ESM; 165 years LND-only
Tier 2: 330 years GCM/ESM; 1650 years LND-only
Tier 3: 280 years GCM/ESM; 120 years LND-only

Overview of Phase 1 experiments

Phase 1 consists of two sets of experiments (see Table 1). The first set of experiments are idealized 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. The idealized deforestation experiment in which as specified area of forest is removed each year for 50 years is new to the land use change modeling community and is designed to be somewhat analogous/complementary to the 1% CO_2 simulations in the DECK. This idealized deforestation experiment has the advantage that it will be easier to ensure conformity across models in terms of the land cover change (differences in the representation of realistic land cover changes across different models is a problem that has plagued prior land cover change model intercomparison projects, e.g. LUCID). Two modeling centers are conducting test idealized deforestation simulations. Additional regional deforestation simulations (Tier 3) are being planned within the LUCID/LUC4C projects. Protocols for these regional experiments will be developed by LUCID and LUC4C.

The second set of Phase 1 experiments are a series of offline land-only simulations, which will build on the LMIP simulation proposed in LS3MIP. This series of experiments is designed to assess how the specification of land cover change and increasingly comprehensive treatment of land management affects the carbon, water, and energy cycle response to land use change. Only a limited number of models will be able to perform all the experiments, but the experimental design will allow for multiple levels of participation, according to each model's capabilities. This set of experiments utilizes state-of-the-art model developments anticipated across several contacted modeling centers and will contribute to the setting of priorities for land use for future CMIPs. Test experiments are planned for 2015 to finalize the experimental design.

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 very 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. The GSWP3 dataset is being put through a thorough analysis and its strengths and limitations, especially with respect to trends, will be documented in one or more papers. LUMIP, in conjunction with LS3MIP, are considering whether or not there is value in requesting runs with an additional forcing dataset (several others century-scale are available) to enable an assessment of forcing uncertainty. Additional offline runs could be an excessive burden on modeling centers so if this is included, it would be in Tier 3, aimed at groups that are interested in pursuing the forcing uncertainty question. Irrespective of the uncertainties, there is strong value in the inclusion of land-only experiments in which all models are forced with the same historical climate since it enables much cleaner comparison across models of the simulated land response to climate change and/or land use change.

Table 1: Phase 1 experiments.

Process understanding	Idealized experiments designed to assess biogeophysical role of land cover change on climate	
idealized_deforest	Idealized deforestation experiment, 20 million km^2 forest removed linearly over a period of 50 years, with an additional 20 years of constant forest cover (Tier 1)	1850-1920
reg_deforest_LND, reg_deforest_ATM, reg_deforest_GCM	Land, atm, AOGCM simulations with some set of tropical, boreal, or temperate deforestation (defined by LUC4C/LUCID) (Tier 3)	1980-2010

Land cover versus land management change landcover_mange_LND (Tier 2)	Assess relative impact of land cover and incrementally more comprehensive land management change on fluxes of water, energy, and carbon; forced with historical observed climate and projected climate anomalies (1850 to 2014)
LND_LULCC_AM	All LULCC and All Management (AM) features for each particular model turned on; 1700 start; transient CO_2, N-dep, aerosol dep, etc.; This run is same as **LMIP-Hist (LS3MIP)** if GCM runs include all management capabilities
LND_LULCC1850	LND_LULCC_AM with land use change starting at 1850 (testing impact of pre-1850 land use)
LND_noLULCC	LND_no land cover change (Same as Tier 1, LND_noLULCC_hist)
LND_grasscrop	LCC with 'grassland' crop/pasture; no land management
LND_gross_vs_net	LND_grasscrop except with net transitions instead of gross
LND_fire	LND_grasscrop with human fire management
LND_woodharv	LND_grasscrop or LND_fire with wood harvest
LND_pasture	LND_grasscrop but with grazing on pastureland
LND_crop	LND_grasscrop but with crop area utilizing prognostic crop model
LND_crop-irrig	LND_crop with realistic transient irrigated area
LND_crop-irrig-fert	LND_crop-irrig with realistic transient fertilization

* It is still being evaluated whether additive or subtractive scheme is preferred for these land only offline experiments.

Overview of Phase 2 experiments

The Phase 2 experiments build off of the CMIP6 Historical and historical LMIP simulations as well as the ScenarioMIP simulations. They will include land-only and coupled historical and future simulations with land use held constant or modified to an alternative land use scenario (Table 2). 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 will be of interest to the Detection and Attribution MIP.

Scientific advantages for particular model configuration:

- Concentration-driven simulations allow focus on biogeophysical impacts on climate and help establish when/where land management could be used as a regional climate mitigation tool.

- Emission-driven simulations allow assessment of the full feedback onto climate and assess whether or not IAM predictions about land use and land use change carbon fluxes are consistent with ESM modeled land use emissions.

- Including experiments in low and medium/high radiative forcing scenarios in concentration-driven scenarios allows examination of how the impact of land use change differs at different levels of climate change and at different levels of CO_2 fertilization.

Consequently, for the projection period, LUMIP includes an additional simulation for both a high and a low radiative forcing scenario with land use from a different SSP-RCP configuration with strongly different land use but with all other forcings remaining the same as in the original ScenarioMIP simulation (e.g., ScenarioMIP SSP3-7 includes strong deforestation; LUMIP experiment will be SSP3-7 but with SSP1-2.6 land use, which is afforestation scenario). 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). See figure 1 for further details of the proposed design.

Table 2: Phase 2 experiments.

Land use change impact on land to atmosphere fluxes of water, energy, carbon		
noLULCC_hist_LND (Tier 1)	Same as LMIP-Hist (LS3MIP) except with land use and land cover held constant at 1850, all human impact removed	1850-2014
Land use change impact on past and future climate (Tier 1)		
noLULCC_hist (Tier 1)	Same as **historical CMIP6** except with land cover/use held constant at 1850, concentration-driven (for DAMIP); two additional ensemble members requested in Tier 2	1850-2014
SSP3-7_SSP1-2.6landuse (Tier 1)	Additional land use policy sensitivity simulation for high radiative forcing scenario, keep all forcings the same as ScenarioMIP SSP3-7 (deforestation scenario), but replace land use from SSP1-2.6 (afforestation) scenario;	2015-2100

	concentration-driven; 2 additional ensemble members requested (Tier 3)	
SSP1-2.6_SSP3-7landuse (Tier 1)	Additional land use policy sensitivity simulation for low radiative forcing scenario, keep all forcings the same as ScenarioMIP SSP1-2.6 (afforestation scenario), but replace land use from SSP3-7 (afforestation) scenario; concentration-driven	2015-2100
esmSSP5-8.5_SSP1-2.6landuse	Additional land use polict sensitivity simulation for high radiative forcing scenario, keep all forcings the same as in C4MIP esmssp5-8.5 scenario except use SSP1-2.6 land use; emission driven	

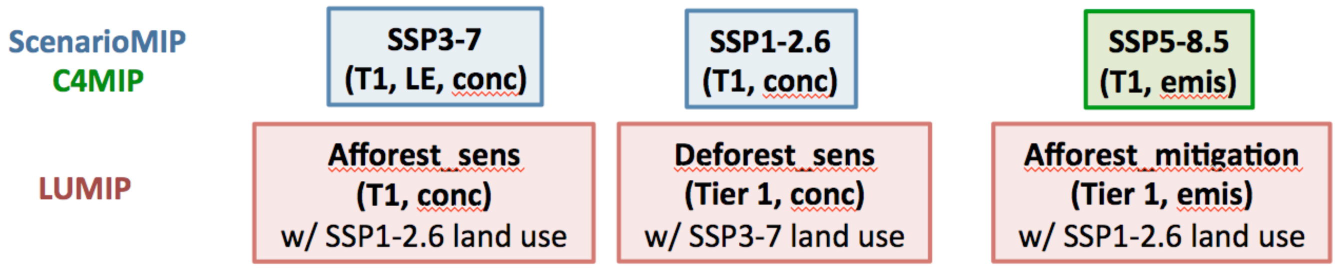

Figure 1: Example set of realistic and sensitivity studies designed to assess potential impact of strongly different land use trajectories on climate outcome.

- **An overview of the proposed evaluation/analysis of the CMIP DECK and CMIP6 experiments***

The goal 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 study. 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. These analyses need to assess how land surface models respond to a land-cover perturbation in uncoupled (off-line) simulations as well as coupling between land and atmosphere components. One axis of analysis that has previously not been investigated in great detail is how a particular model's regional land-atmosphere coupling strength signature affects how the model simulates the impact of land use change on climate. Here, LUMIP will interface with LS3MIP to investigate the cross-relationship between land-atmosphere coupling strength and land-use change impacts on weather and climate.

In addition, LUMIP will promote the development of biogeophysical and biogeochemical metrics of land use change, based on observations, that will help constrain model dynamics and dovetails with expanding emphasis in CMIP on metrics. Any useful metrics will be integrated into the International Land Model Benchmarking (ILAMB) package that is currently under development. The availability of both land-only and coupled historic simulations enables a much more systematic assessment of the roles of land and atmosphere in the simulated response to land use change.

LUMIP also proposes to develop a set of metrics that 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, the 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 (5^{o} by 5^{o} and 10^{o} by 10^{o}) to continental to 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). Effects on extremes (e.g. Davin et al. 2014) will receive particular attention.

Analysis could focus on critical regions, such as the intensive agricultural region in the central United States and the deforestation region in the Amazon, telescoping out from point to continental scale for each region. Five primary variables will be considered (net radiation, evapotranspiration, temperature, precipitation, and land carbon stocks) that together characterize the biogeophysical and biogeochemical impacts of land use on climate. The first two variables, net radiation and evapotranspiration (ET) define the surface biogeophysical response to land use change and will be evaluated in both offline and coupled model contexts. The temperature and precipitation response to biogeophysical changes in net radiation and ET will be evaluated in land-atmosphere simulations only. Land carbon stocks can be evaluated in offline and coupled simulations.

There are several axes of analysis that can be performed within this framework that are relevant to assessing land use-climate effects relative to natural variability and greenhouse gas-induced climate change. For instance, by varying the number of years and/or the number of ensemble members included in our analysis, one can establish over what time/spatial scale a land use change signal can be detected. One can also investigate the relative difficulty in isolating a land use-climate signal in transient climate simulations with anthropogenic greenhouse gas forcing versus, for example, timeslice atmosphere-land simulations.

- **Proposed timing***

The initial plans for LUMIP have been developed through conference calls and especially during a series of meetings during the summer of 2014.

2013 August 5-9: Initial concept, Aspen
2013 October 3: Presentation of Initial concept, WGCM Meeting
2014 Spring: Workshop 1, GLP Meeting
2014 July 17-18: GEWEX – Biogeophysics
2014 July 21-22: Hamburg – Biogeochemistry
2014 July 28-Aug 1: EMF Snowmass Meeting
2014 August 4-8: AGCI Aspen Joint-MIP Workshop
2014 September 1: Testing of idealized model experiments
2014 September 15: Initial proposal due to CMIP6 Panel
2014 October 8-10: Presentation of revised proposal, WGCM Meeting
2015 January: New prototype land use data/data format released to modeling groups
2015 March 31, final proposal due to CMIP6 Panel
2015 Model I/O and testing with new prototype land use data
2015 October, LandMIP meeting in Zurich to finalize protocol details and begin analysis coordination
2015 Fall, prepare and submit two GMD papers for LUMIP: one on land use dataset and one on experimental protocol and subgrid archiving
2016 January: Initiate multi-model idealized Phase 1 experiments
2016 January: Final land use data made available* (*pending final scenario selection)
2016 Summer: Phase 1 experiments delivered to ESGF
2016 Phase 1 experiments analysis and papers
Starting mid-2016: Phase 2 GCM/ESM realistic experiments, contingent on ScenarioMIP schedule
2018-2019: Model analysis and synthesis, LUMIP SSC will coordinate analysis and submit at least one overview paper to which all modeling center representatives will be invited to join

- **Selected Key References** *

Note that this list of references is representative only. Many additional references on land use and land use change impact on climate are available.

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Pitman, A. J., de Noblet-Ducoudré, N., Cruz, F. T., Davin, E. L., Bonan, G. B., Brovkin, V., ... & Voldoire, A. (2009). Uncertainties in climate responses to past land cover change: First results from the LUCID intercomparison study. Geophysical Research Letters, 36(14).

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- **Appendix A: Sub-grid archiving of selected land output for CMIP6**
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Co Task Leads: Elena Shevliakova and David Lawrence

Note: A detailed protocol for sub-grid archiving, including instructions about how models should deal with 'edge cases' (e.g., what if a model doesn't represent one of the land use tiles) is being developed and will be circulated among the modeling centers. A final protocol will be included in the GMD special issue paper and will also be posted on the LUMIP website.

1. Motivation

The majority of CMIP5-class climate models and Earth system models (ESMs) represent land sub-grid spatial heterogeneity by splitting each land grid into sections (i.e. tiles or units) with similar ecological, biogeochemical, and hydrological characteristics. Current land components capture two kinds of sub-grid heterogeneity: 1) hydrological - land surfaces covered by liquid or frozen water (e.g. lakes, wetlands, glaciers) or not (e.g. bare and vegetated surfaces) and 2) land-use and land management induced (e.g. cropland, pastures, urban, natural and secondary, i.e., harvested forests, plantations, abandoned land). Sub-grid tiling applies to both above- and below-ground sections of the land components. Physical, ecological, and biogeochemical land state variables and surface fluxes are calculated separately for each tile. However, frequently, including in the CMIP5 archive, the tile-specific variables were averaged and the grid-cell mean values were reported. Consequently, a large amount of valuable information was lost with respect to how each surface type with different hydrological and land-use properties responds to climate change and/or direct anthropogenic modifications.

In order to better characterize surface climate, its variability and change, we propose to expand the CMOR data convention in order to capture horizontal land sub-grid heterogeneity. In addition to the land-grid cell values, we propose to request a subset of selected variables on multiple land tiles. This reporting and archiving modification will significantly expand the utility of Earth System Model output for scientific analysis and climate change impacts studies.

Each land model has a unique tiling scheme so the archiving protocol needs to be general enough to work for the range of existing model structures.

2. Proposed sub-grid reporting

2.1 Types of tiles

In the context of CMIP6 we propose to report tile-specific information *for a subset of 4 categories* to capture land-use induced surface heterogeneity: (1) Natural and Secondary land types (including bare ground and vegetated wetlands), (2) pasture-land, (3) croplands, and (4) urban. The remaining tiles, such as lakes, rivers and glaciers, will be excluded from the reported tile-specific values. The proposed set of land-use tile reporting units closely corresponds to land-use units 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 vegetation (i.e., natural vegetation that has previously been harvested or establishes on abandoned agricultural lands) are combined because most land models do not yet distinguish between these two land types.

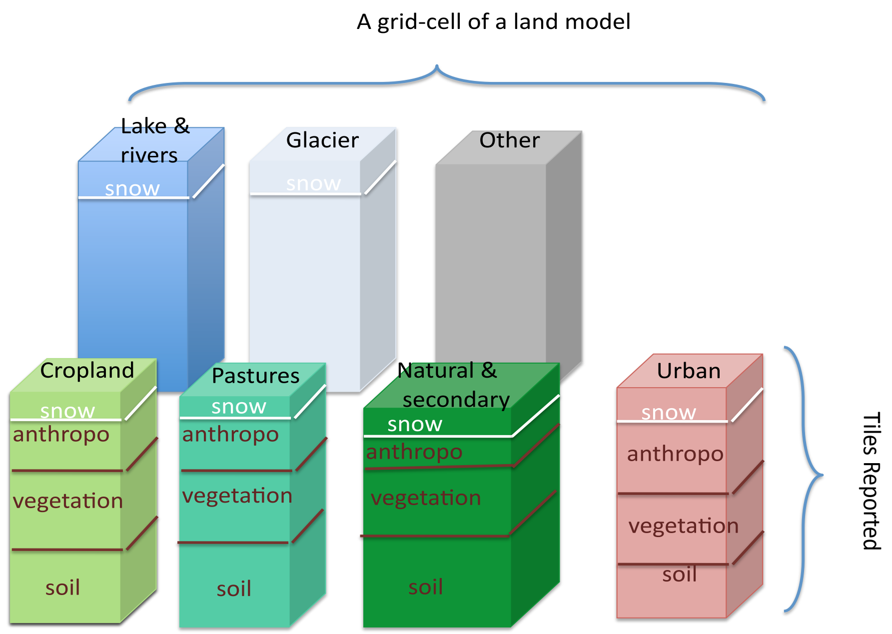

Figure 1.Proposed reporting structure for land-tiles

Tile type	*Tile Suffix*	*Comment*
Urban and rural settlement	*"urb"*	
Primary and secondary lands	*"psl"*	*Forest, grasslands, etc or bare*
Croplands	*"crp"*	
Managed pasturelands	*"pst"*	

For selected key variables, data is requested for each tile separately, in addition to the grid cell mean. The tiles containing biogeochemical information will report up to four stocks of biogeochemical tracers (e.g. Carbon, Nitrogen) – vegetation, soil, litter, and anthropogenic storage. The latter is used in a subset of land models and reflects the fact that some harvested carbon is not released into the atmosphere immediately, but rather with some time-delay from a year to century (e.g., wood products, food)

2.2 Variables reported by tile

Subgrid tile variables should be submitted according to the following structure, using Leaf Area Index (LAI) as an example:

laiLut(lon, lat, time, landusetype4)

landusetype4 dimension with the order spl, crp, pst, urb where "spl" = secondary and primary land, "crp" = cropland, "pst" = pastureland, and "urb" = urban.

Notes for tiled variable reporting: Sum of fractional area for urb+spl+crp+pst may not add up to 1 for grid cells with lakes or glaciers. If a model does not represent one of the requested tiles, then it should be reported as missing value. In cases where more than one land use tile shares information (e.g., if pastureland and cropland share same soil column), then duplicate information should be provided for both tiles. Further details on tile reporting will be included in the LUMIP GMD paper.

A limited set of variables are requested (see LUMIP data request spreadsheet) including variables that describe (a) the subgrid structure and how it evolves through time, (b) biogeochemical fluxes, (c) biogeophysical variables, and (d) LULCC carbon transfers, and (e) carbon stocks on land use tiles.

We recognize that models have very different implementation of LU processes and may only be able to report a subset of variables.