Advancing our understanding of the impacts of historic and projected land use in the Earth System

The Land Use Model Intercomparison Project (LUMIP)

Chairs: David Lawrence (NCAR) and George Hurtt (University of Maryland)

SSG: Almut Arneth, Victor Brovkin, Kate Calvin, Andrew Jones, Chris Jones, Peter Lawrence, Nathalie de Noblet-Ducoudré, Julia Pongratz, Sonia Seneviratne, Elena Shevliakova

with input from many from Earth System Modeling, Integrated Assessment Modeling, and historical land use communities

https://cmip.ucar.edu/lumip
LUMIP Goals

What are the effects of land use and land-use 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 against climate change?

- Fossil fuel vs. land use change
- Biogeochemical vs. biogeophysical impact of land use
- Land cover vs. land management impacts
- Modulation of land use impact on climate by land-atmosphere coupling strength (LS3MIP)
- Modulation of global CO$_2$ fertilization by land use

CMIP6 Questions: How does Earth System respond to forcing?
WCRP Grand Challenge: Biospheric forcings and feedbacks, Water Availability, Climate Extremes
LUMIP Major Activities

• Data standardization
  – Repeat and mature land use harmonization process → enhanced land-use data set for CMIP6, passing maximum amount of common information between relevant communities (Historical, IAMs, ESMs)
  – Provide additional required land management datasets
  – Data output: new variables, subgrid land-use tile variables

• Model experiments
  – Experiments designed to isolate, quantify, and understand land use and land management effects on climate

• Model metrics and diagnostics
  – Develop metrics to assess/quantify model performance with respect to land use impacts on climate
  – Synthesis activity to collect existing metrics
LUMIP/LU Forcing Timeline

- 2013 Summer: Concept, Aspen AGCI
- 2014 July-August: GEWEX, Hamburg, Aspen meetings
- 2014 September: LUMIP proposal to CMIP submitted
- 2015 January: Prototype Land-use dataset released (v0.1)
- 2015 July: CMIP6 Endorsement
- 2015 October: WGCM/CMIP6/LandMIP workshops
- 2016 January: Historic land-use dataset released (LUH2_v1.0)
- 2016 March: GMD papers submitted
- 2016 September: GMD paper published
- 2016 October: LUH2_v2.0h released
LUMIP Experimental Design

Overall Approach:
Two parts: 1) idealized simulations, 2) realistic simulations
Tiered prioritization of experiments
Includes coupled and land-only simulations (520 yrs Tier 1 GCM/ESM)

Part 1  Idealized model experiments:
Improve process understanding/assessment of how models represent impact of changes in land state on climate;
Quantify model sensitivity to potential land cover and land management changes

Part 2  Realistic model experiments:
Isolate the role of historical and future land cover/use change on climate relative to other forcings, assess potential for climate mitigation through land use
Idealized global deforestation
GCM (Tier 1)

- Remove 20 million km$^2$ forest over 50 years from top 30% forest area grid cells, starting from 1850 control
- Controlled assessment of coupled model response to deforestation
Historic period No LULCC experiments
GCM and land-only (Tier 1)

• Assess impact of LULCC in historical period for water, carbon, energy fluxes and climate (C4MIP, LS3MIP)
• Assess land model response to historic LULCC (LS3MIP)
• Assess how land-atmosphere coupling strength modulates climate, weather, extremes response to LULCC (LS3MIP)
• Relevant for detection and attribution (DAMIP)

Built off of and compared to CMIP6 historical
Long pre-industrial control will be utilized in signal-to-noise analysis

NOTE: Guidance as to definition of “No LULCC” provided in LUMIP GMID paper, but implementation will be model dependent; contact LUMIP SSC with questions
Land cover change vs land management experiments (Phase 1, Tier 2)

Set of land-only historic simulations (variants of LMIP-Hist) with one-at-a-time modification of particular aspects of land management; Evaluate impact of land use on fluxes of water, energy, and carbon

1. Year 1700 instead of 1850 start
2. No LULCC change
3. Alternate land use histories
4. No shifting cultivation
5. Crop and pasture as unmanaged grassland
6. Crops with crop model but no irrigation/fertilization
7. No irrigation
8. No fertilization
9. No wood harvest
10. No grazing on pastureland
11. Constant 1850 CO₂ (N dep?)
12. Constant climate
Shifting cultivation

- Shifting cultivation (gross LU transition)
- Without shifting cultivation (net LU transition)
- State after gross transition
- State after net transition
### Land use change impact on future climate expts

<table>
<thead>
<tr>
<th>Main Scenario</th>
<th>SSP1-2.6</th>
<th>SSP3-7</th>
<th>SSP5-8.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSP1-2.6</td>
<td>ScenarioMIP Conc.-driven</td>
<td>LUMIP Conc.-driven</td>
<td></td>
</tr>
<tr>
<td>SSP3-7</td>
<td>LUMIP Conc.-driven</td>
<td>ScenarioMIP Conc.-driven</td>
<td></td>
</tr>
<tr>
<td>SSP5-8.5</td>
<td>LUMIP Emissions-driven</td>
<td></td>
<td>C4MIP Emissions-driven</td>
</tr>
</tbody>
</table>

A. Forest Area

- SSP1-2.6
- SSP5-8.5
- SSP3-7
Subgrid land-use tile data request

LUMIP is requesting sub-grid information for four sub-grid categories (i.e., tiles) for selected variables to permit more detailed analysis of land-use induced surface heterogeneity. The four categories are:

1. Primary and secondary land
2. Cropland
3. Pastureland
4. Urban
Subgrid land-use tile data request

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1. Primary and secondary land
2. Cropland
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Selected Subgrid Variables (not the full list, see LUMIP website)

**Biogeophysical variables**
- tasLut – near-surface air temperature
- hussLut – near-surface specific humidity
- hflsLut – latent heat flux
- hfssLut – sensible heat flux
- rsusLut – surface upwelling shortwave (albedo)
- laiLut – leaf area index

**Biogeochemical variables, carbon stocks/fluxes**
- gppLut – gross primary productivity
- nppLut – net primary productivity
- cSoilLut – carbon mass in soil pool
- cVegLut – carbon mass in vegetation
- cLitterLut – carbon mass in litter pool

**LULCC fraction changes**
- fracInLut – fraction transferred into land-use type
- fracOutLut – fraction transferred out of LUT

LUMIP LUT vars requested for following expts

- CMIP6 Historical (coupled and land-only)
- ScenarioMIP
- C4MIP scenario expts
- LUMIP

STATUS

New variable names and area_types have been proposed to CF-conventions mailing list and are under discussion
Example aggregation onto Land-Use Tiles for CLM

CLM tiling structure

Gridcell

Landunit

Vegetated

Lake

Urban

Glacier

Crop

Column

Soil

Roof

Sun Wall

Shade Wall

Pervious

Unirrig

Irrig

TBD

MD

HD

CLM

structure

PFT

PFT1

PFT2

PFT3

PFT4 ...

Crop1

Crop1

Crop2

Crop2 ...

PFT
Example aggregation onto Land-Use Tiles for CLM

CLM tiling structure

Landunit
- Vegetated
- Lake
- Urban
- Glacier
- Crop
- Pasture

Column
- Soil
- Roof
- Sun Wall
- Shade Wall
- Pervious
- Unirrig
- Irrig
- Unirrig
- Irrig

PFT
- PFT1
- PFT2
- PFT3
- PFT4
- Crop1
- Crop2
- Crop2
Land Use Metrics and Diagnostics

- Task: Develop/collect set of metrics to assess/quantify model performance with respect to land use impacts on climate
- Synthesis activity/paper of existing metrics (Edouard Davin has initiated for biogeophysics)

Tropical pasture vs rainforest

Tropical farmland vs rainforest

ΔT_s or ΔT (K)

- Observed ΔT
- Observed ΔT_s
- Calculated ΔT_s
- Radiative forcing
- Energy distribution associated with changes in roughness
- Energy distribution associated with changes in Bowen ratio
LUMIP HOME

LUMIP | LAND USE MODEL INTERCOMPARISON PROJECT

- LUMIP Proposal to CMIP Panel - Updated June 10, 2015
- Proposed LUMIP Experiments List for CMIP6 - see Experiments tab and look for LUMIP
- LUMIP New Variables List for CMIP6 - see New variables tab
- Land Use Harmonization (LUH2 v0.2) README - September 9, 2015
- Land Use Harmonization (LUH2 v0.1) README - January, 2015

LUMIP GOOGLE GROUP

We will update the LUMIP community on simulations and datasets and make plans for analysis through this google group. To sign up, click here

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.

PRIMARY CONTACTS

- George Hurtt (gchurtt@umd.edu, U. Maryland)
- Dave Lawrence (dlawren@ucar.edu, NCAR)

SCIENTIFIC STEERING COMMITTEE

Almut Arneth (KIT), Victor Brovkin (Max Planck), Kate Calvin (PNNL), Andrew Jones (LBNL), Chris Jones (Hadley Centre), Peter Lawrence (NCAR), Nathalie de Noblet Ducoudré (IPSL), Julia Pongratz (Max Planck), Sonia Seneviratne (ETH-Zurich), Elena Shevliakova (GFDL)

https://cmip.ucar.edu/lumip
LUMIP/LU Forcing Timeline

- 2016 (autumn) through 2018: Model simulations
  - Ideally, groups would run land-only simulation first and benchmark simulated/imposed land cover time series
  - Also preferred that groups run the idealized deforestation experiment early
- 2016 December: LUH2 harmonized datasets for SSPs released ???
- 2017 Begin analysis (coordination through LUMIP SSG)
- 2017 Land-use change impacts metrics/benchmarks synthesis papers
- 2018 Spring: possible joint LUMIP, C4MIP, LS3MIP meeting
- 2018 Summer: possible LUMIP meeting to present/discuss papers/analysis
- 2021 IPCC AR6?
**Land-use Forcing**

**FUTURES:** In progress now (6). Finalizing input datasets from IAMs, generating draft harmonized datasets, reviewing and iterating with each IAM teams as needed, monthly with all IAM teams.

**HISTORICAL: LUH2 v2h Release (10/14/16):** The updated release of the historical land-use forcing dataset (LUH2 v2h) covers the period 850-2015 and corrects all known issues and notices identified with the previous version (LUH2 v1.0h). This dataset replaces the previously released dataset (LUH2 v1.0h). This product is the result of a series of prototypes released previously, uses the established data format, and will connect smoothly to gridded products for the future. Additional ‘High’ and ‘Low’ historical products in development.

**Data Availability:** http://luh.umd.edu (available), CMIP (in progress)

**LUMIP:** Paper published (Lawrence et al 2016), Kickoff telecon October 26, 2016.
Acknowledgements

**DOE-SciDAC:** Louise Chini (UMD), Steve Frolking (UNH), Ritvik Sahajpal (UMD), Matt Hansen (UMD), Dave Lawrence (NCAR), Peter Lawrence (NCAR), Peter Thronton (DOE), Bill Collins (LBL), Andy Jones (LBL), Jay Edmonds (JGCRI), Kate Calvin (JGCRI), Kees Klein Goldewijk (PBL)

**LUMIP-SSG:** Dave Lawrence (NCAR), Almut Arneth (KIT), Victor Brovkin (MPI), Kate Calvin (JGCRI), Andy Jones (LBL), Chris Jones (UKMO), Peter Lawrence (NCAR), Nathalie de Noblet-Ducoudré (IPSL), Julia Pongratz (MPI), Sonia Seneviratne (ETH), Elena Shevliakova (GFDL)

**Other:** Ole Mertz (KU), Andreas Christensen (KU), Justin Fisk (UMD), Andreas Heinimann (UBE), Johann Jungclaus (MPI), Jed Kaplan (EPFL), Fernando Sedano (UMD)
LUH2 Major Attributes for CMIP6

- LUH2 v2h (historical update) released October 14, 2016
- Updated Common history Reference, + High and low* cases
- Multiple harmonized futures, CMIP6 ScenarioMIP (6), Added 1.5 degree cases* (6)
- Spatial domain, Global
- Spatial resolution, 0.25 x 0.25 degree
- Temporal domain, 850-2100 (850-2300*)
- Temporal resolution, annual
- 12 possible land-use states including separation of Primary and Secondary natural vegetation into Forest and Non-forest sub-types, Pasture into Managed Pasture and Rangeland, and Cropland into multiple crop functional types (C3 annual, C3 perennial, C4 annual, C4 perennial, N fix)
- >100 possible land-use transitions per grid cell per year, including crop rotations, shifting cultivation, ag changes, wood harvest
- Updated static basemaps, historical inputs, shifting cultivation estimates
- F/NF (LandSat) constraints
- Gridded agriculture management layers including irrigation, fertilizer, tillage*, and biofuel management
- Partitioning of woof harvest fuel/non-fuel
- Expanded Diagnostic Package

>50x CMIP5 data
LUH2 v1.0h (April 29, 2016)

Lawrence et al 2016
Global Agricultural Area: HYDE 3.2* and HYDE 3.1

LUH2 v1.0h (April 29, 2016)
Annual Changes in Global Agricultural Area: HYDE 3.2* and HYDE 3.1

LUH2 v1.0h (April 29, 2016)
Expanded Diagnostic Package (Tabular, Examples 65)

<table>
<thead>
<tr>
<th>Diagnostic</th>
<th>Time-period</th>
<th>Region</th>
<th>LUH2_v2h</th>
<th>LUH2_v1b</th>
<th>Hurtt 2011 [LUH1]</th>
<th>Hurtt 2006</th>
<th>Units</th>
<th>Reference data</th>
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<tbody>
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<td>* Total Cropland area</td>
<td>1990</td>
<td>Global</td>
<td>15.17</td>
<td>15.17</td>
<td>15.13</td>
<td>12.3</td>
<td>10^6 km^2</td>
<td></td>
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<td>* Total Pasture area</td>
<td>1990</td>
<td>Global</td>
<td>32.72</td>
<td>32.72</td>
<td>33.13</td>
<td>25.8</td>
<td>10^6 km^2</td>
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<tr>
<td>* Primary land area</td>
<td>1990</td>
<td>Global</td>
<td>56.15</td>
<td>55.7</td>
<td>54.57</td>
<td>57.7</td>
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<td>4 Total gross transitions</td>
<td>2000</td>
<td>Global</td>
<td>1.86</td>
<td>1.85</td>
<td>2.90</td>
<td>0.55 - 4.2</td>
<td>10^6 km^2</td>
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<tr>
<td>5 Total net transitions</td>
<td>2000</td>
<td>Global</td>
<td>0.23</td>
<td>0.22</td>
<td>0.17</td>
<td>0.0 - 0.17</td>
<td>10^6 km^2</td>
<td></td>
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<tr>
<td>* Median secondary forest mean age</td>
<td>2015</td>
<td>Global</td>
<td>43.78</td>
<td>37.18</td>
<td>n/a</td>
<td>n/a</td>
<td>years</td>
<td>30 - 40 years, Ben Poulter, NACP 2013</td>
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<td>18 Secondary land increase</td>
<td>1700 - 2000</td>
<td>Global</td>
<td>13.18</td>
<td>12.25</td>
<td>17.19</td>
<td>10.0-44.0</td>
<td>10^6 km^2</td>
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<td>24 Agricultural land undergoing shifting cultivation</td>
<td>2000</td>
<td>Global</td>
<td>0.32</td>
<td>0.32</td>
<td>0.58</td>
<td>0.48-0.65</td>
<td>10^6 km^2/yr</td>
<td>Andreas, Ole personal communication: 0.3</td>
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<tr>
<td>27 * Total wood clearing</td>
<td>850 - 1990</td>
<td>Global</td>
<td>356.16</td>
<td>336.97</td>
<td>336.97</td>
<td>n/a</td>
<td>Pg C</td>
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<td>37 * Forest area</td>
<td>2015</td>
<td>Global</td>
<td>37.21</td>
<td>36.68</td>
<td>n/a</td>
<td>n/a</td>
<td>10^6 km^2</td>
<td>Sexton, 2016: 32.1-41.4</td>
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<tr>
<td>44 * Fertilizer use</td>
<td>2012</td>
<td>Global</td>
<td>106.60</td>
<td>105.89</td>
<td>n/a</td>
<td>n/a</td>
<td>Tg N/yr</td>
<td>Zhang, 2016: 100</td>
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<tr>
<td>45 * Irrigated area</td>
<td>2003</td>
<td>Global</td>
<td>2.51</td>
<td>2.51</td>
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<td>n/a</td>
<td>10^6 km^2</td>
<td>FAO: 2.77</td>
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<td>50 * Plant total biomass on all lands</td>
<td>Potential</td>
<td>Global</td>
<td>718.11</td>
<td>749.94</td>
<td>731.0545424</td>
<td>Pg C</td>
<td>Kucharik, 2000: 557.4, Sitch, 2003: 923; Pan, 2013: 772</td>
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<td>52 * Plant AGB on pantropical forest lands</td>
<td>2007 - 2008</td>
<td>Pantropical</td>
<td>184.23</td>
<td>177.87</td>
<td>176.6110456</td>
<td>Pg C</td>
<td>Avitabile, 2016: 187.5</td>
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<td>59 * Plant total biomass on all lands</td>
<td>2005</td>
<td>Global</td>
<td>434.31</td>
<td>422.35</td>
<td>430.8956451</td>
<td>Pg C</td>
<td>Pan, 2013: 393.4; (annualreviews.org, Table 2)</td>
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LUH2 v2h (Oct 14, 2016)
## Future Scenarios (ScenarioMIP)

### Table 2. ScenarioMIP experimental design.

<table>
<thead>
<tr>
<th>Scenario name</th>
<th>Forcing category</th>
<th>2100 forcing $^1$ (W m$^{-2}$)</th>
<th>SSP</th>
<th>Use by other MIP$^2$s $^5$</th>
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<tr>
<td>Tier 1$^3$</td>
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<td>SSP5-8.5</td>
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<td>8.5</td>
<td>5</td>
<td>C$^4$MIP, GeoMIP, ISMIP6, RFMIP</td>
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<td>SSP3-7.0</td>
<td>High</td>
<td>7.0</td>
<td>3</td>
<td>AerChemMIP, LUMIP</td>
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<td>SSP2-4.5</td>
<td>Medium</td>
<td>4.5</td>
<td>2</td>
<td>VIACS AB, CORDEX, GeoMIP, DAMIP, DCPP</td>
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<tr>
<td>SSP1-2.6</td>
<td>Low</td>
<td>2.6</td>
<td>1</td>
<td>LUMIP</td>
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<tr>
<td>Tier 2</td>
<td></td>
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<tr>
<td>21st century scenarios</td>
<td></td>
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<tr>
<td>SSP4-6.0</td>
<td>Medium</td>
<td>5.4</td>
<td>4</td>
<td>GeoMIP</td>
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<tr>
<td>SSP4-3.4</td>
<td>Low</td>
<td>3.4</td>
<td>4</td>
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<tr>
<td>SSP5-3.4-OS</td>
<td>Overshoot</td>
<td>3.4</td>
<td>5</td>
<td></td>
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<tr>
<td>SSPa-b</td>
<td>Low</td>
<td>Around or below 2.0</td>
<td>1 (prelim.)</td>
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### Ensembles$^4$

<table>
<thead>
<tr>
<th>Scenario name</th>
<th>Forcing category</th>
<th>2100 forcing $^1$ (W m$^{-2}$)</th>
<th>SSP</th>
<th>Use by other MIP$^2$s $^5$</th>
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</thead>
<tbody>
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<td>SSP3-7.0</td>
<td>Nine-member ensemble</td>
<td>7.0</td>
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### Extensions

<table>
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<th>Scenario name</th>
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<th>Use by other MIP$^2$s $^5$</th>
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<td>SSP5-8.5-Ext</td>
<td>Long-term extension</td>
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<td>SSP5-3.4-OS-Ext</td>
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</tbody>
</table>

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O’Neill et al 2016

*Received draft data*
Pre-harmonization Comparison LUH2 and IAMs

Cropland area

Pasture area

Forest area

Irrigated area

N Fertilizer usage

LUH2 v2h (Oct 14, 2016)
Draft Harmonization (SSP3-7 AIM)
### Land-Use Harmonization 2 (CMIP6)

**New History**
- Hyde 3.2 based
- Landsat F/NF
- Multiple crop types (5)
- Multiple pasture types (2)
- Updated Forest Cover/B
- Updated Wood harvest
- Updated Shifting Cultivation
- Extended time domain (850-2015)

**New Mgt. Layers**
- **Agriculture**
  - Fraction of cropland irrigated
  - Fraction of cropland flooded
  - Fraction of cropland fertilized
  - Fertilizer application rates
  - Fraction of cropland tilled
  - Fraction of cropland for biofuels
- **Crop rotations**
- **Wood Harvest**
  - Fraction used for industrial products
  - Fraction used for commercial biofuels
  - Fraction used for fuelwood

**New Future Scenarios**
- Six futures, SSP-based

**New Resolution**
- 0.25°

**New Transition Matrix**

```
<table>
<thead>
<tr>
<th></th>
<th>Pri F</th>
<th>Pri NF</th>
<th>Sec F</th>
<th>Sec NF</th>
<th>C3 Ann</th>
<th>C4 Ann</th>
<th>C3 per</th>
<th>C4 per</th>
<th>C3 N-Fix</th>
<th>Pasture</th>
<th>Rangeland</th>
<th>Urban</th>
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~ 50x information content of CMIP5!