Land Use and Land Cover Change in CTSM

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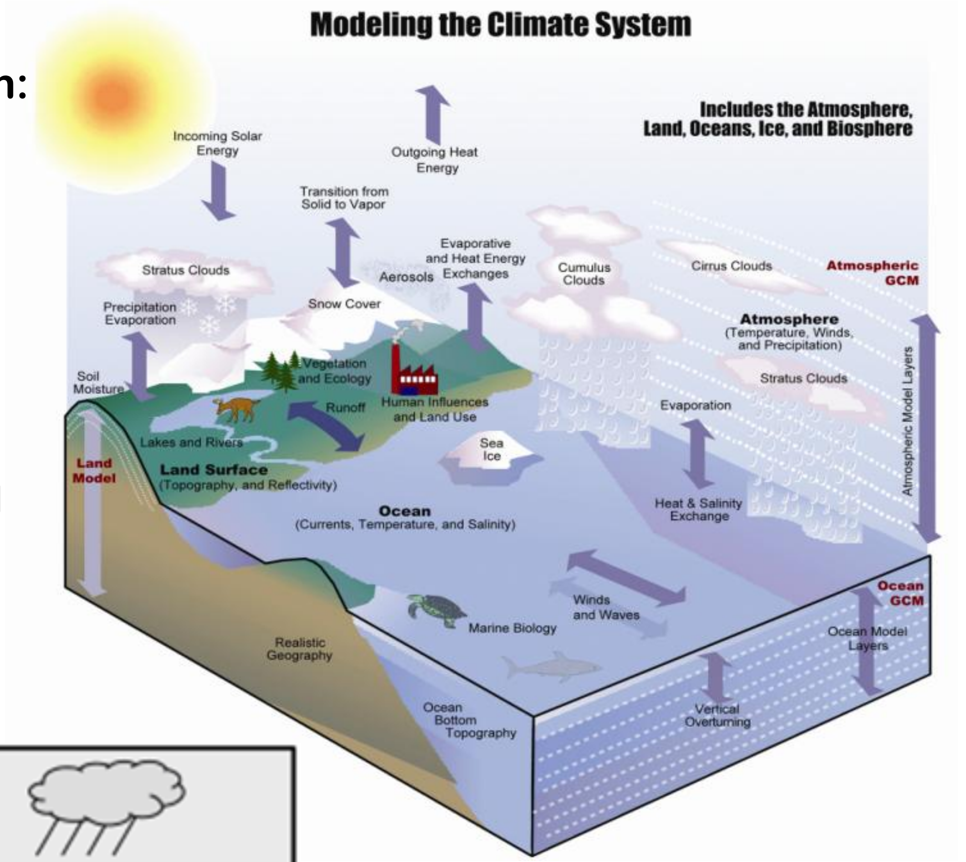
Understanding Human Land Use in the Climate System: Investigations with an Earth System Model (NCAR CESM)

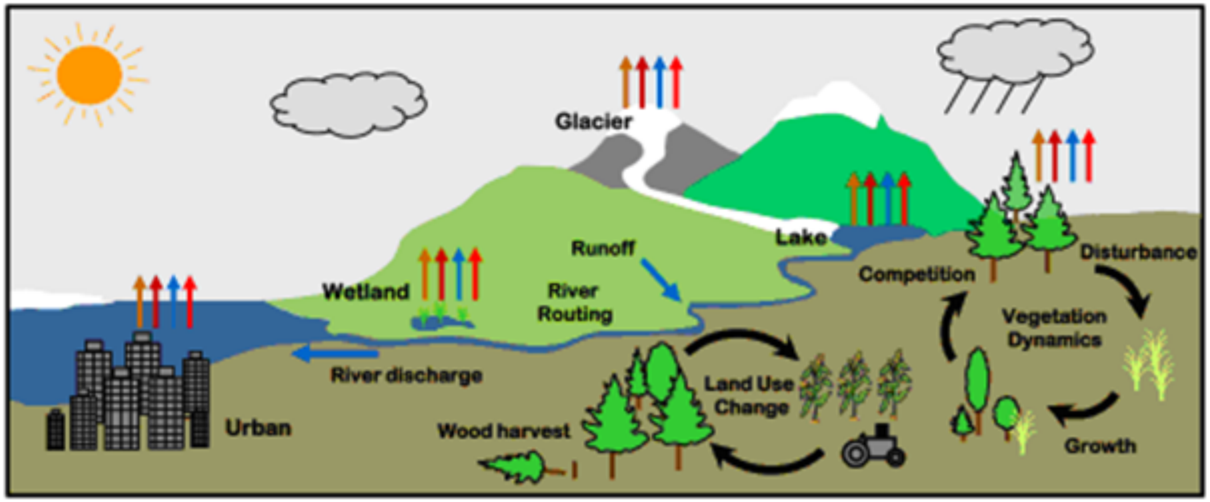


The land is a critical interface through which:

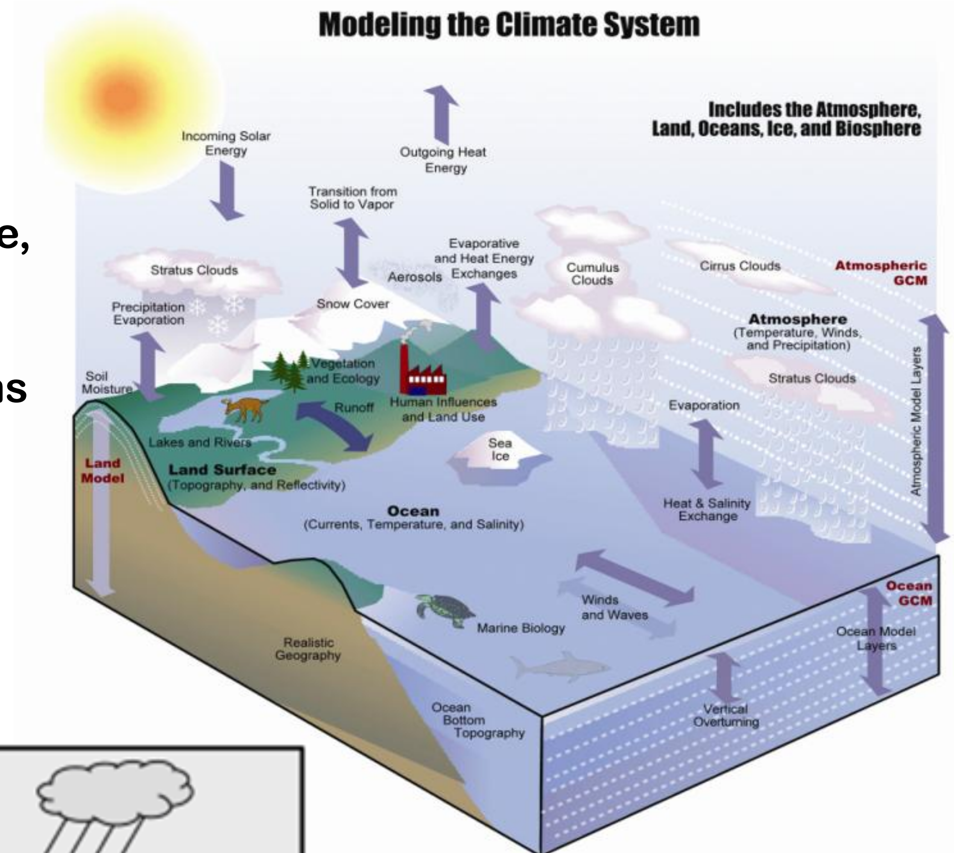
1. Climate and climate change impacts humans and ecosystems

and

2. Humans and ecosystems can force global environmental and climate change



Understanding Human Land Use in the Climate System: Investigations with an Earth System Model (NCAR CESM)

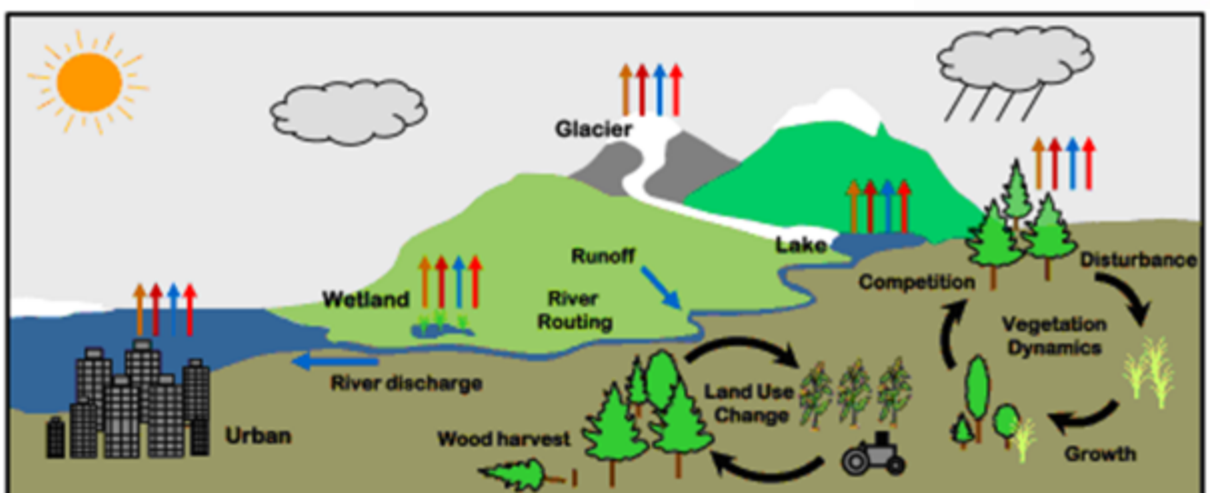


Land Management in CESM:

- How are we transforming Natural Ecosystems through Deforestation, Pasture, Wood Harvesting, or Afforestation?

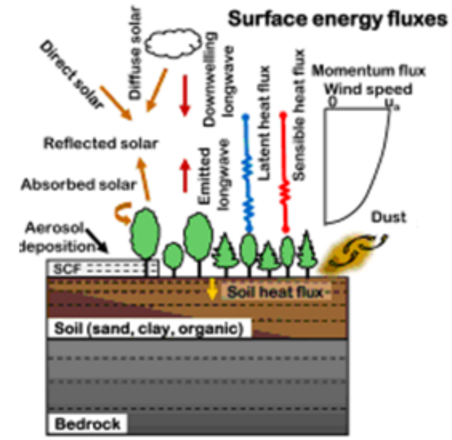
- How will Natural and Disturbed Ecosystems respond to changes in climate and CO_2?

- How will Humanity Feed itself as the population grows, society becomes more affluent, and agriculture is impacted by climate and changing CO_2?

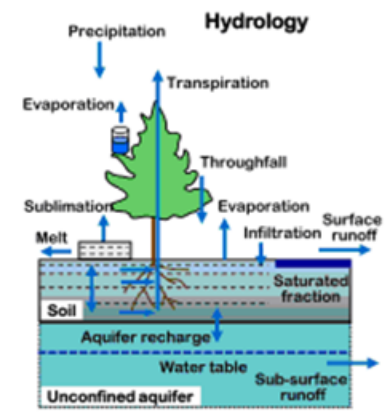


Land Use in the Climate System Changes

1. Surface Energy Fluxes:
- Solar Energy Fluxes (Albedo – Vegetation, Snow, Soils)
- Long Wave Energy Fluxes (Surface Temp & Emissivity)
- Latent Heat Fluxes (Transpiration, Evaporation)
- Sensible Heat Fluxes (Surface Temp & Roughness)



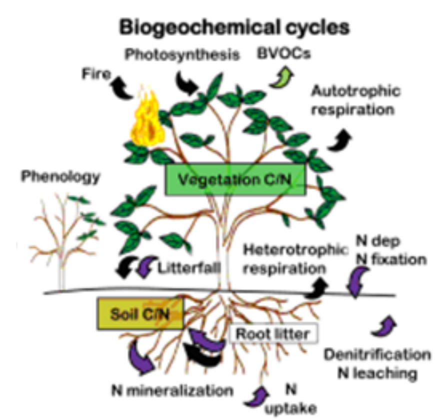
2. Surface Hydrology:
- Rain and Snow (Vegetation, Snow Pack, Runoff)
- Transpiration, Evaporation, Snow melt, Sublimation
- Soil Moisture and Aquifer recharge and drainage
- Climate Feedback through Precipitation Changes



3. Biogeochemistry (Carbon and Nitrogen Cycles):
- Plant Photosynthesis and Respiration

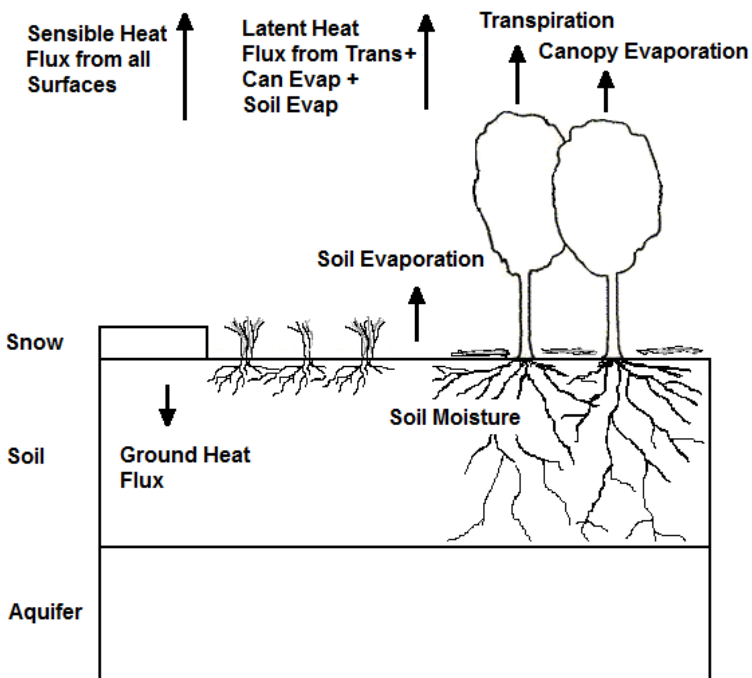
$$6\ CO_2 + 6\ H_2O + light \rightarrow C_6H_{12}O_6 + 6\ O_2$$

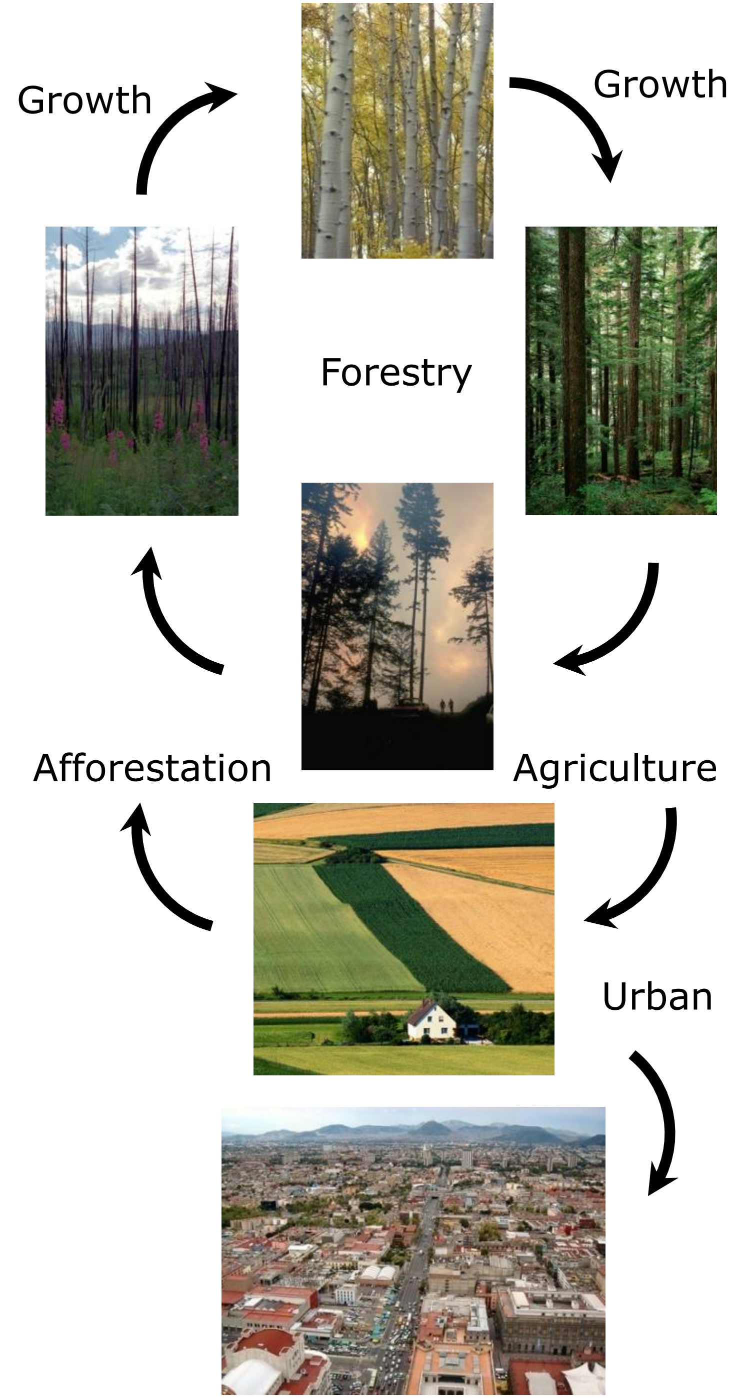
- Carbohydrates are allocated to Leaves, Roots, Wood
- Leaves, roots and wood become litter, debris, soil C
- Organic decomposition and fire remove carbon
- Nitrogen is cycled impacting growth and decay



Land Cover Change Biogeophysics

CLM4 Heat Fluxes





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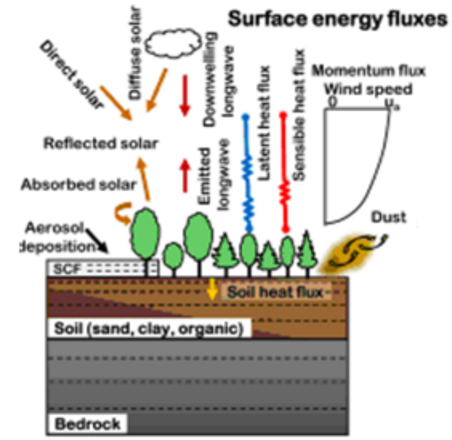

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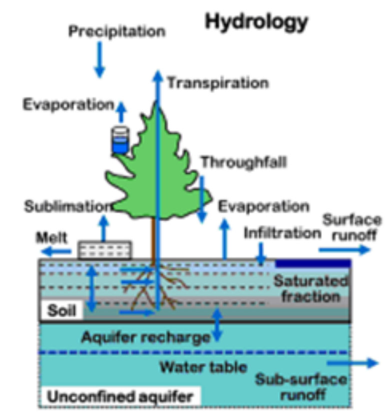

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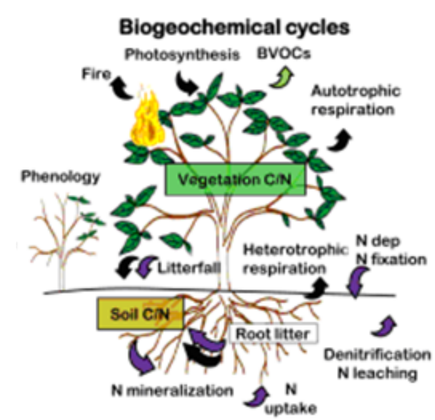

Land Cover Change Hydrology Field Studies

Based on the relationship between Deforestation and Agriculture in 171 catchments, *Zhang et al.* (2001) developed a simplistic vegetation based relationship between Annual Precipitation and Evapo-Transpiration:

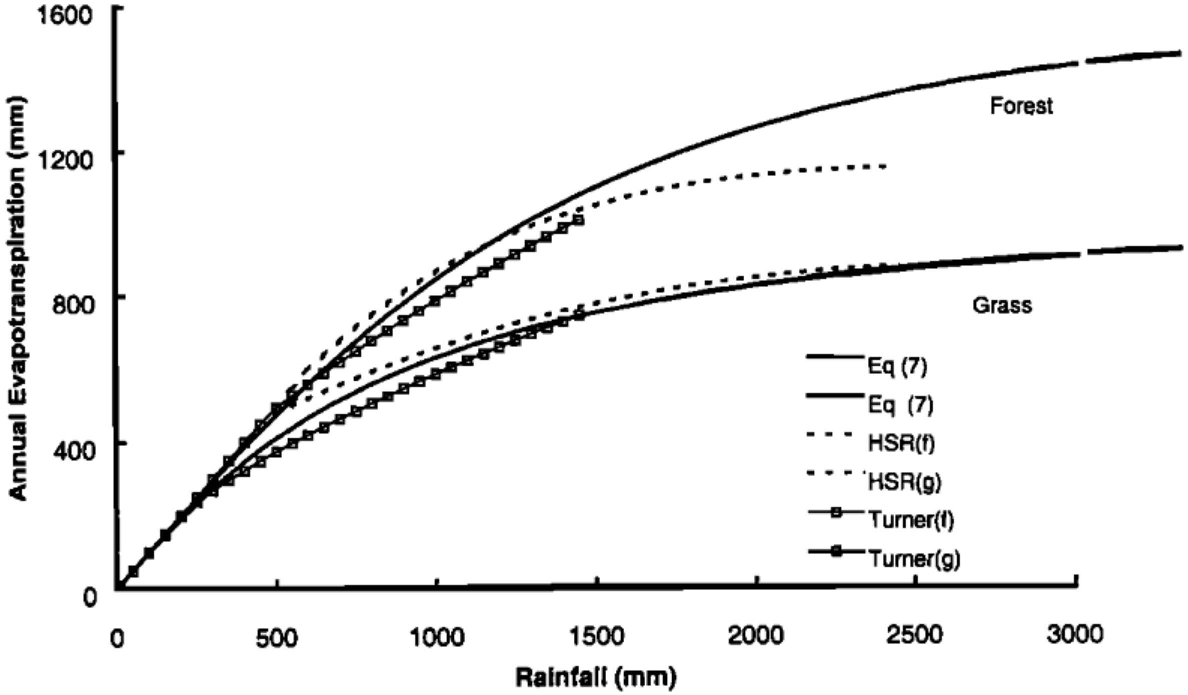

Figure 8. Comparison of equation (8) with the empirical relationships developed by *Holmes and Sinclair* [1986] and *Turner* [1991] for forested and grassed catchments.

Land Use in the Climate System Changes

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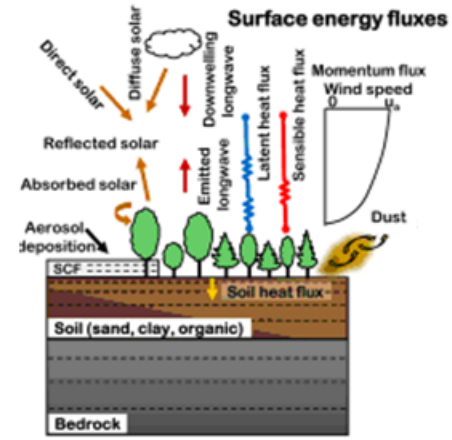

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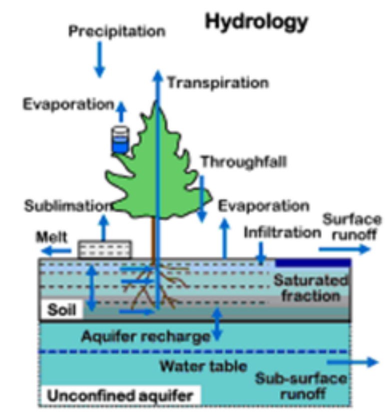

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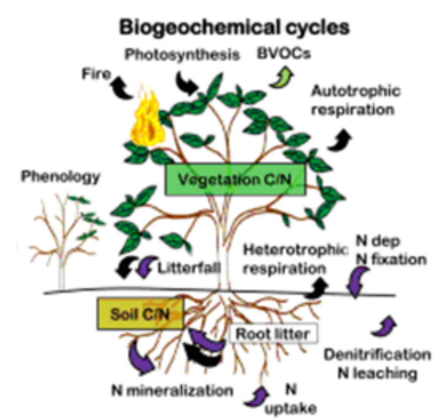
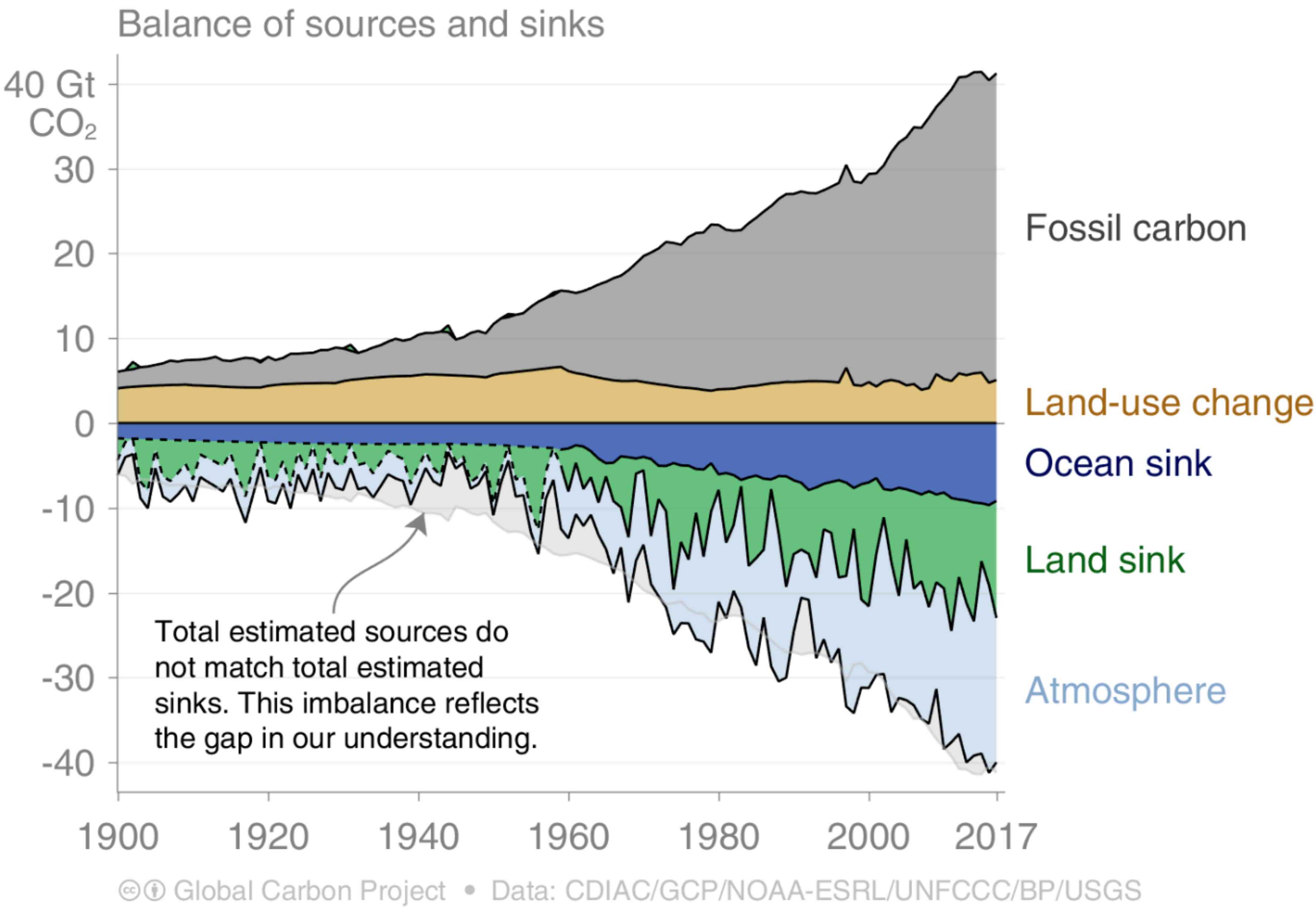


Land Cover Change Contribution to Carbon Emissions



CLM5 CMIP6 – New Land Surface Data Sets

1. Historical and SSP - RCP land use and land cover change time series have been compiled through the Land Use and Scenario Model Intercomparison Projects (LUMIP and ScenarioMIP).

2. The Global Land Model (GLM) has been extended to 12 land units to better represent dynamics of agriculture and forests. The new land units include:

- Primary Forest
- Primary Non Forest
- Secondary Forest
- Secondary Non Forest
- Crop C3 Annual
- Crop C3 Perennial
- Crop C3 Nitrogen Fixing
- Crop C4 Annual
- Crop C4 Perennial
- Grazing Pasture
- Grazing Rangeland
- Urban

3. New management information for Crops and Forests is provided with transient N Fertilizer and Irrigation prescription, and new Wood Harvest

CMIP6 LUMIP CLM5 Land Use Harmonization (LUH2)

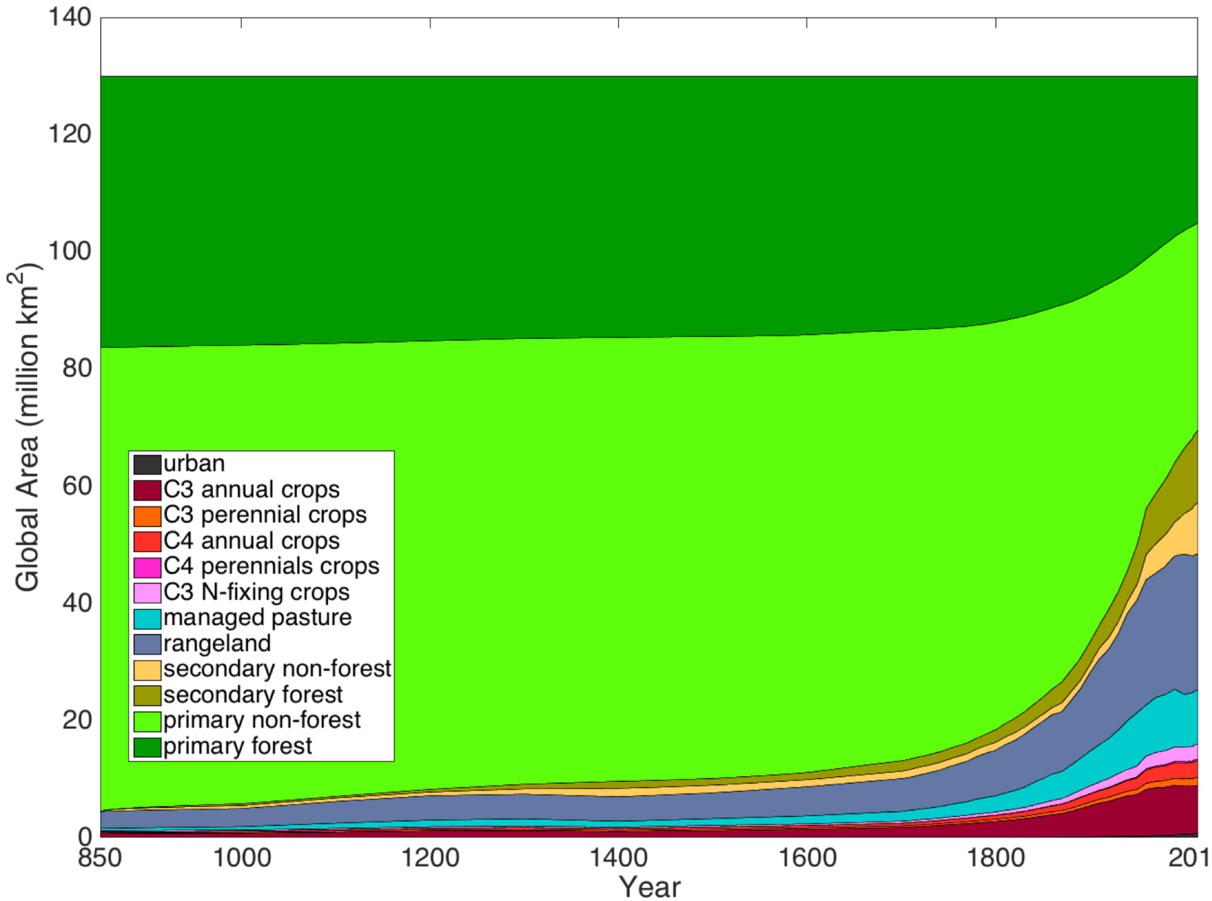
~ 50x information content of CMIP5!

New Resolution
0.25° grid-cell fraction

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

New Management Layers
Agriculture
Fraction of cropland irrigated
Fraction of cropland flooded
Fraction of cropland fertilized
Industrial Fertilizer application
Fraction of cropland for biofuels
Crop rotations
Wood Harvest
Fraction industrial products
Fraction commercial biofuels
Fraction fuelwood

New Future Scenarios
Six futures, SSP-based



CLM5 Human Land Management

CESM2 and CLM5 specify Land Use and Land Cover Change through annually prescribed natural vegetation and crop distributions that are combined with human management. The LUMIP/CMIP6 time series require that annual grid cell data is generated that represents:

- Changes in forest cover through time from the Forest / non forest information provided by the LUH2 time series (this was inferred in CMIP5).

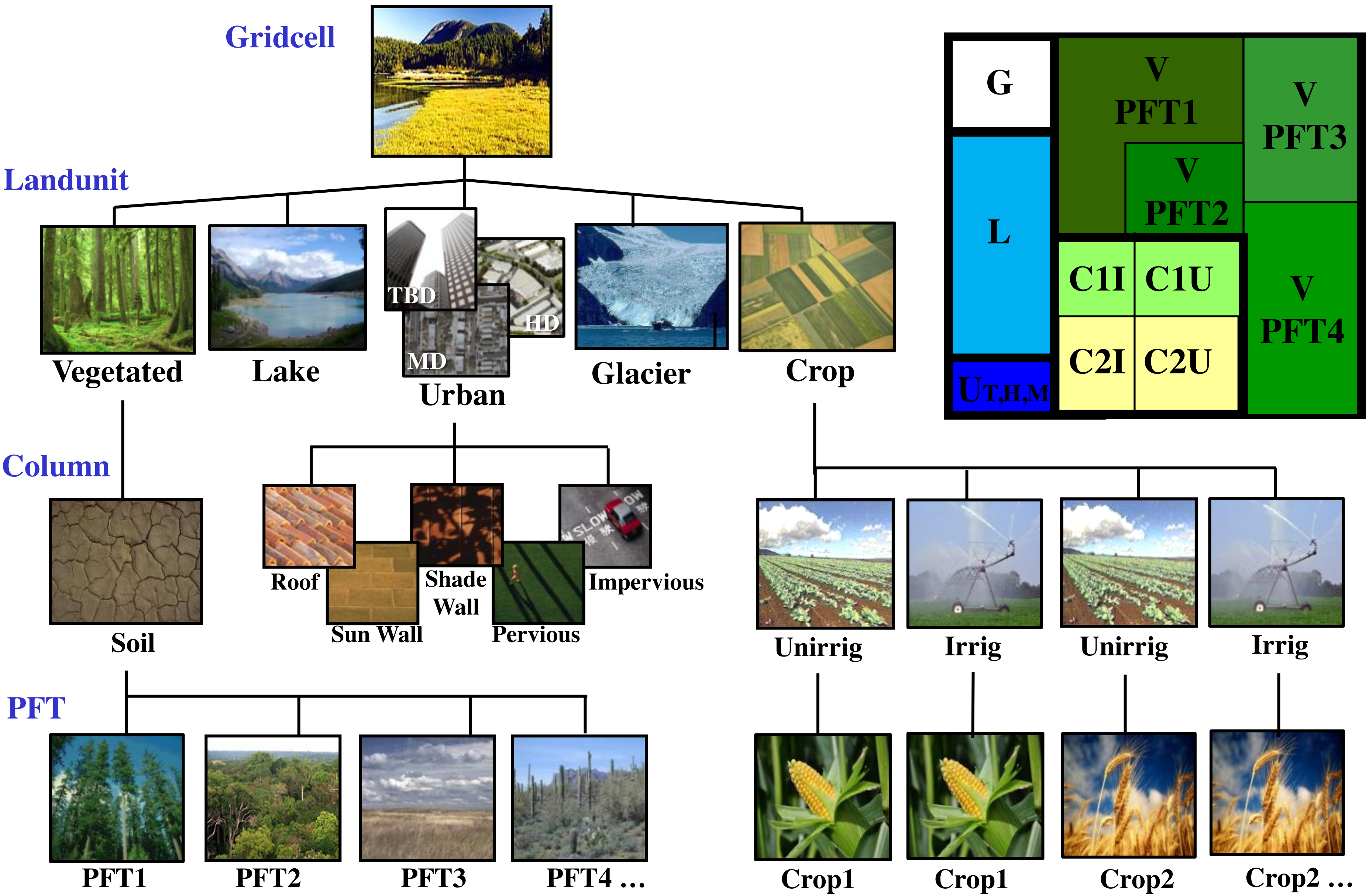
- Wood Harvest prescribed in a carbon amount to be extracted as biomass rather than a fraction of trees as was done in CLM4 CN

- Transient C3/C4 Crops of the LUMIP time series be modeled with the CLM5 Crop model which specifies planting dates, life histories and harvest rules for 32 individual crops for each grid cell and each year (only maize, cotton, rice, sugarcane, soybean, and wheat are currently parameterized)

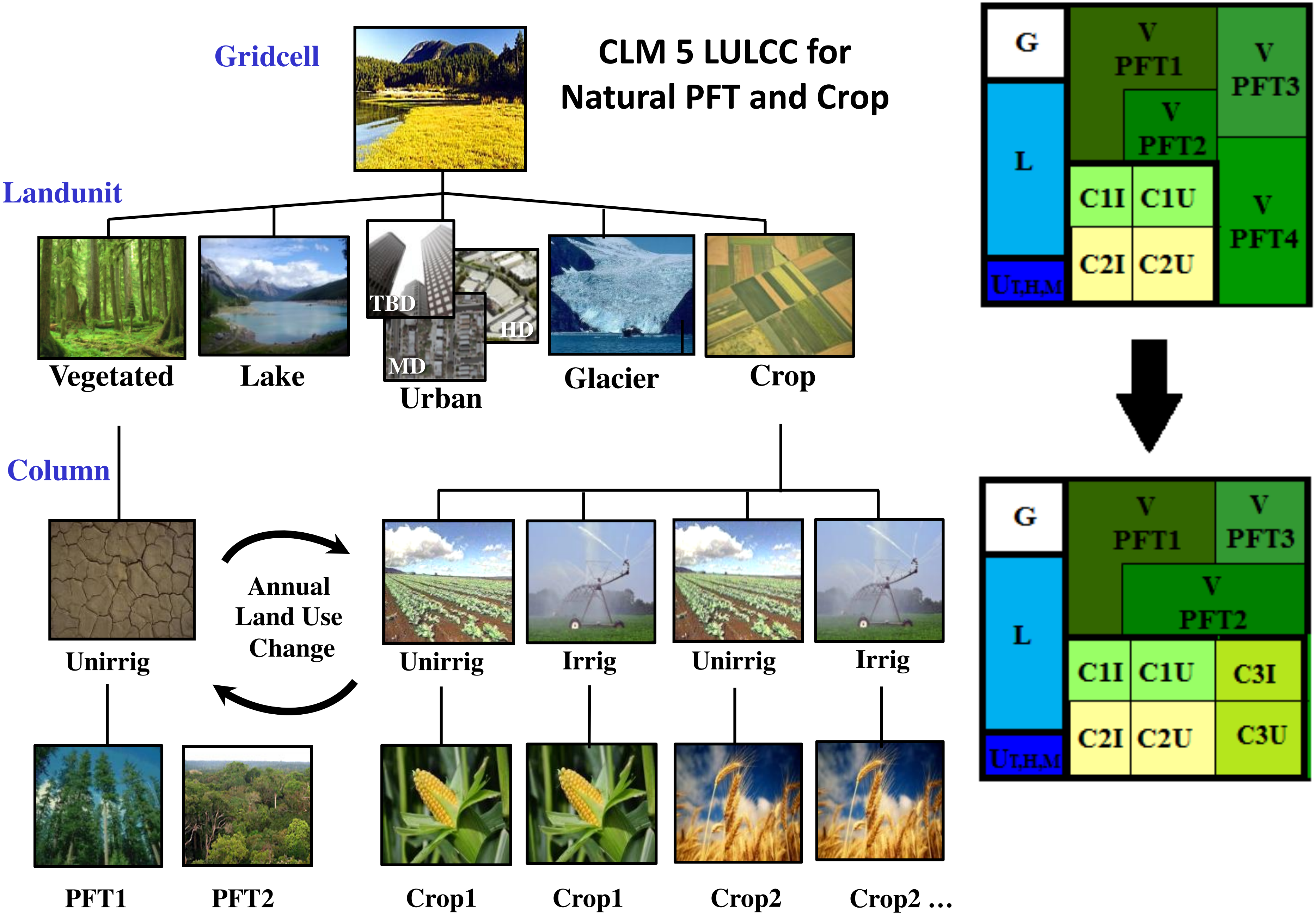
- Fertilizer and irrigation management are specified by crop and grid cell for every year of the time series

- CLM5 has optional Shifting Cultivation captured through Gross Transitions

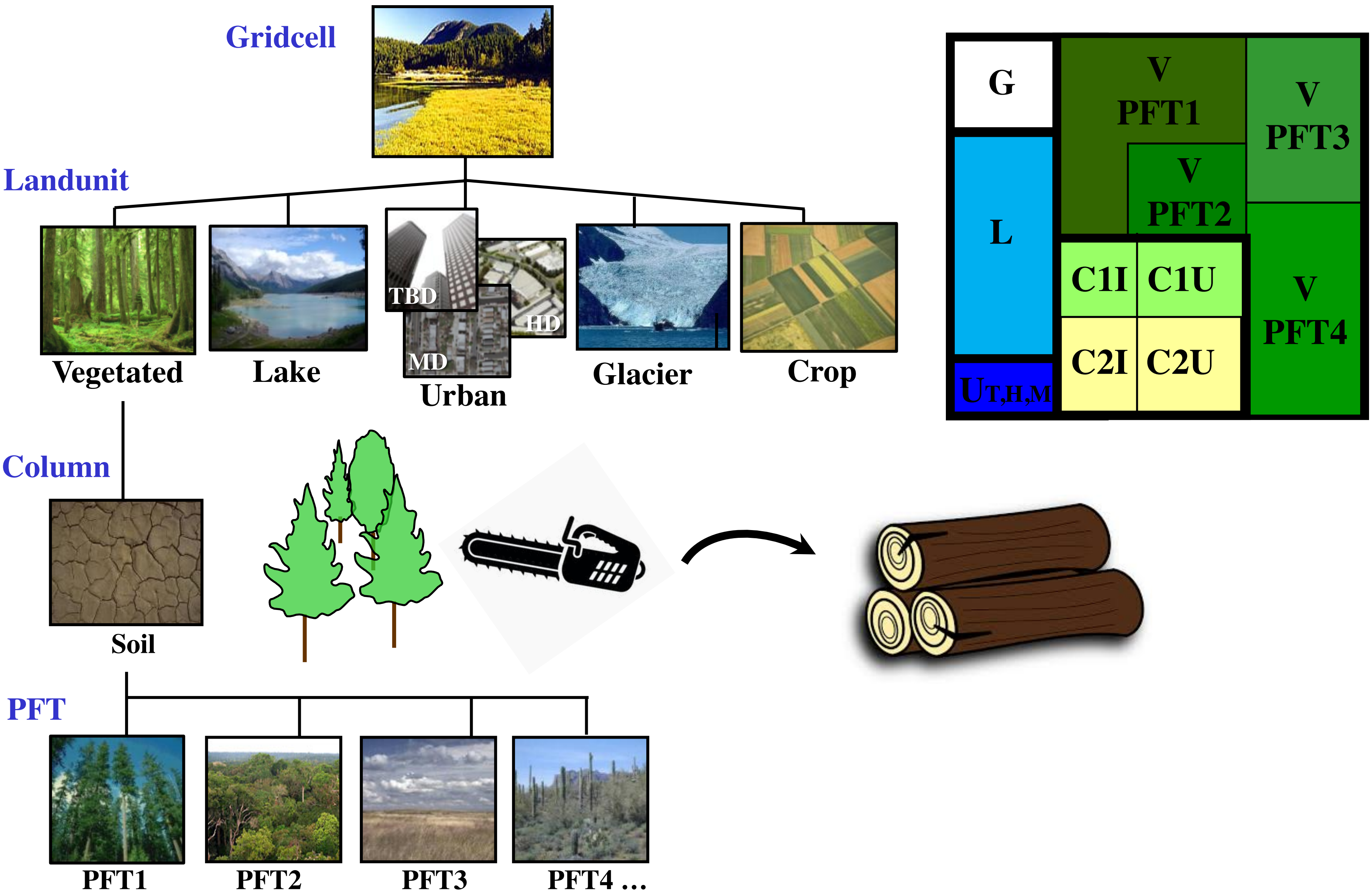
CLM5 Land Use and Land Cover Change Representation



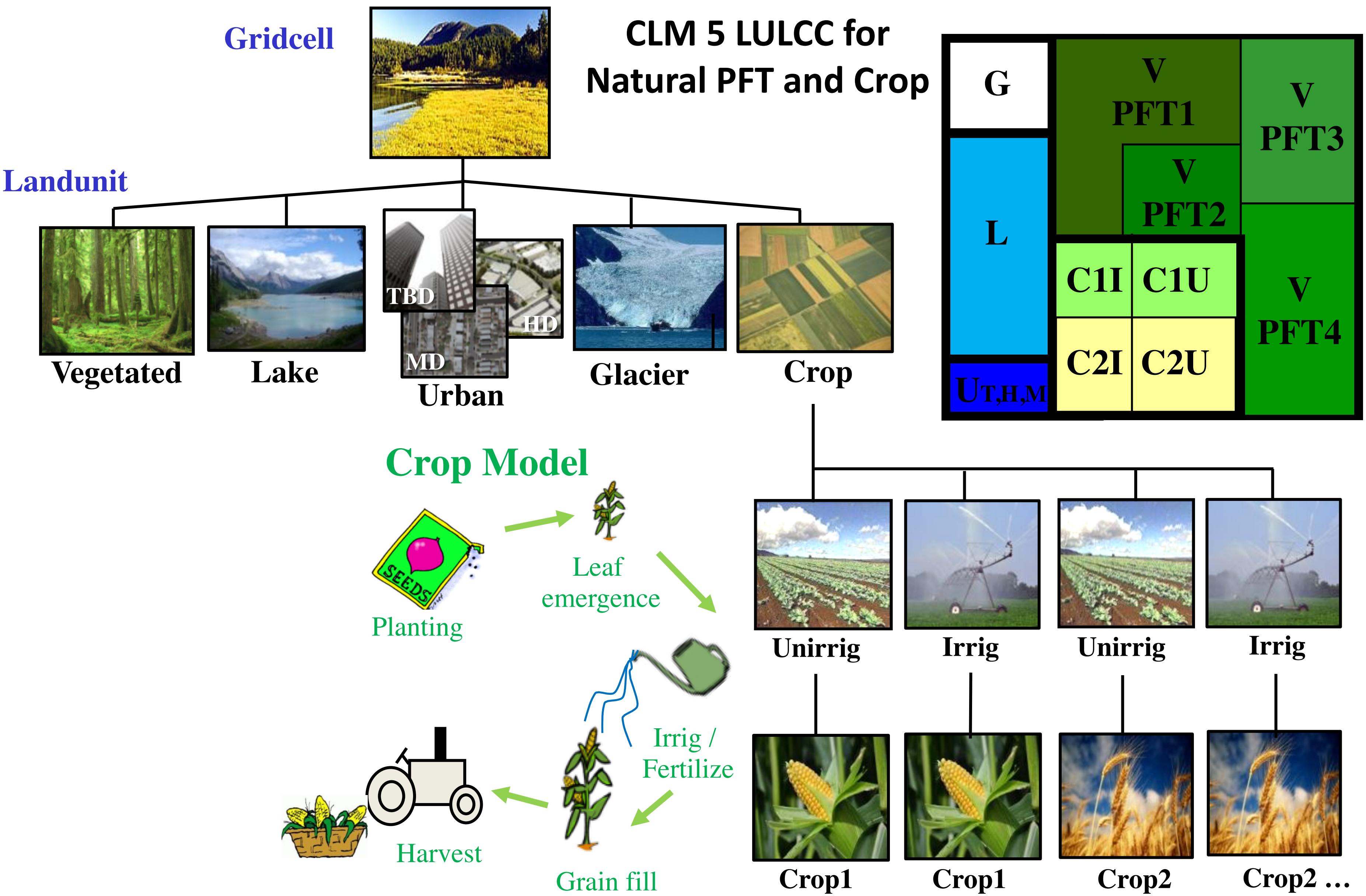
CLM5 Land Cover Change – Prescribed Annual Changes



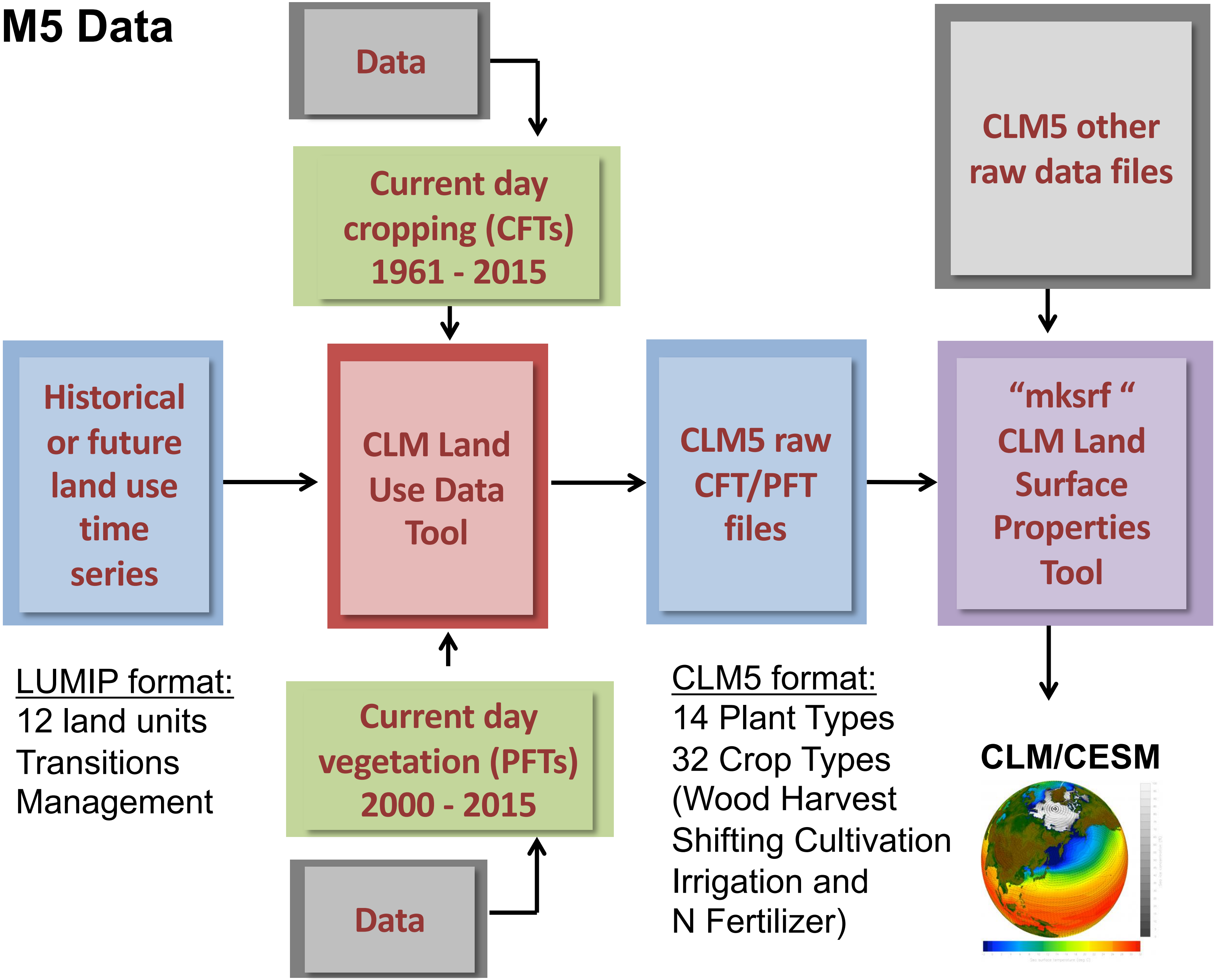
CLM5 Land Use – Prescribed Wood Harvest (biomass)



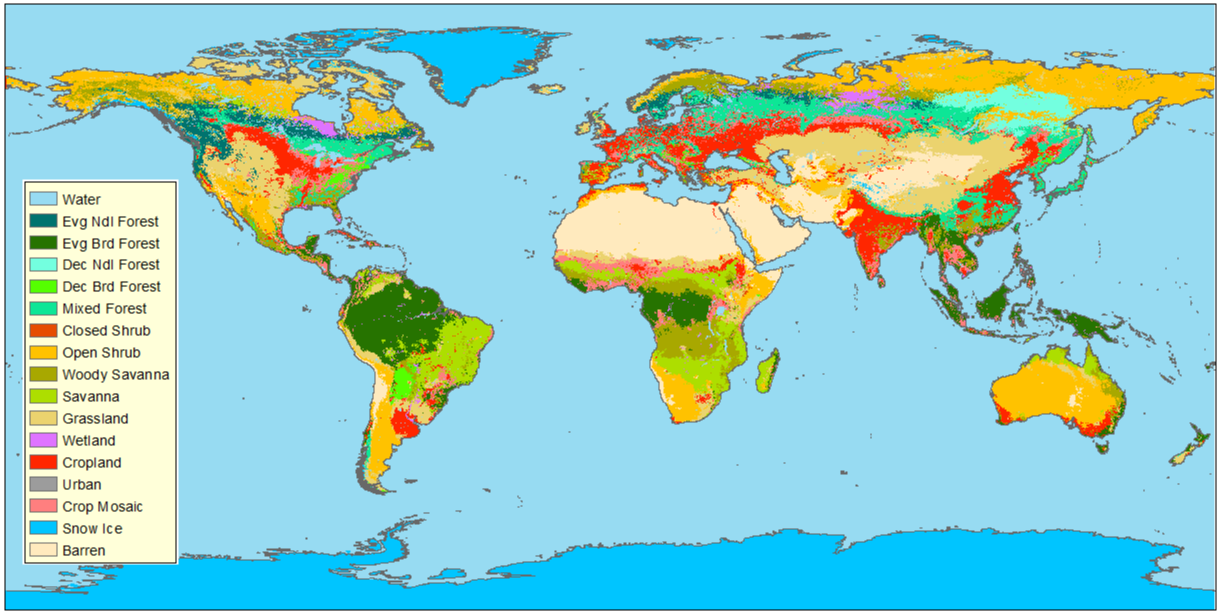
CLM5 Land Use – Crop Model Prescribed Management



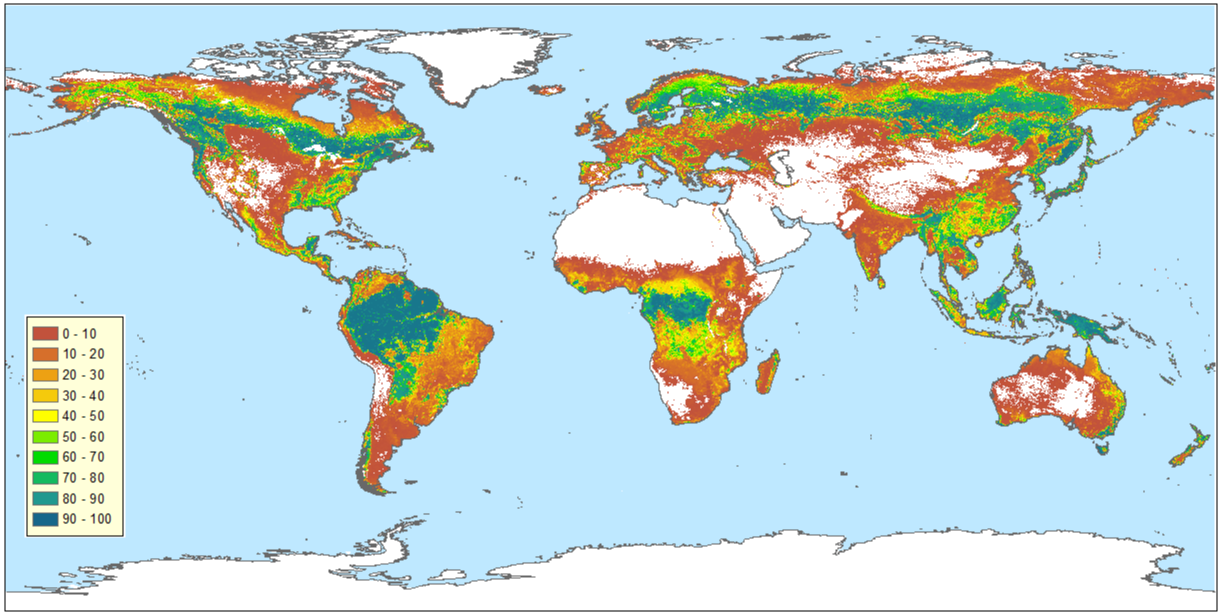
CLM5 Data


Data
Current day cropping (CFTs) 1961 - 2015
CLM5 other raw data files
Historical or future land use time series
CLM Land Use Data Tool
CLM5 raw CFT/PFT files
“mksrf “ CLM Land Surface Properties Tool
LUMIP format:
12 land units
Transitions
Management
Current day vegetation (PFTs) 2000 - 2015
Data
CLM5 format:
14 Plant Types
32 Crop Types
(Wood Harvest
Shifting Cultivation
Irrigation and
N Fertilizer)
CLM/CESM

MODIS Land Cover - IGBP Classes (2003 - 2012)



CLM5 Percent Tree Cover 2005



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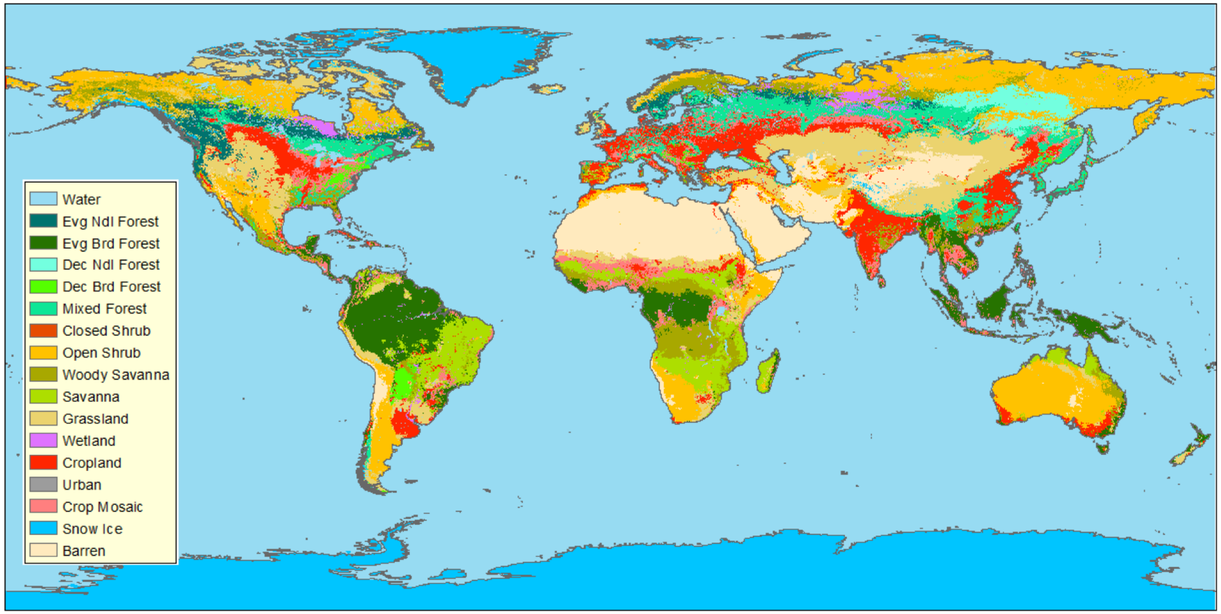
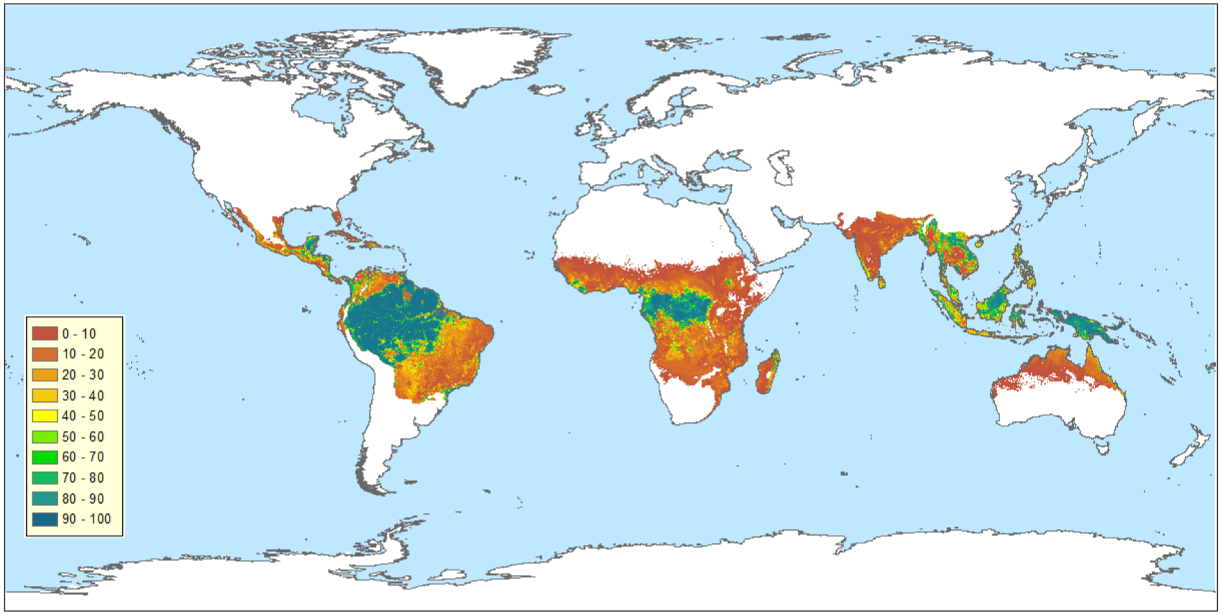


CLM5 Percent Broadleaf Evergreen Tropical Tree 2005



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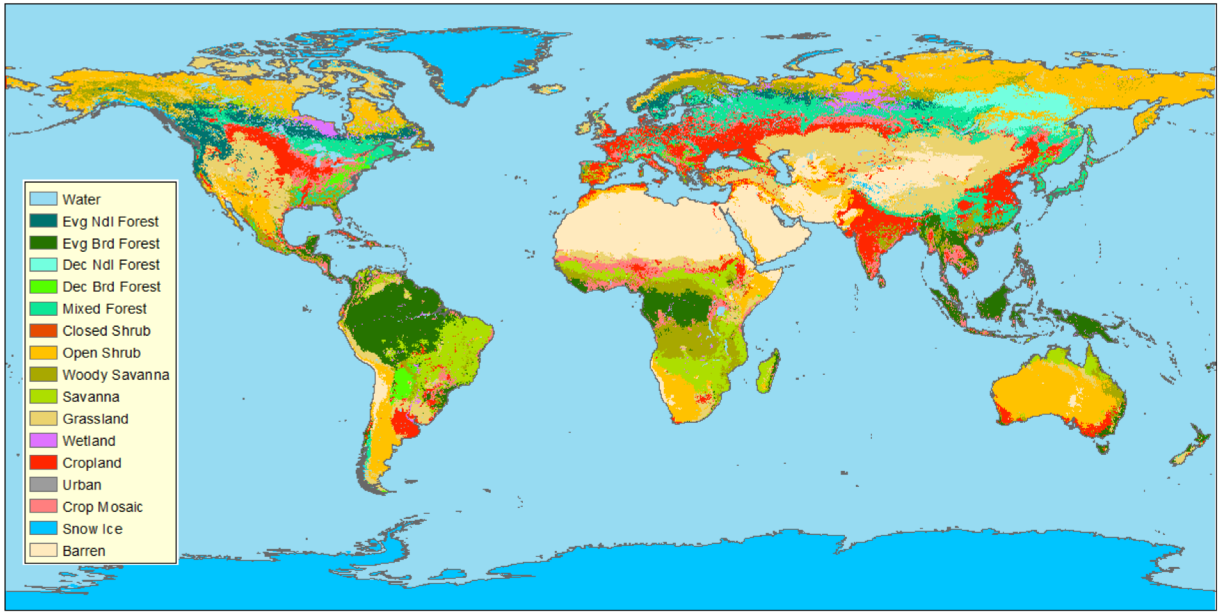
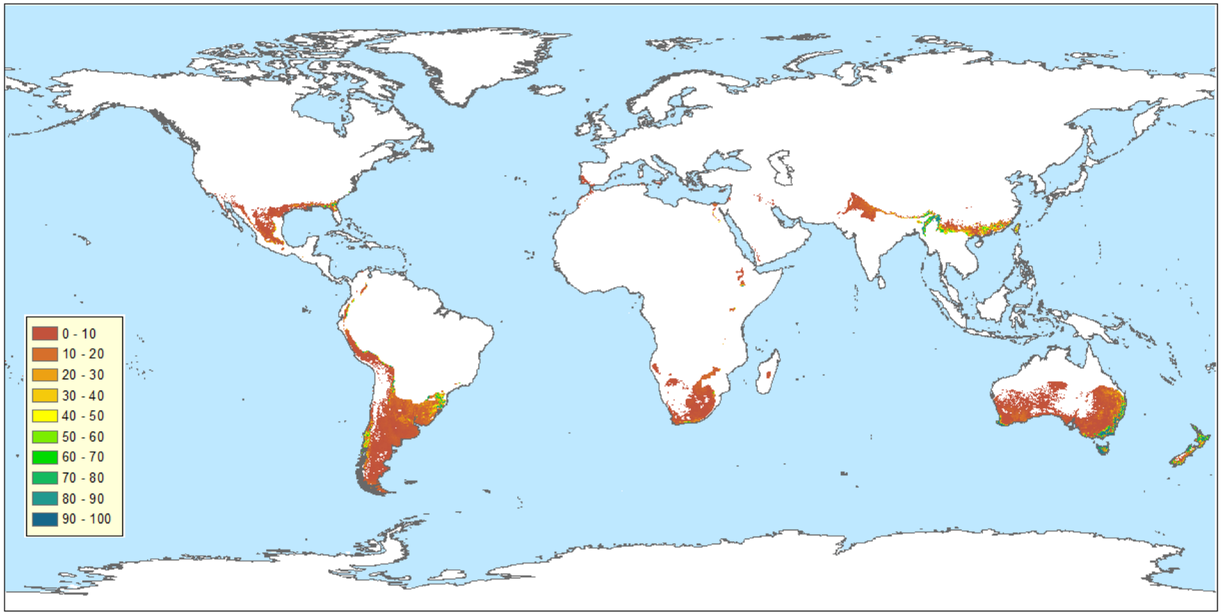
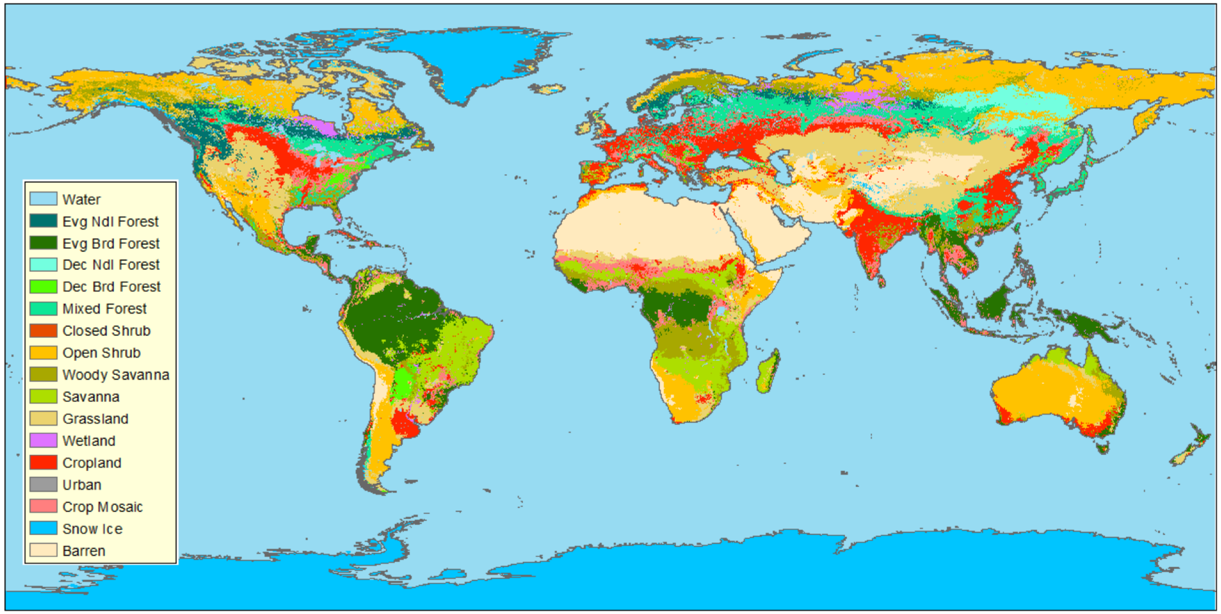


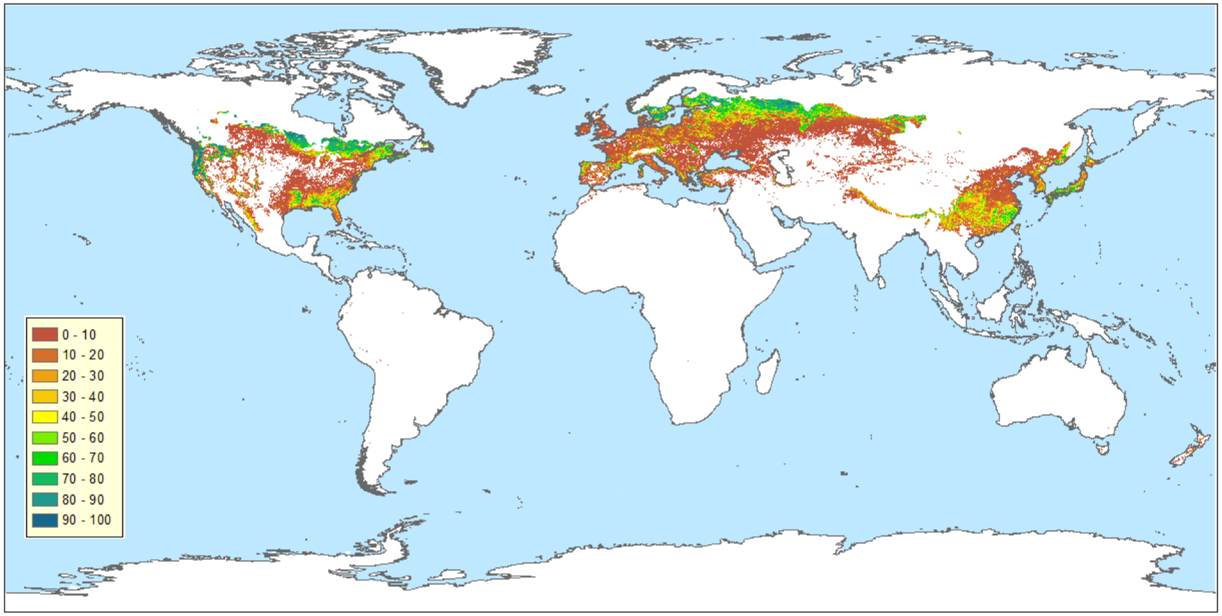
CLM5 Percent Broadleaf Evergreen Temperate Tree 2005



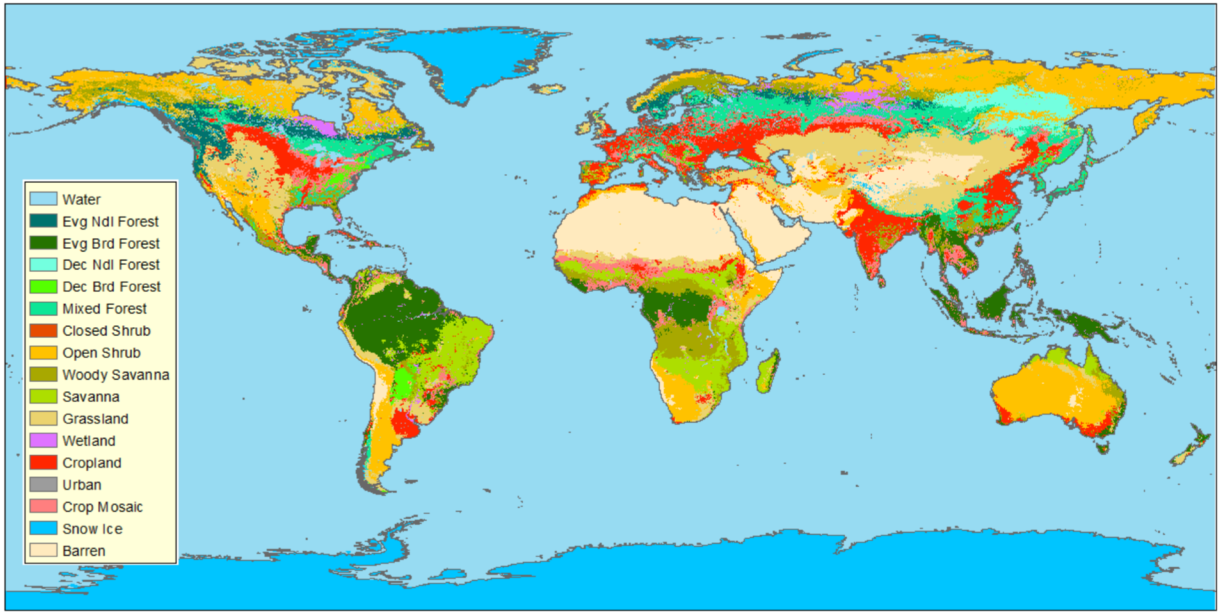
MODIS Land Cover - IGBP Classes (2003 - 2012)



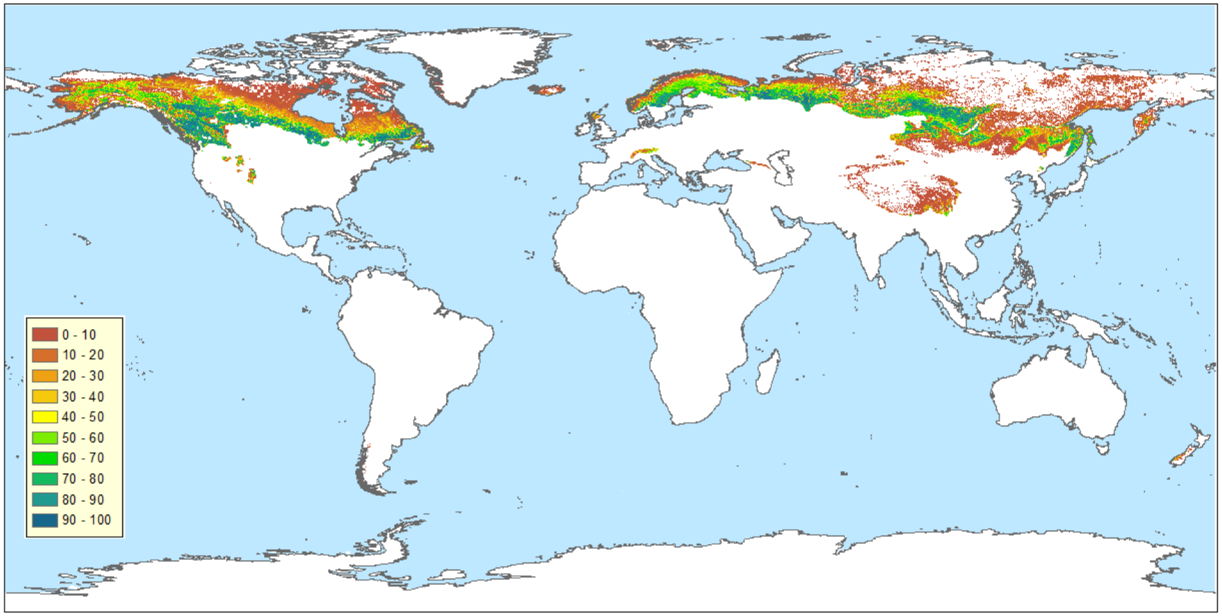
CLM5 Percent Needleleaf Evergreen Temperate Tree 2005



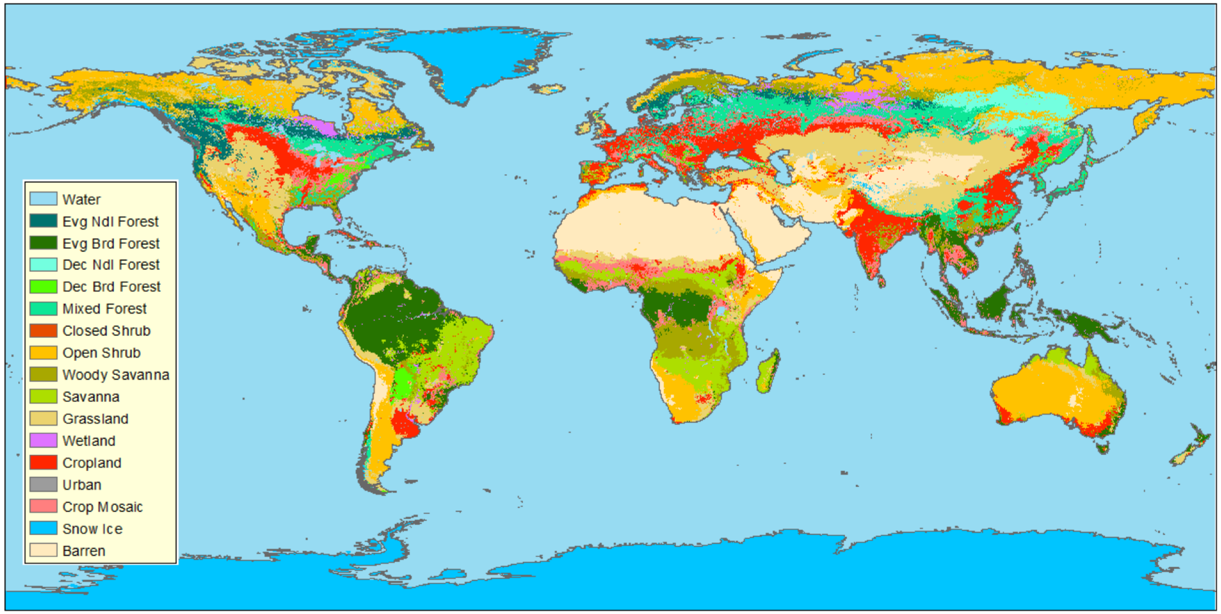
MODIS Land Cover - IGBP Classes (2003 - 2012)



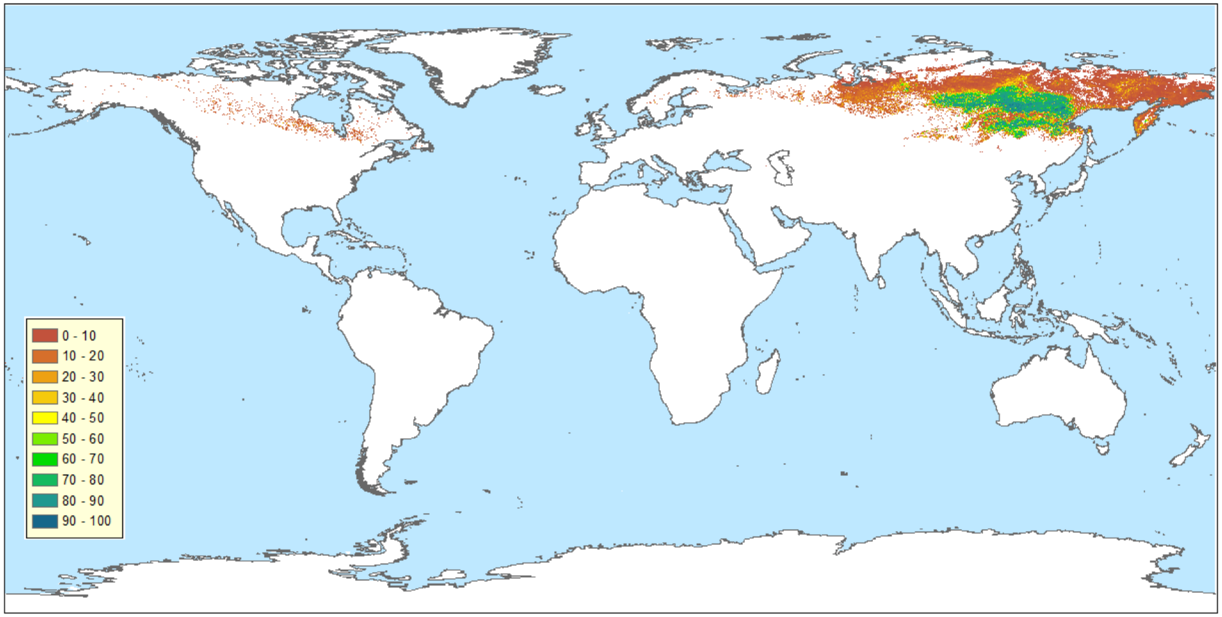
CLM5 Percent Needleleaf Evergreen Boreal Tree 2005



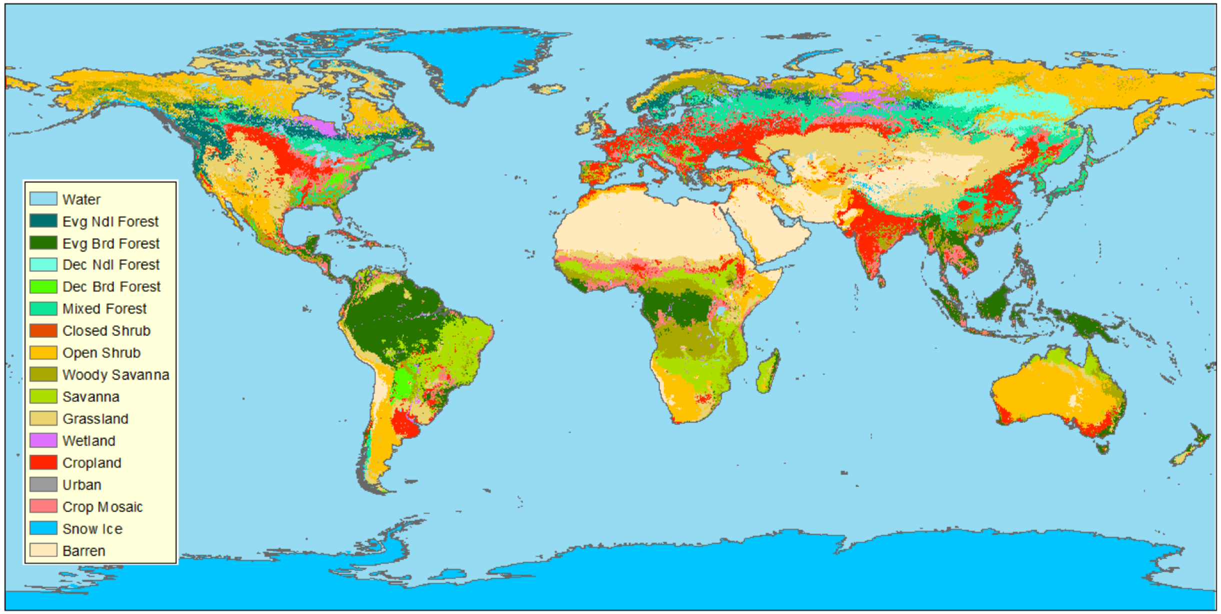
MODIS Land Cover - IGBP Classes (2003 - 2012)



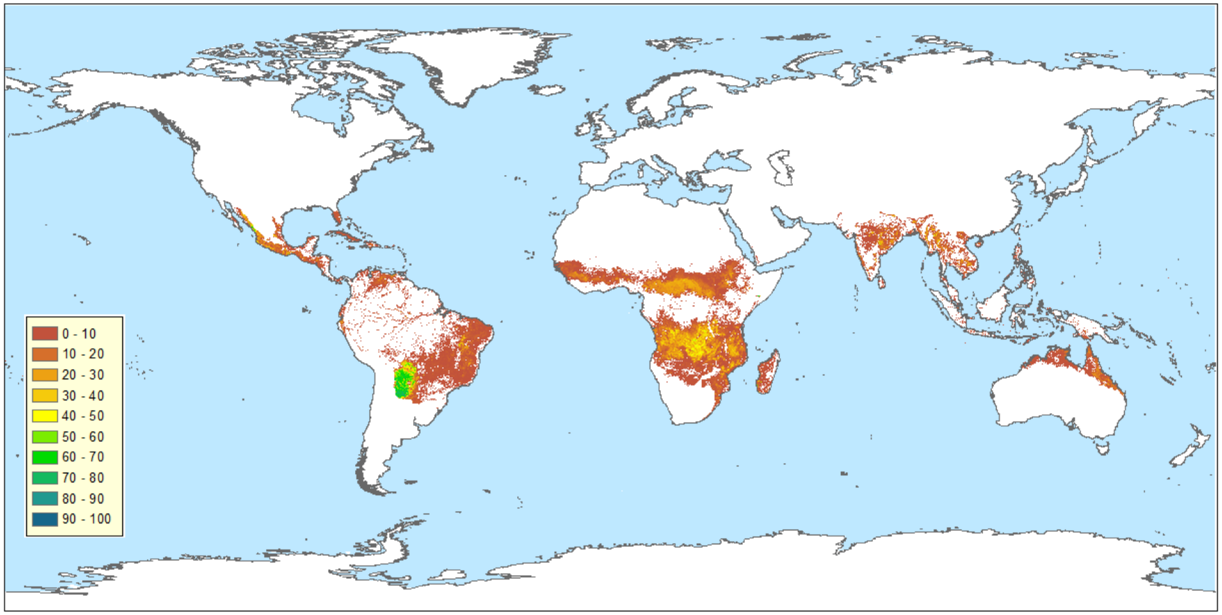
CLM5 Percent Needleleaf Deciduous Boreal Tree 2005



MODIS Land Cover - IGBP Classes (2003 - 2012)



CLM5 Percent Broadleaf Deciduous Tropical Tree 2005



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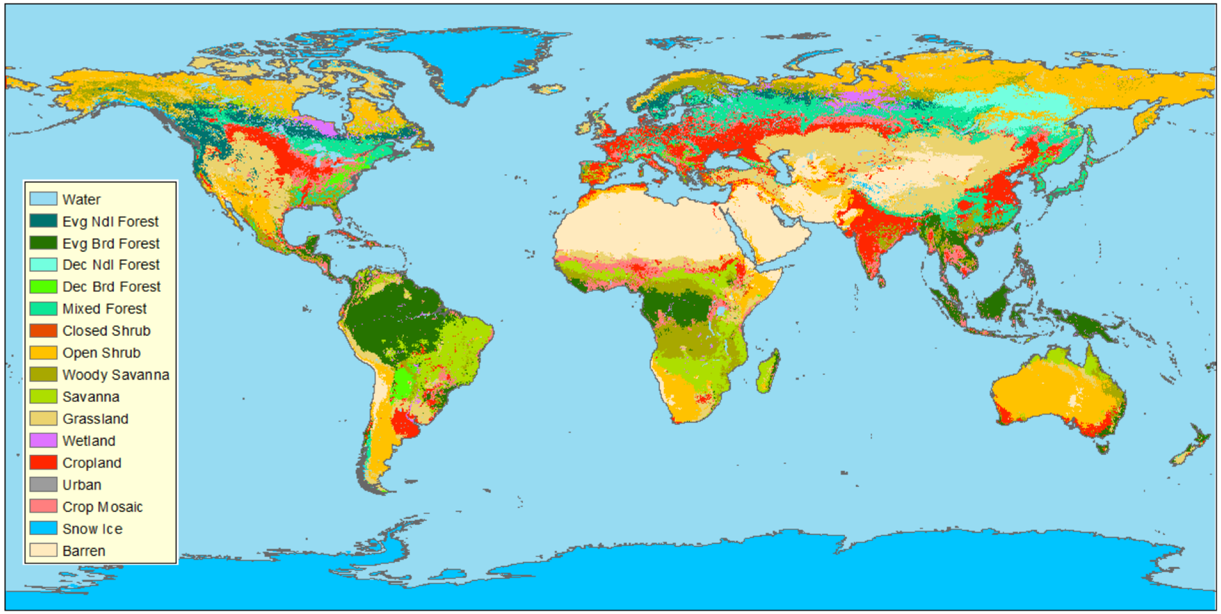
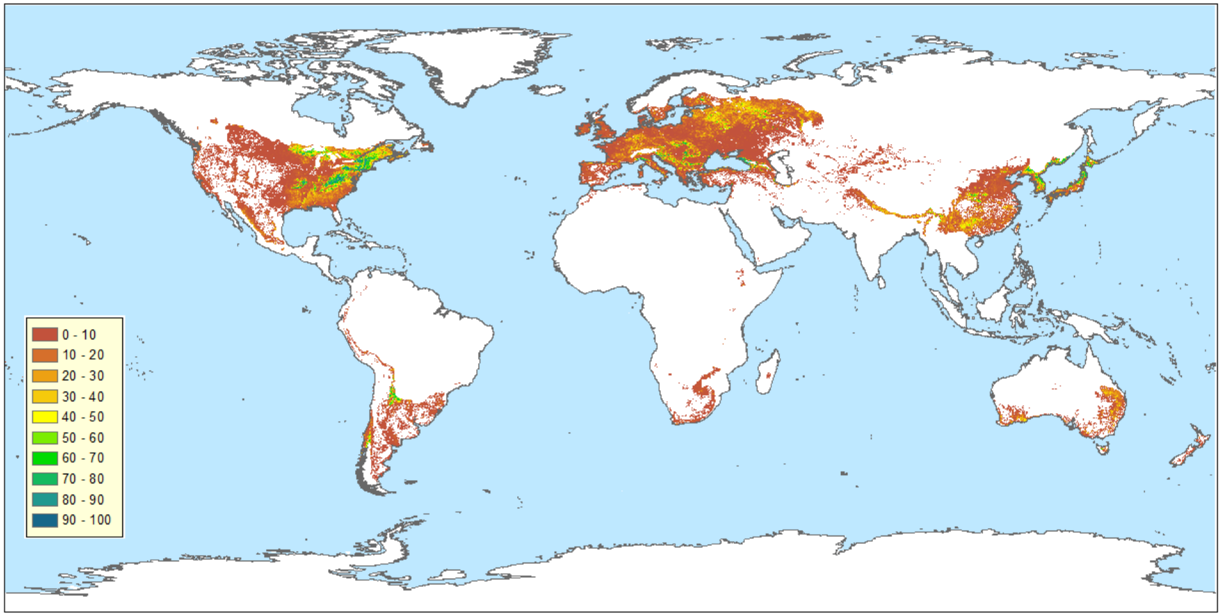
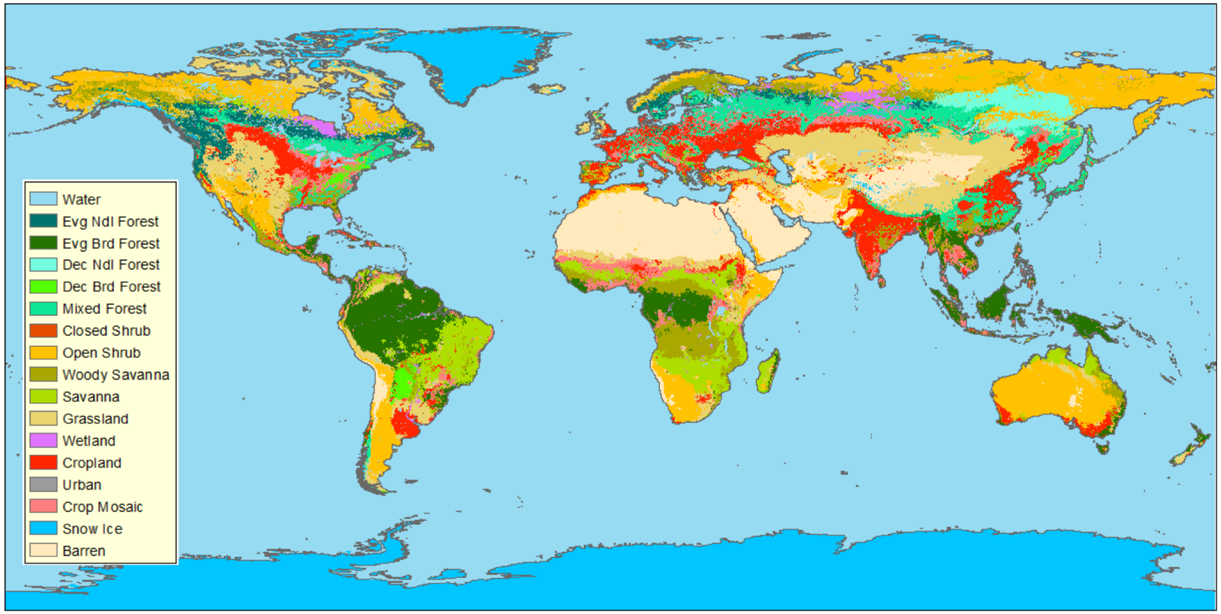


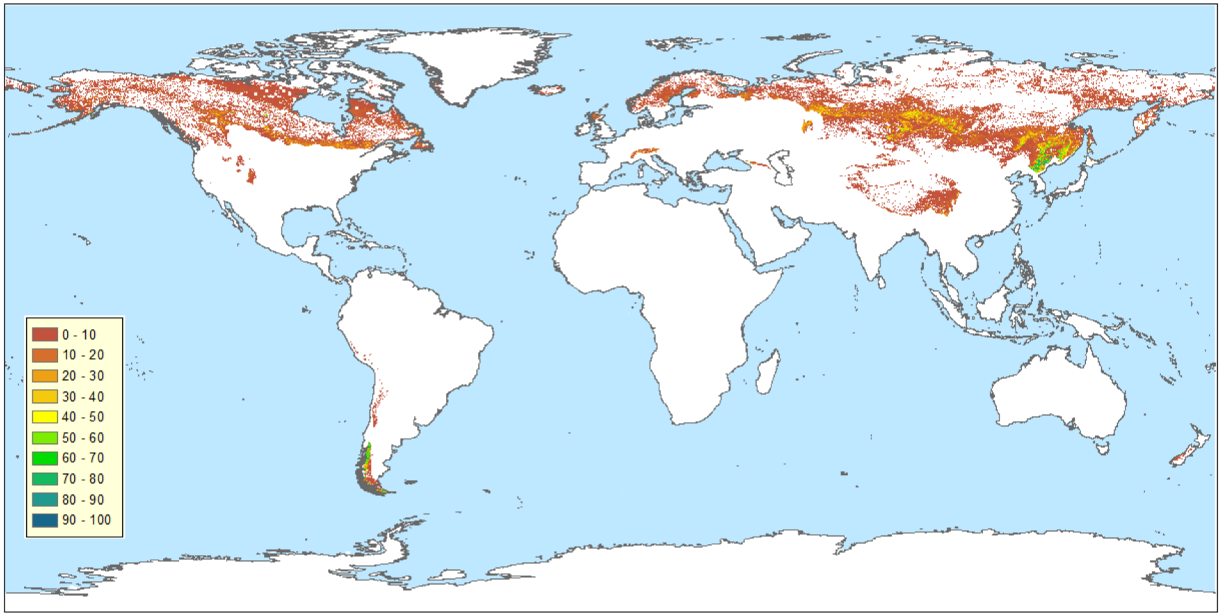
CLM5 Percent Broadleaf Deciduous Temperate Tree 2005



MODIS Land Cover - IGBP Classes (2003 - 2012)



CLM5 Percent Broadleaf Deciduous Boreal Tree 2005



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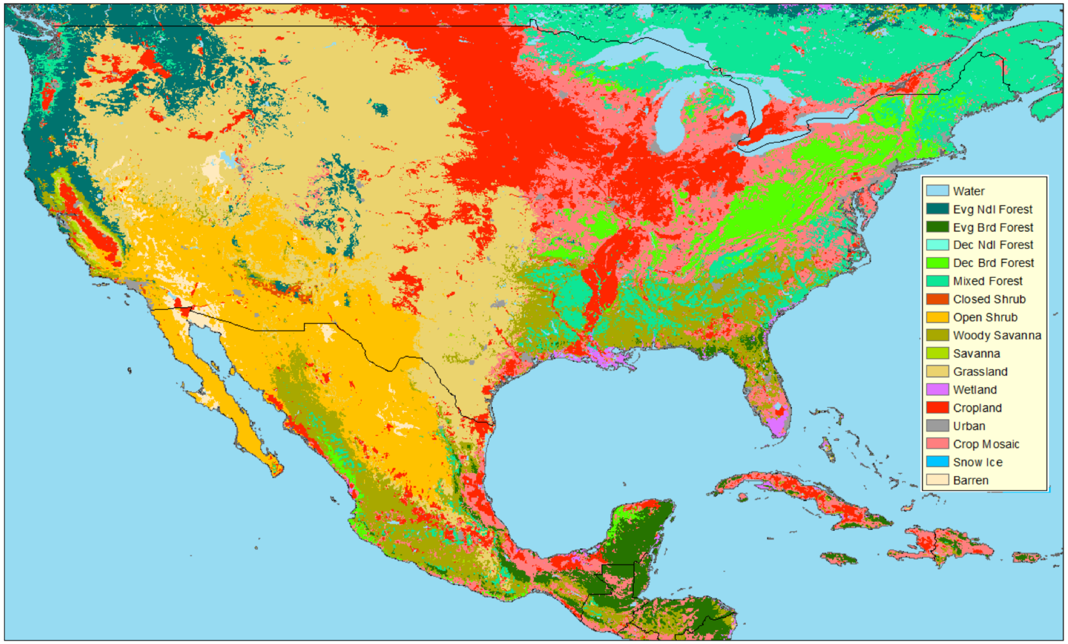
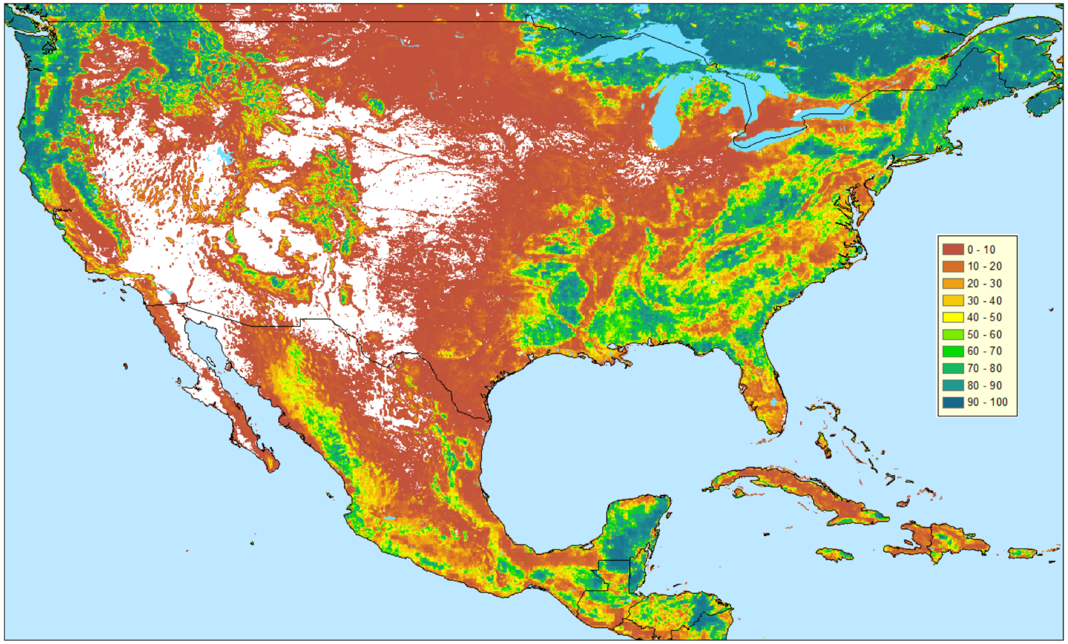
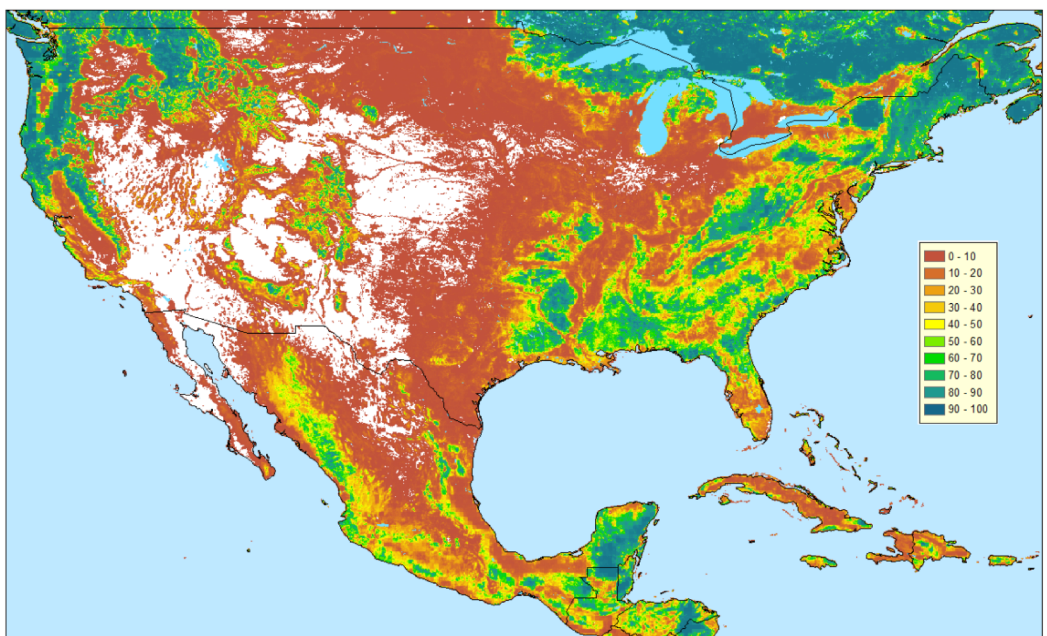


CLM5 Percent Tree Cover 2005

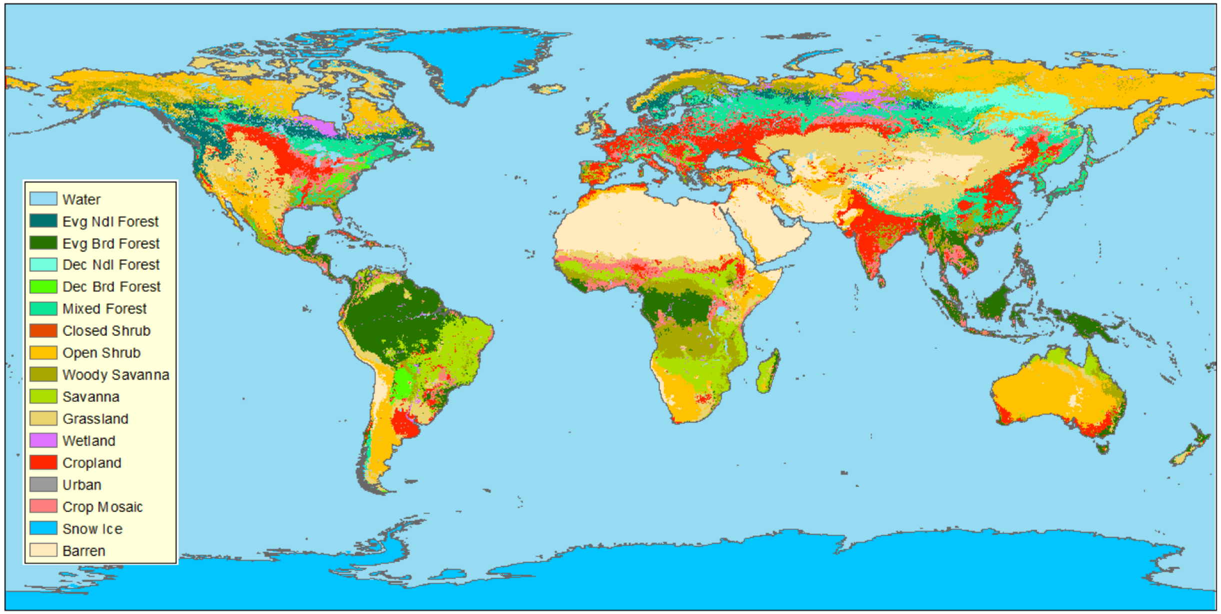


Google Earth - Quickbird 2015

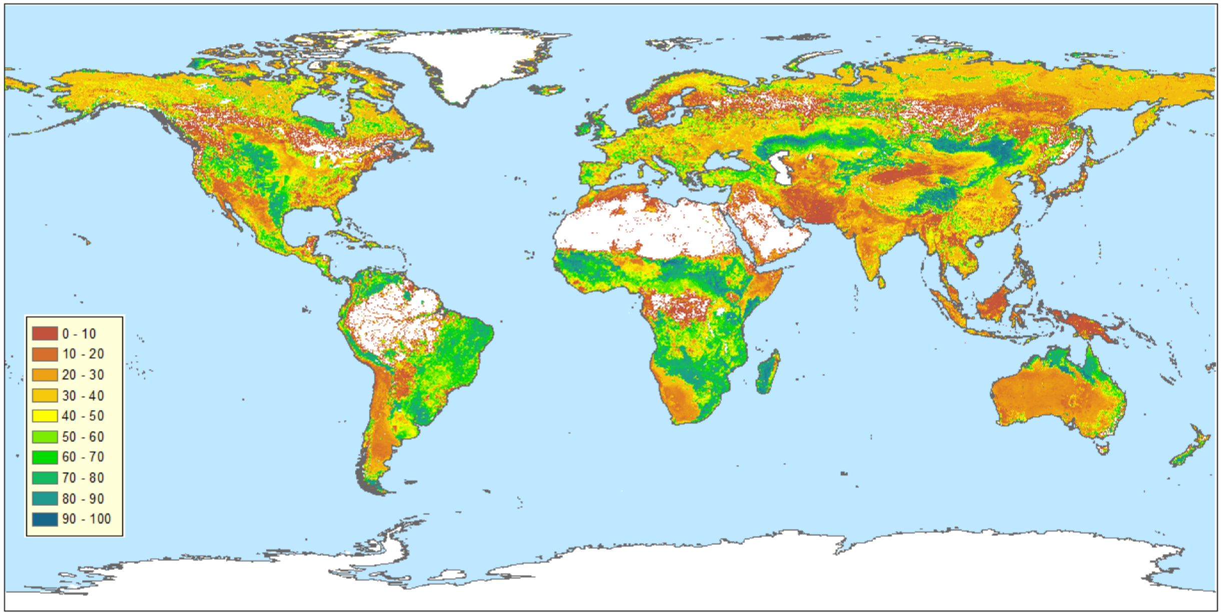
CLM5 Percent Tree Cover 2005



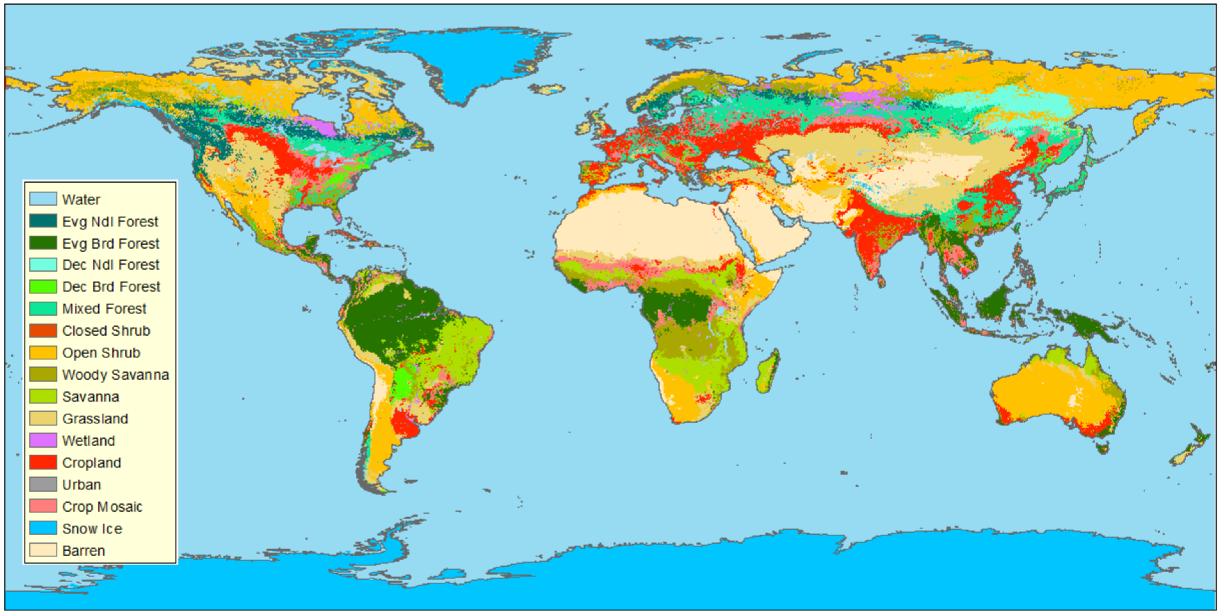
MODIS Land Cover - IGBP Classes (2003 - 2012)



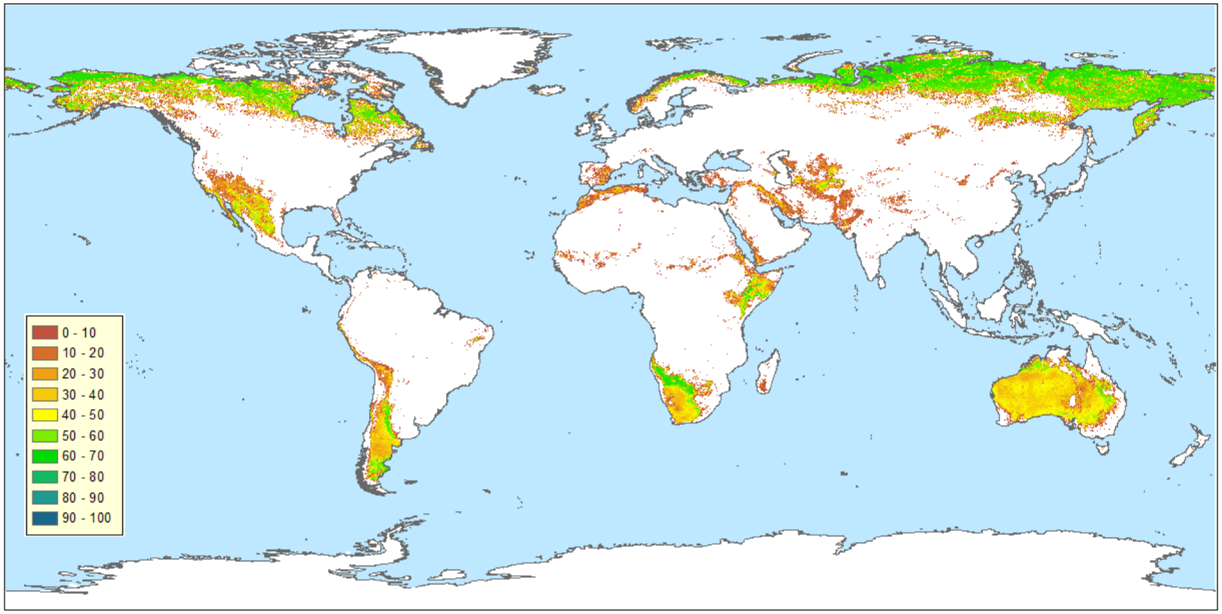
CLM5 Percent Grass 2005



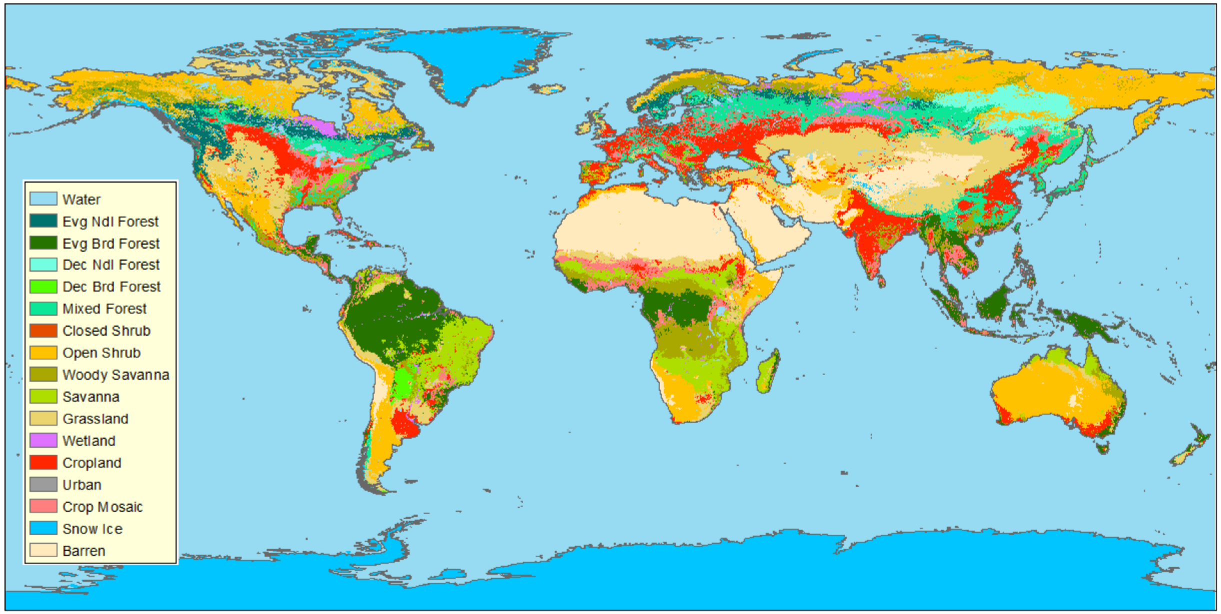
MODIS Land Cover - IGBP Classes (2003 - 2012)



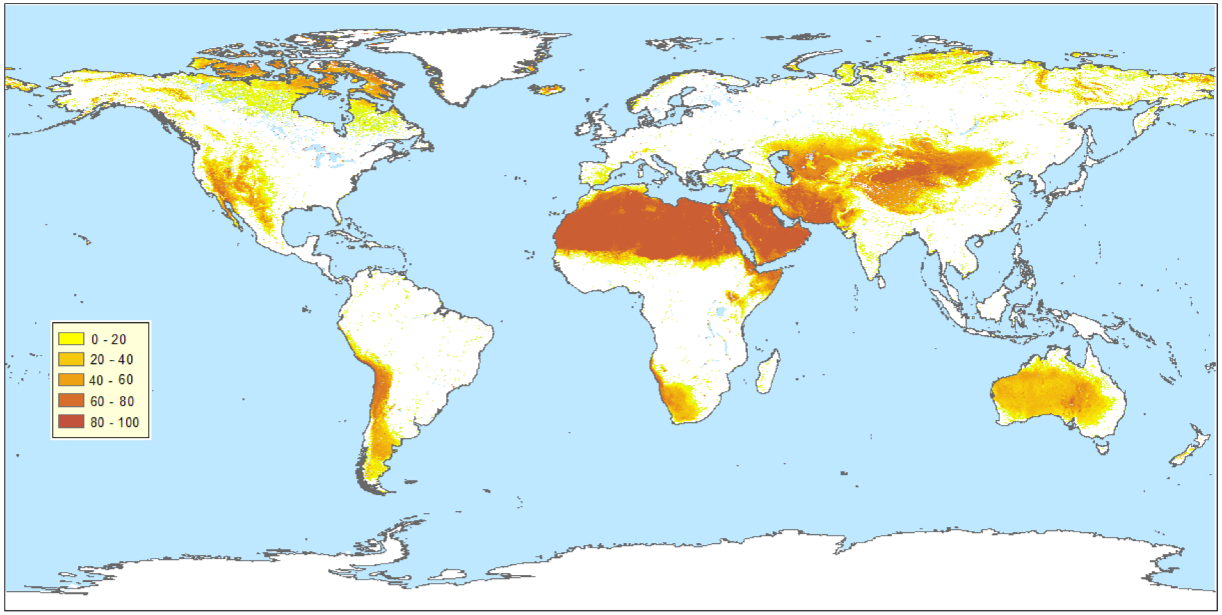
CLM5 Percent Shrub 2005

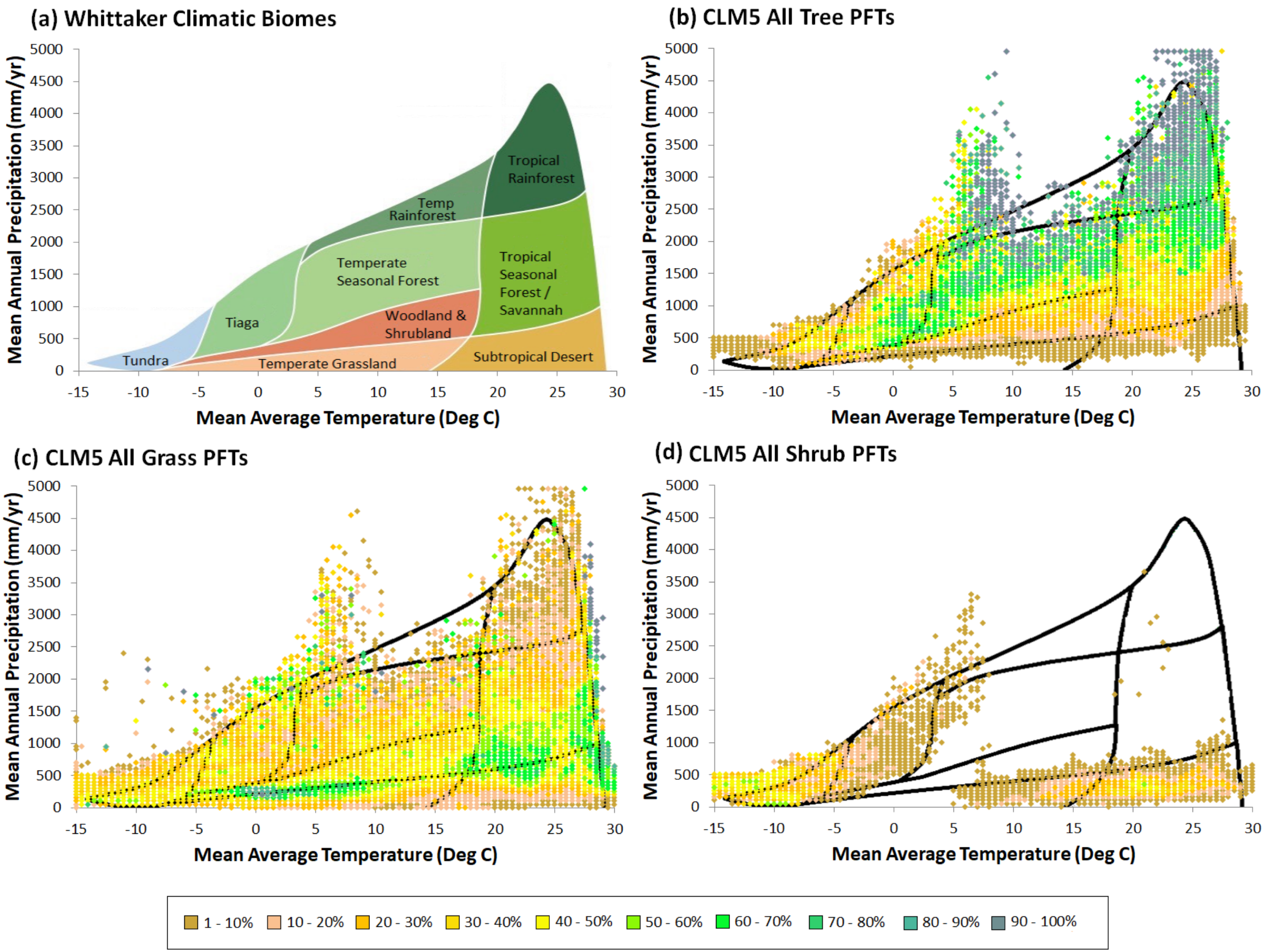


MODIS Land Cover - IGBP Classes (2003 - 2012)

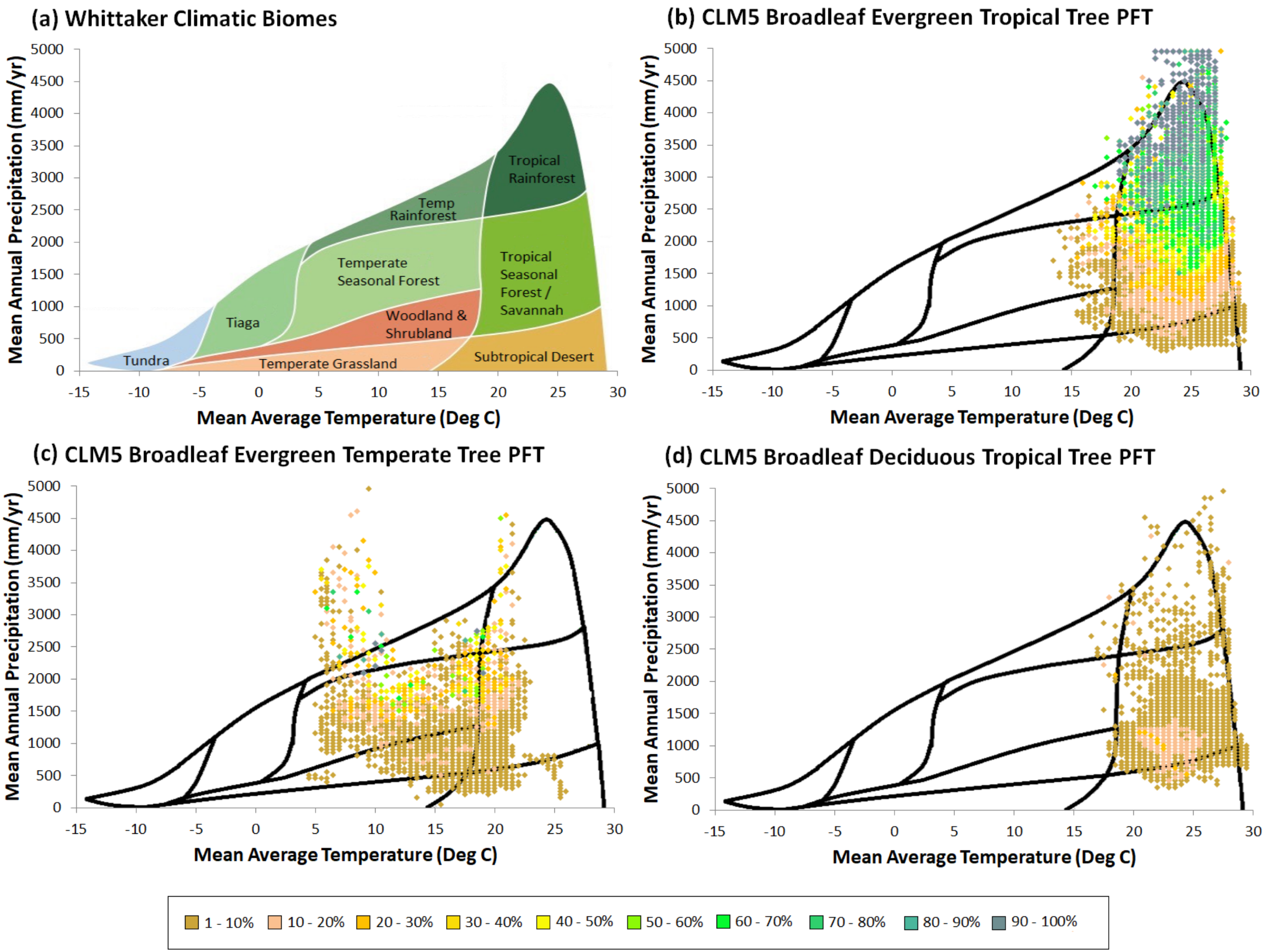


CLM5 Percent Bare Soil 2005



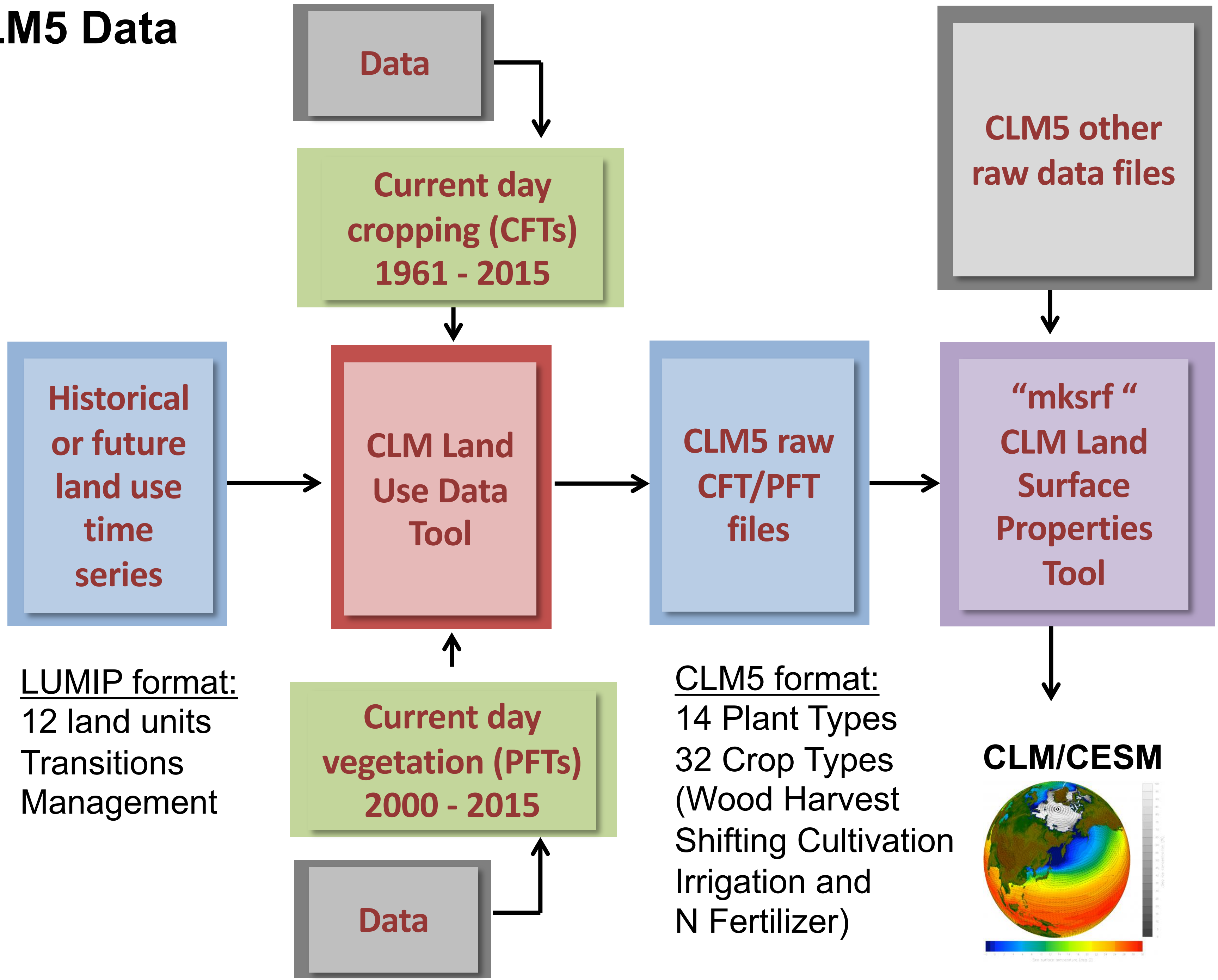


(a) Whittaker Climatic Biomes
(b) CLM5 All Tree PFTs
(c) CLM5 All Grass PFTs
(d) CLM5 All Shrub PFTs
Mean Annual Precipitation (mm/yr)
Mean Average Temperature (Deg C)
Tropical Rainforest
Temp Rainforest
Temperate Seasonal Forest
Tropical Seasonal Forest / Savannah
Tiaga
Woodland & Shrubland
Tundra
Temperate Grassland
Subtropical Desert
1 - 10%
10 - 20%
20 - 30%
30 - 40%
40 - 50%
50 - 60%
60 - 70%
70 - 80%
80 - 90%
90 - 100%



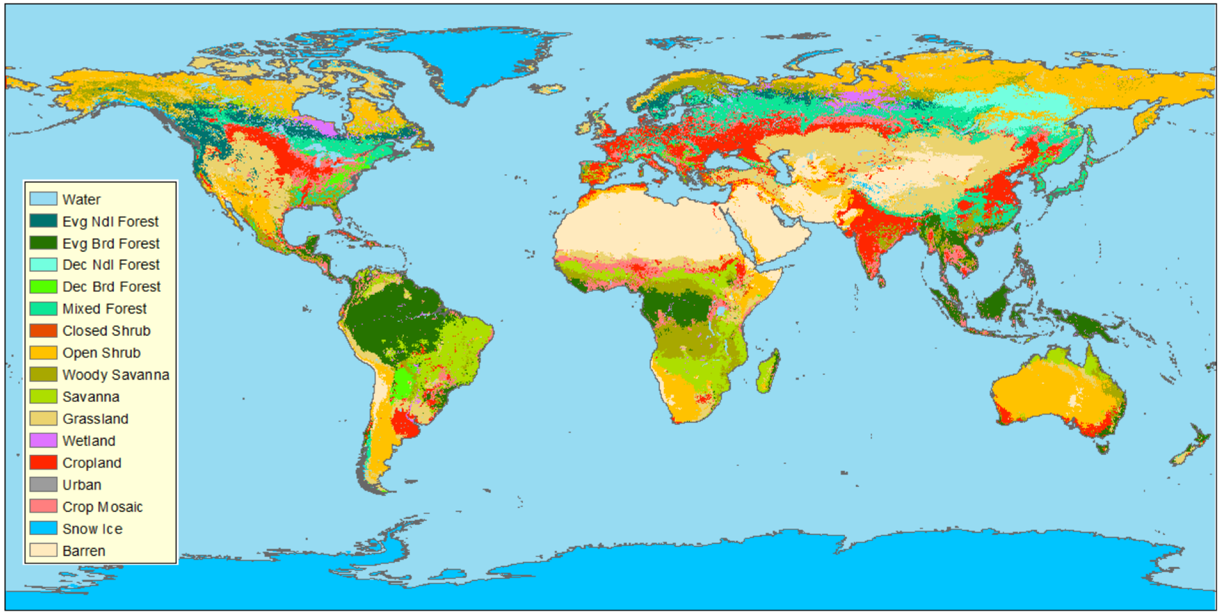
(a) Whittaker Climatic Biomes
Tropical Rainforest
Temp Rainforest
Temperate Seasonal Forest
Tropical Seasonal Forest / Savannah
Tiaga
Woodland & Shrubland
Tundra
Temperate Grassland
Subtropical Desert
(b) CLM5 Broadleaf Evergreen Tropical Tree PFT
(c) CLM5 Broadleaf Evergreen Temperate Tree PFT
(d) CLM5 Broadleaf Deciduous Tropical Tree PFT
Mean Annual Precipitation (mm/yr)
Mean Average Temperature (Deg C)
1 - 10%
10 - 20%
20 - 30%
30 - 40%
40 - 50%
50 - 60%
60 - 70%
70 - 80%
80 - 90%
90 - 100%

CLM5 Data

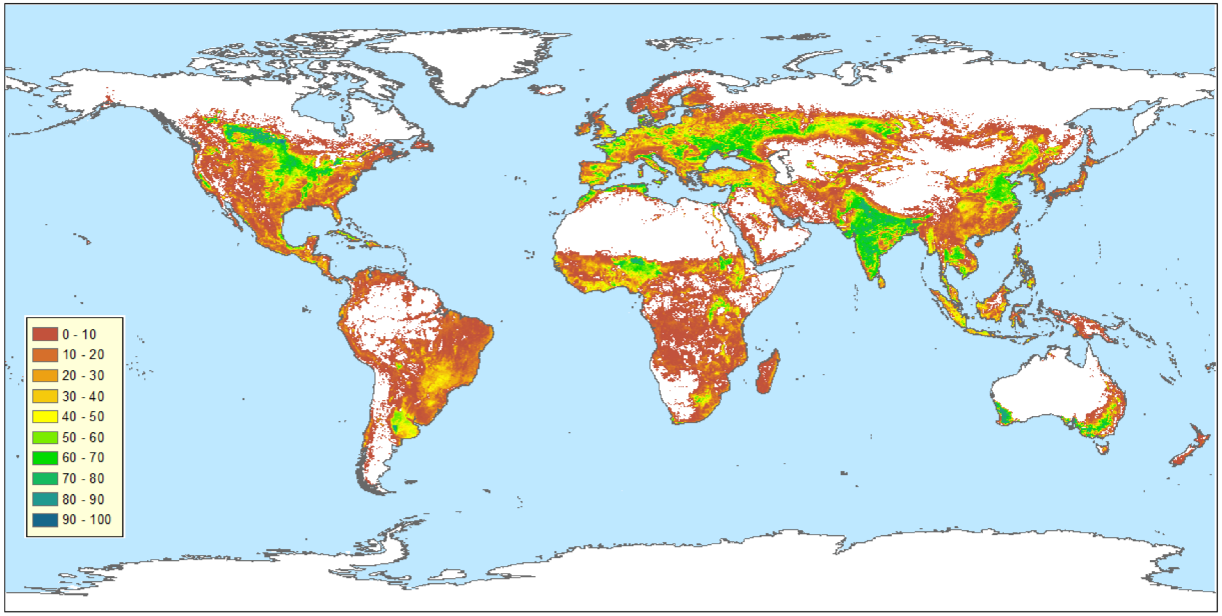


Data
Current day cropping (CFTs) 1961 - 2015
CLM5 other raw data files
Historical or future land use time series
CLM Land Use Data Tool
CLM5 raw CFT/PFT files
"mksrf " CLM Land Surface Properties Tool
LUMIP format:
12 land units
Transitions
Management
Current day vegetation (PFTs) 2000 - 2015
Data
CLM5 format:
14 Plant Types
32 Crop Types
(Wood Harvest
Shifting Cultivation
Irrigation and
N Fertilizer)
CLM/CESM

MODIS Land Cover - IGBP Classes (2003 - 2012)



CLM5 Percent Crop 2005



LUMIP => 64 CLM5 Rainfed and Irrigated Crop Types Mapped using EARTHSTAT – UN FAOSTAT distributions

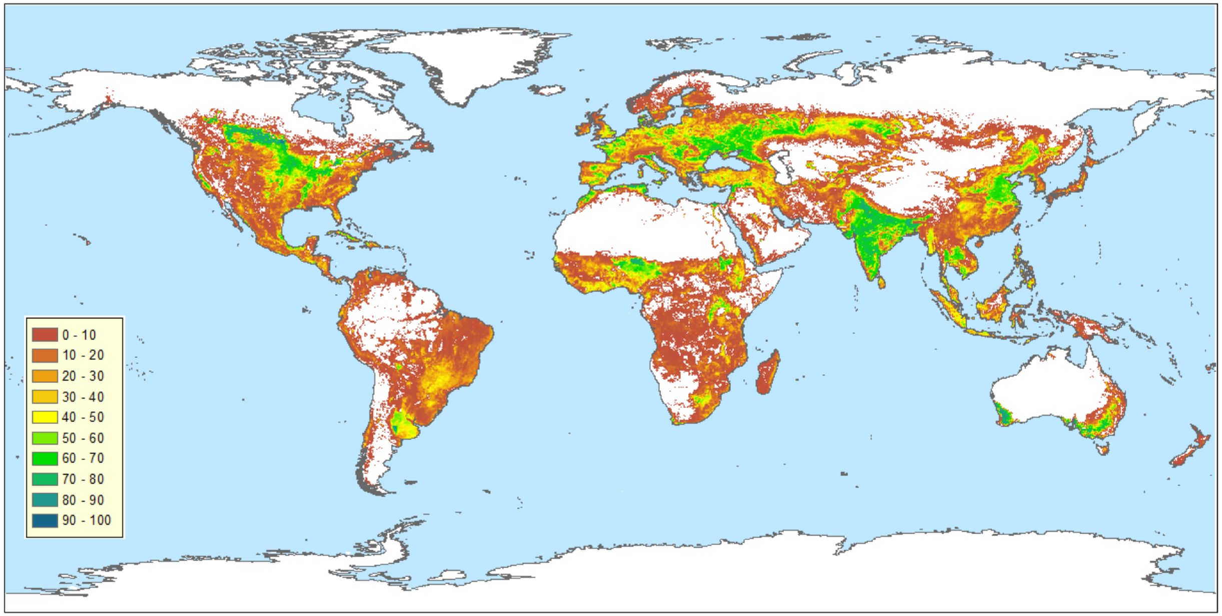
CFT	CFT	CFT	CFT	CFT
15. C3 Generic Crop	29. Rye	43. Datepalm	57. Pulses	71. Miscanthus
16. C3 Generic Crop Irrigated	30. Rye Irrigated	44. Datepalm Irrigated	58. Pulses Irrigated	72. Miscanthus Irrigated
17. Temperate Corn	31. Winter Rye	45. Foddergrass	59. Rapeseed	73. Switchgrass
18. Temperate Corn Irrigated	32. Winter Rye Irrigated	46. Foddergrass Irrigated	60. Rapeseed Irrigated	74. Switchgrass Irrigated
19. Spring Wheat	33. Cassava	47. Grapes	61. Rice	75. Tropical Corn
20. Spring Wheat Irrigated	34. Cassava Irrigated	48. Grapes Irrigated	62. Rice Irrigated	76. Tropical Corn Irrigated
21. Winter Wheat	35. Citrus	49. Groundnuts	63. Sorghum	77. Tropical Soybean
22. Winter Wheat Irrigated	36. Citrus Irrigated	50. Groundnuts Irrigated	64. Sorghum Irrigated	78. Tropical Soybean Irrigated
23. Temperate Soybean	37. Cocoa	51. Millet	65. Sugarbeet	
24. Temperate Soybean Irrigated	38. Cocoa Irrigated	52. Millet Irrigated	66. Sugarbeet Irrigated	
25. Barley	39. Coffee	53. Oilpalm	67. Sugarcane	
26. Barley Irrigated	40. Coffee Irrigated	54. Oilpalm Irrigated	68. Sugarcane Irrigated	
27. Winter Barley	41. Cotton	55. Potatoes	69. Sunflower	
28. Winter Barley Irrigated	42. Cotton Irrigated	56. Potatoes Irrigated	70. Sunflower Irrigated	

CLM5 Crop Distributions from LUMIP Crop Types

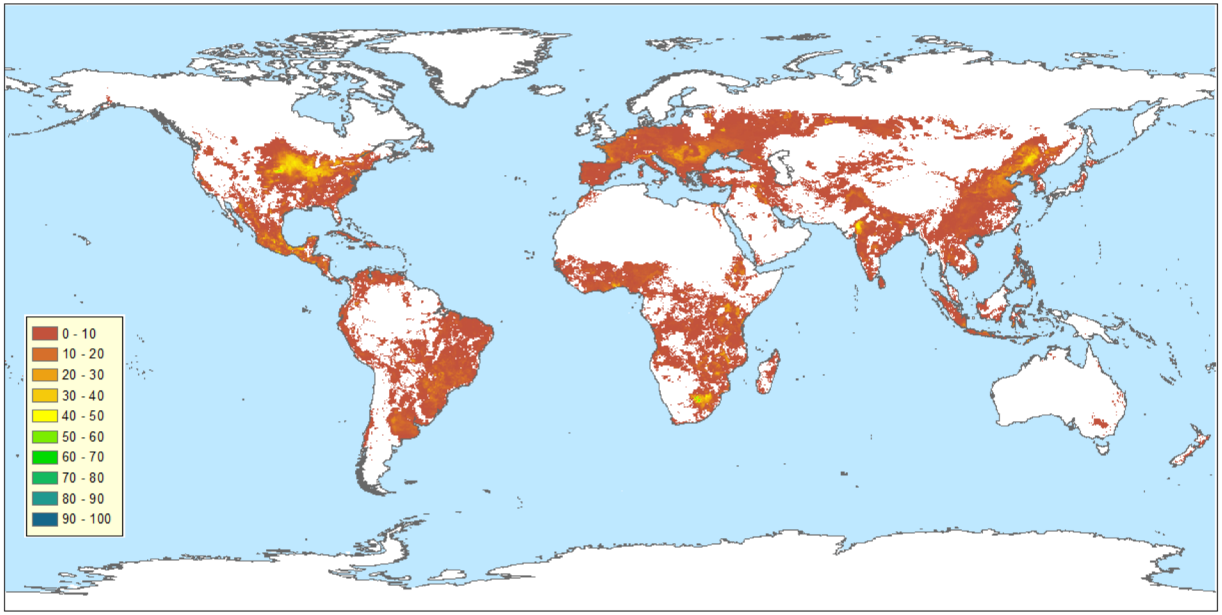
Remap Annual LUH2 Crop Land Units to 32 CLM5 Crop Functional Types using current day (1961 – 2015) crop distributions from EARTHSTAT and UN FAOSTAT:

- C3Ann -> Wheat, Rice, Cotton, Barley, Rye, Sunflower, Cassava, Potatoes, Sugar beet, Rape seed, Fodder grass, Generic C3 Crop
- C4Ann -> Maize, Millet, Sorghum
- C3Per -> Oil palm, Citrus, Date palm, Grapes, Cocoa, Coffee
- C4Per -> Sugar cane
- C3Nfx -> Soybeans, Groundnuts, Pulses

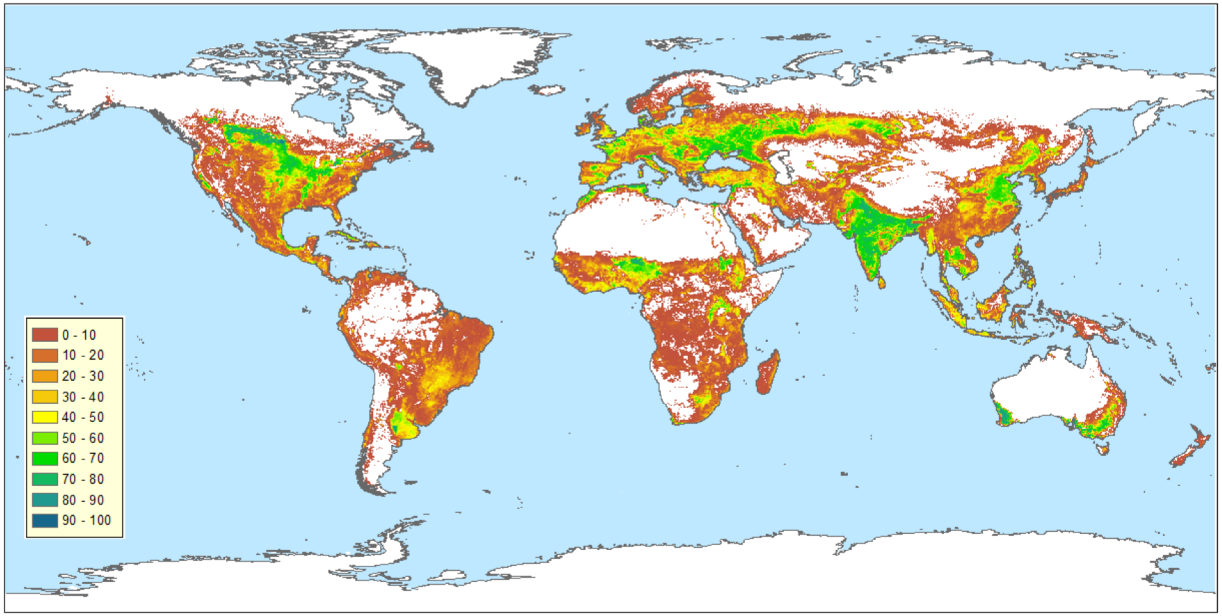
CLM5 Percent Crop 2005



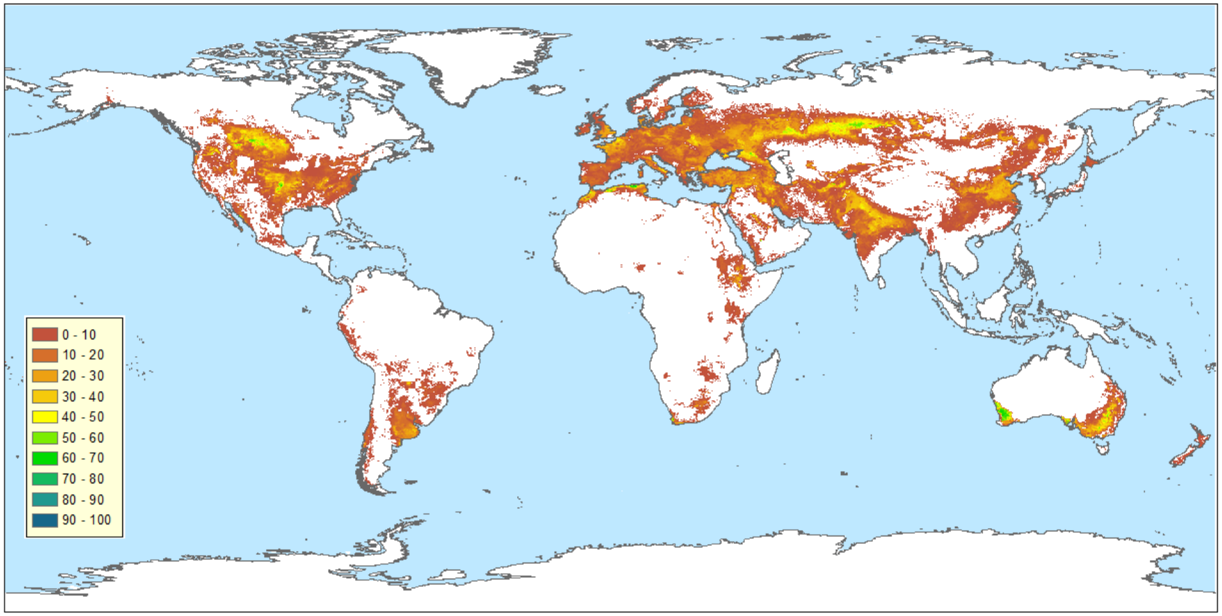
CLM5 Percent Corn 2005



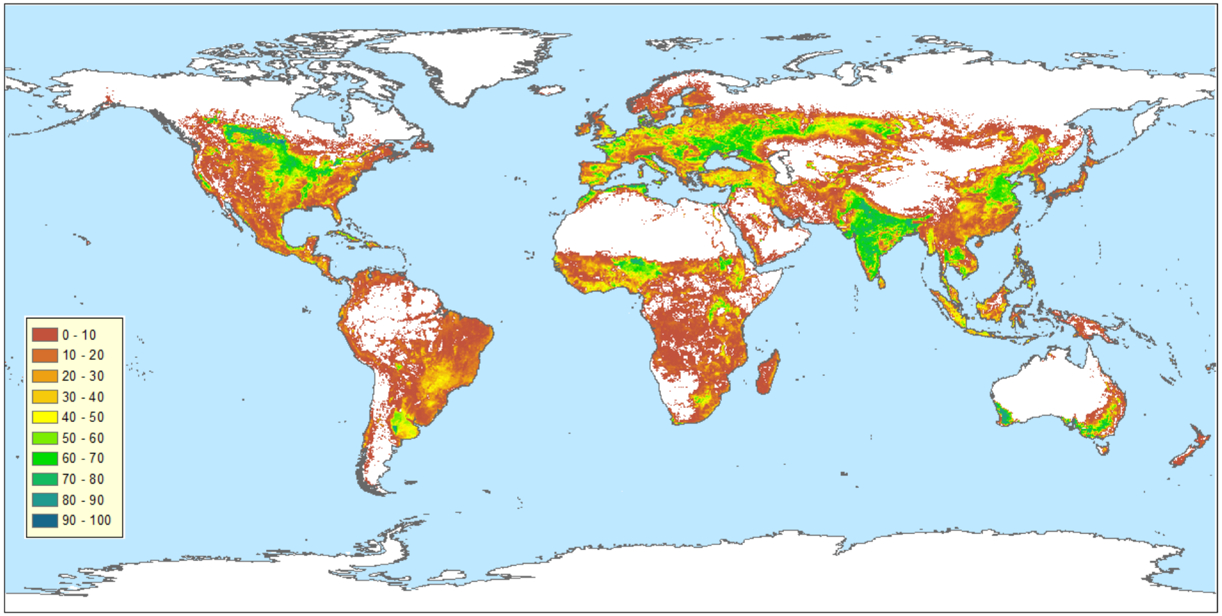
CLM5 Percent Crop 2005



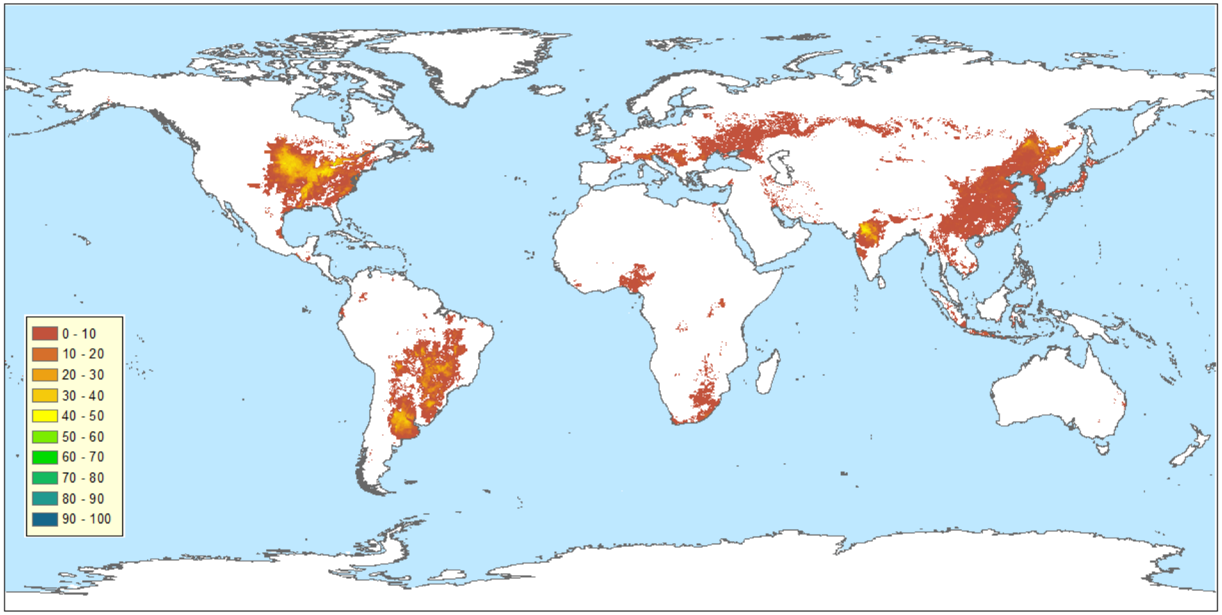
CLM5 Percent Wheat 2005



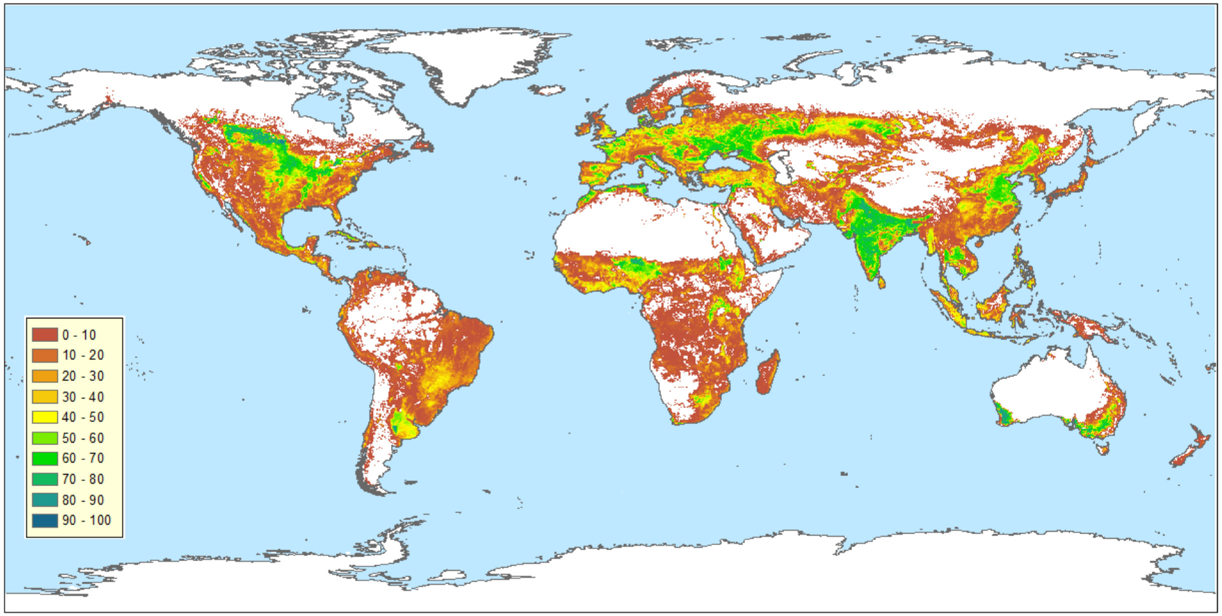
CLM5 Percent Crop 2005



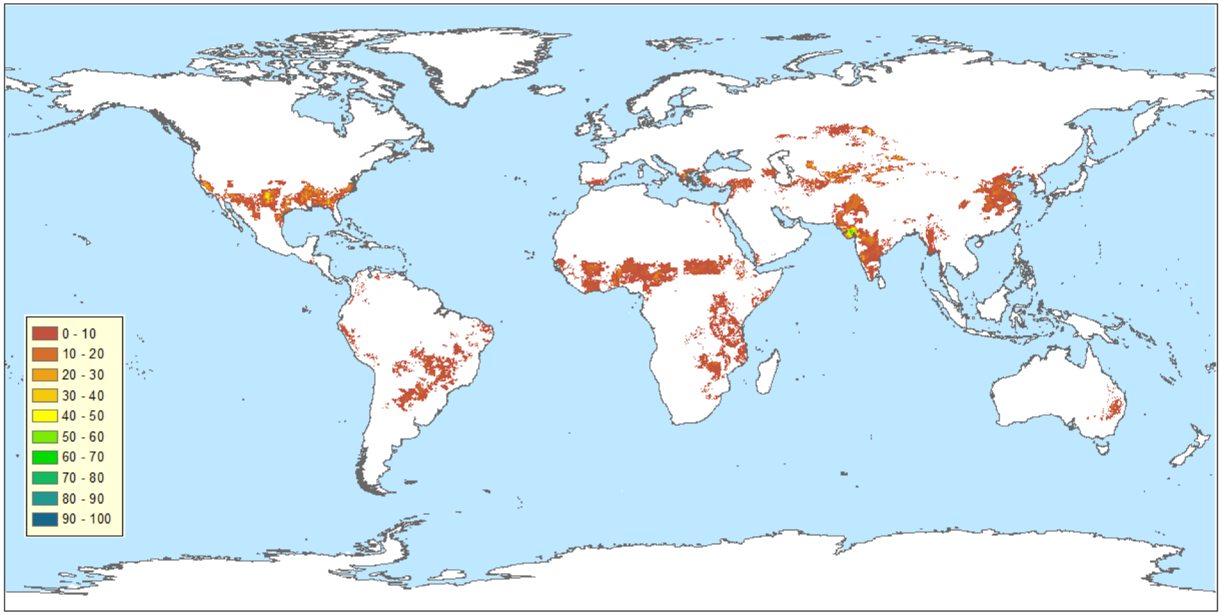
CLM5 Percent Soybean 2005



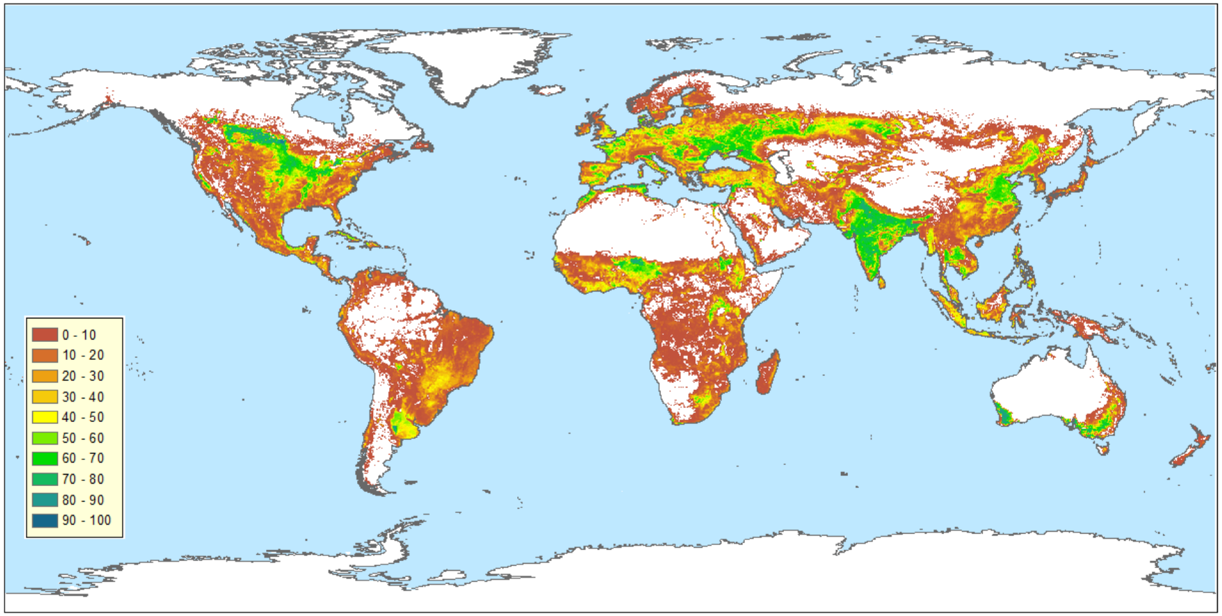
CLM5 Percent Crop 2005



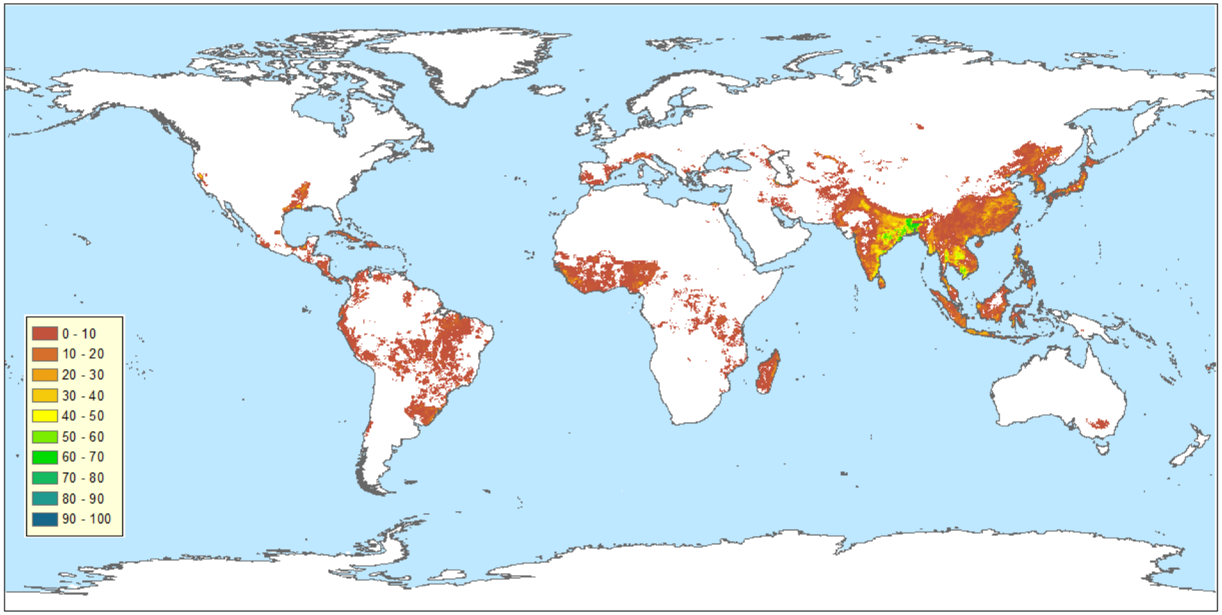
CLM5 Percent Cotton 2005



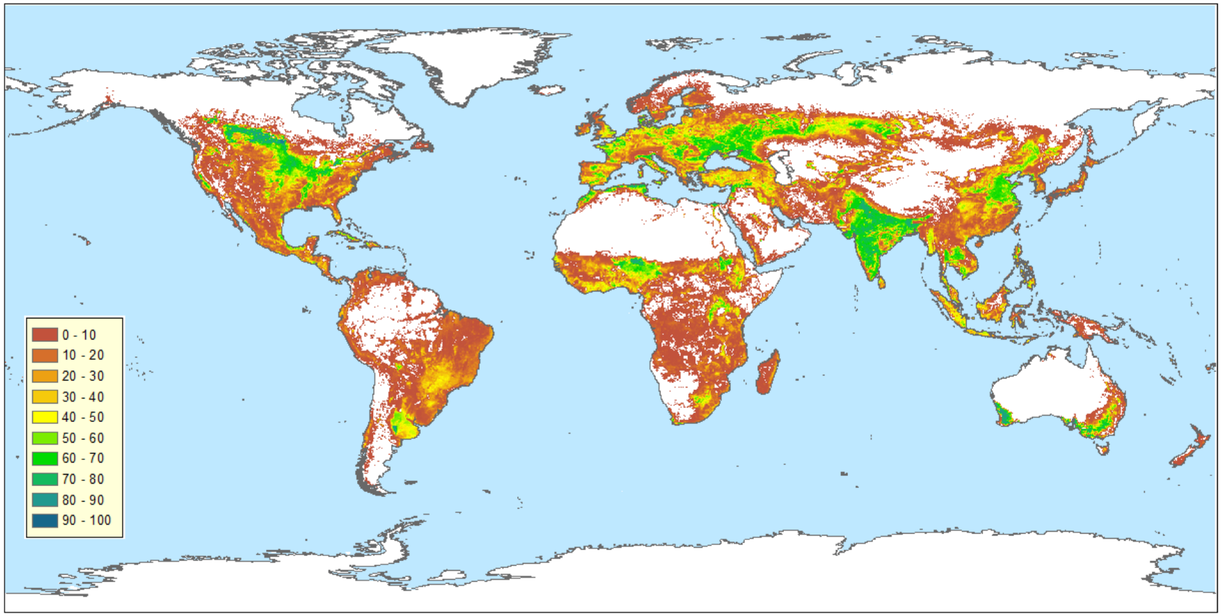
CLM5 Percent Crop 2005



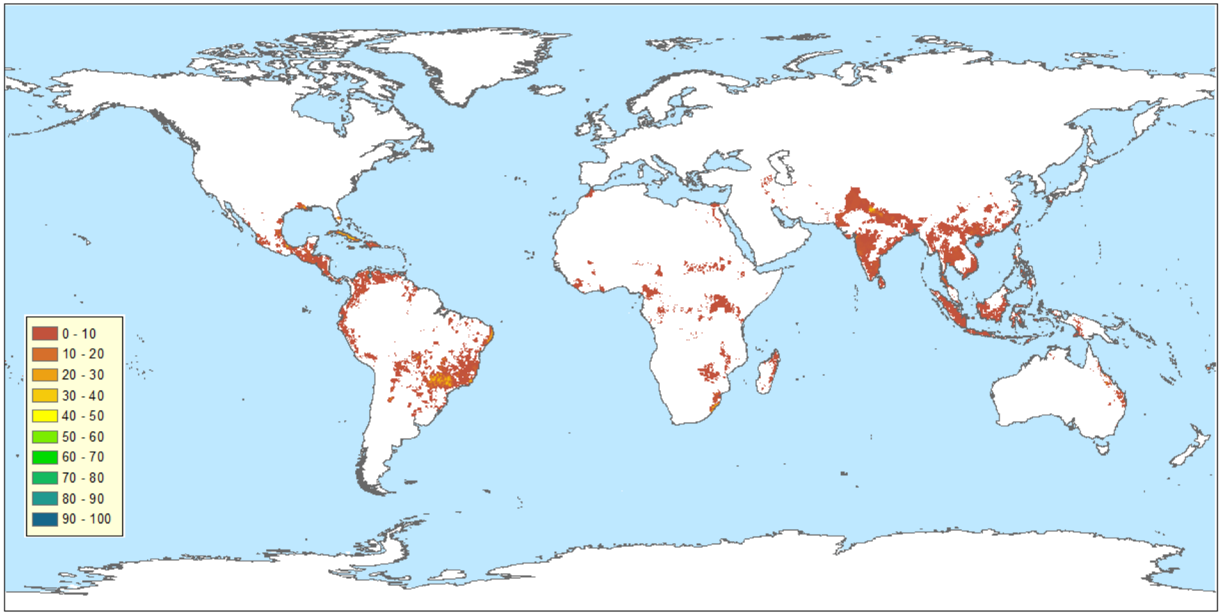
CLM5 Percent Rice 2005



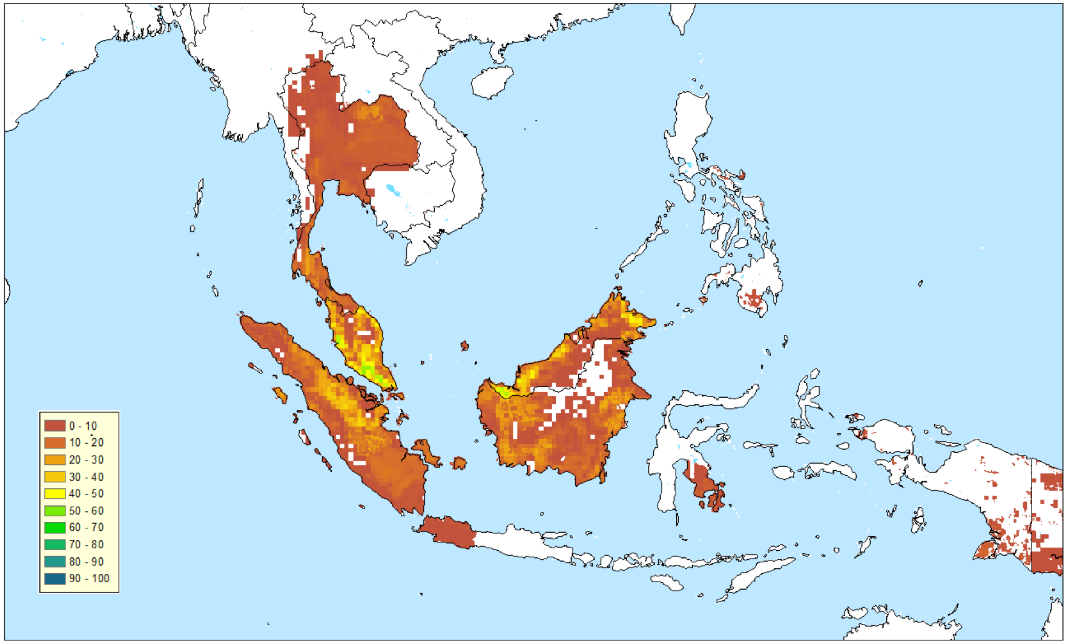
CLM5 Percent Crop 2005



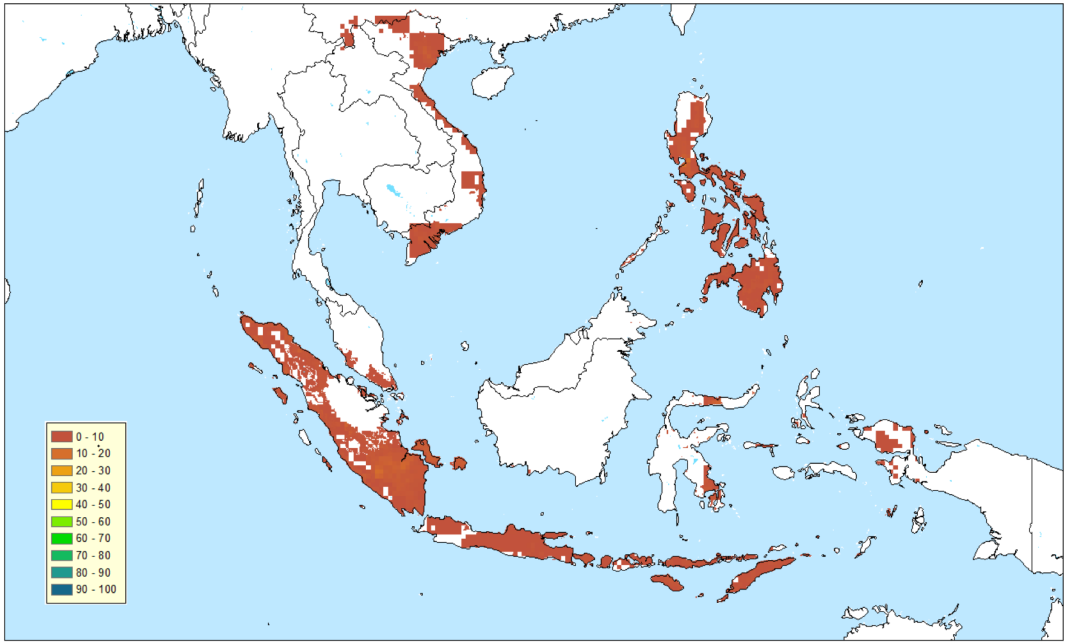
CLM5 Percent Sugarcane 2005



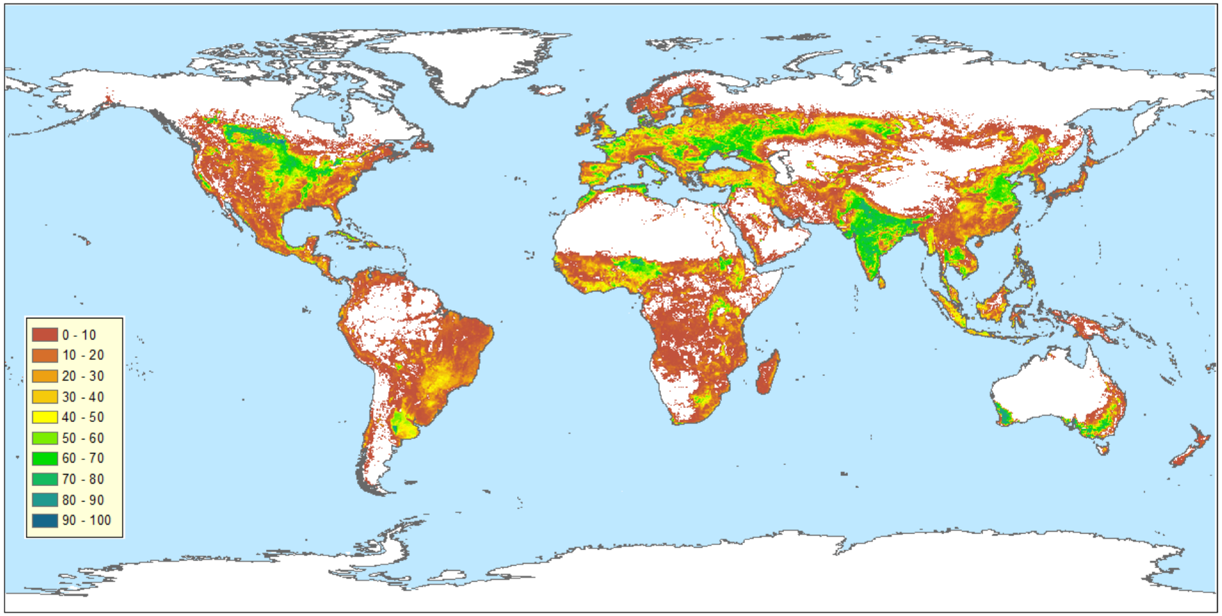
CLM5 Oil Palm 2005



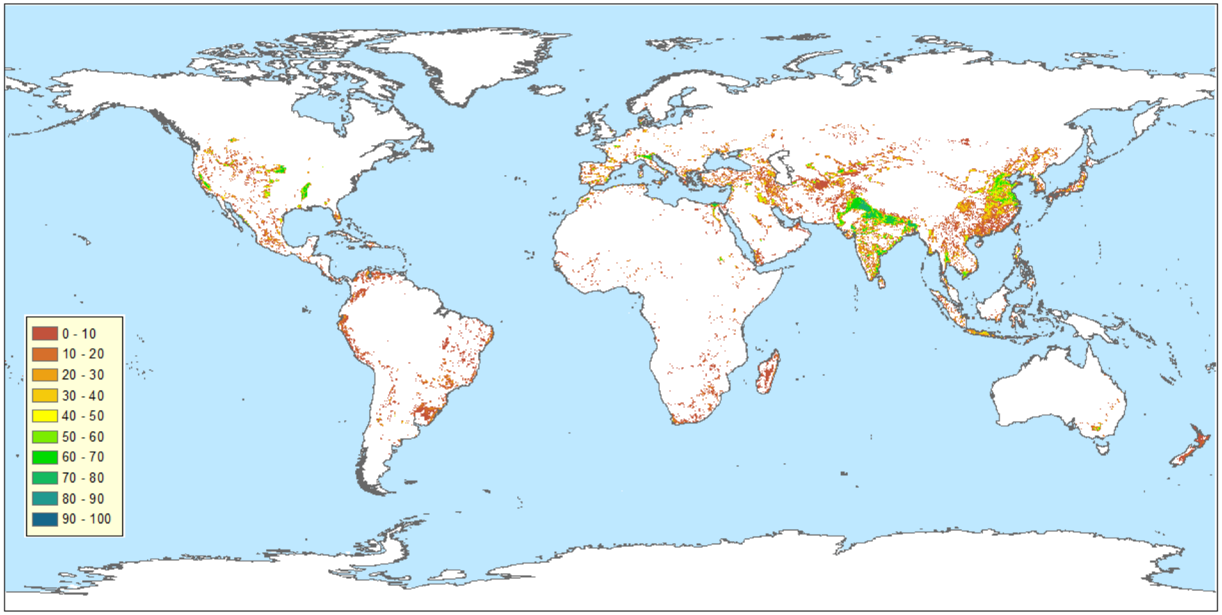
CLM5 Coffee 2005



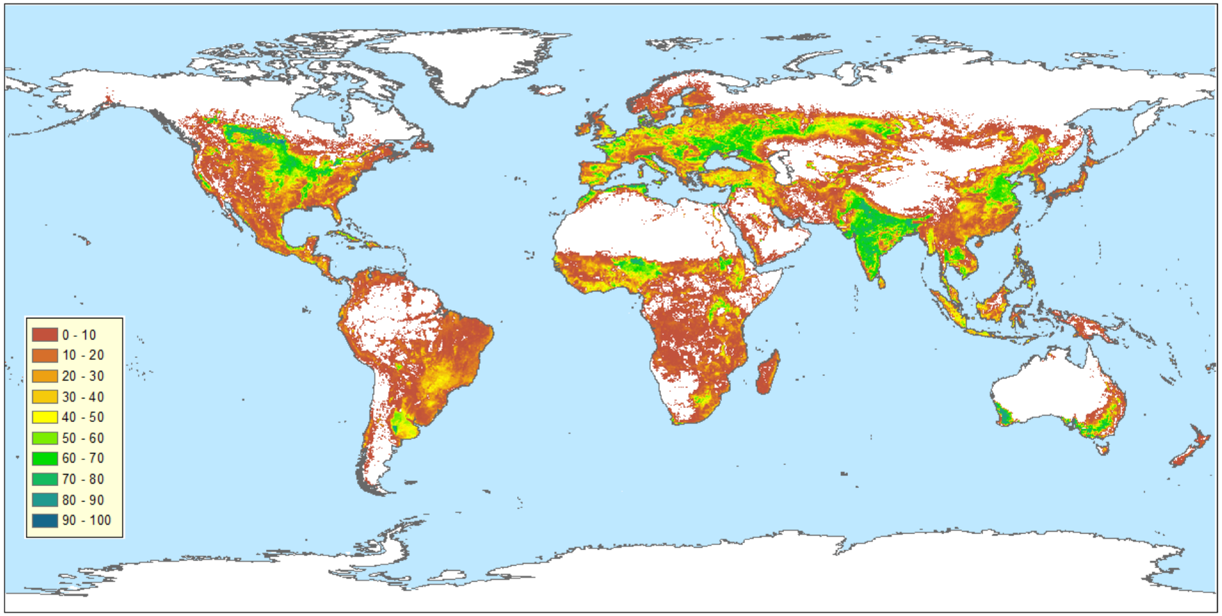
CLM5 Percent Crop 2005



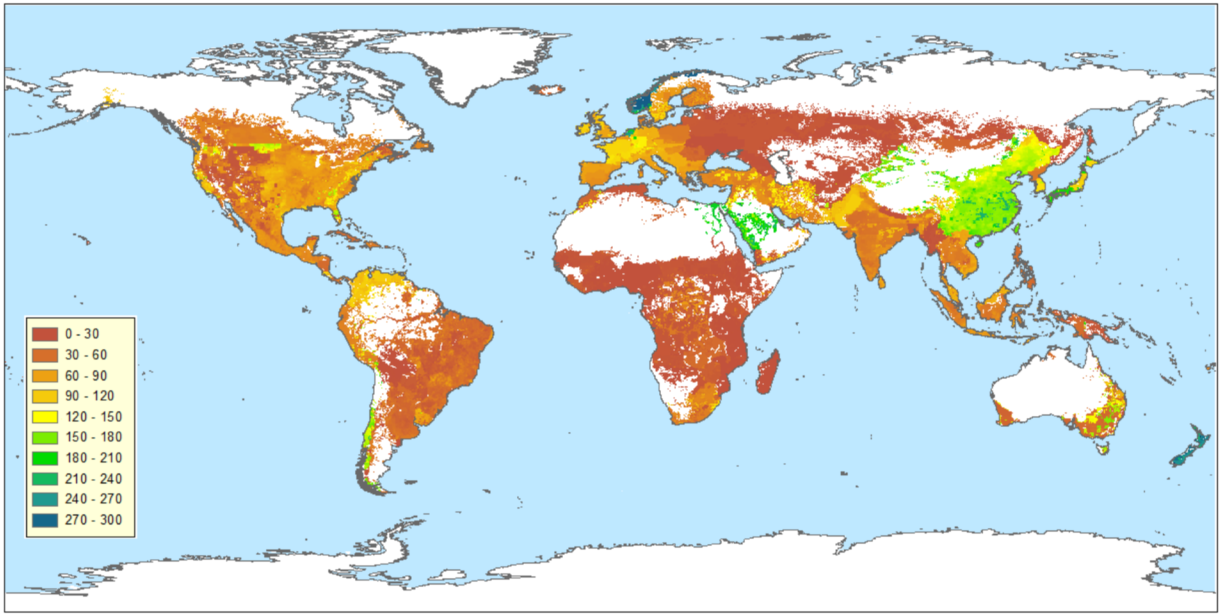
CLM5 Percent Crop Irrigated 2005



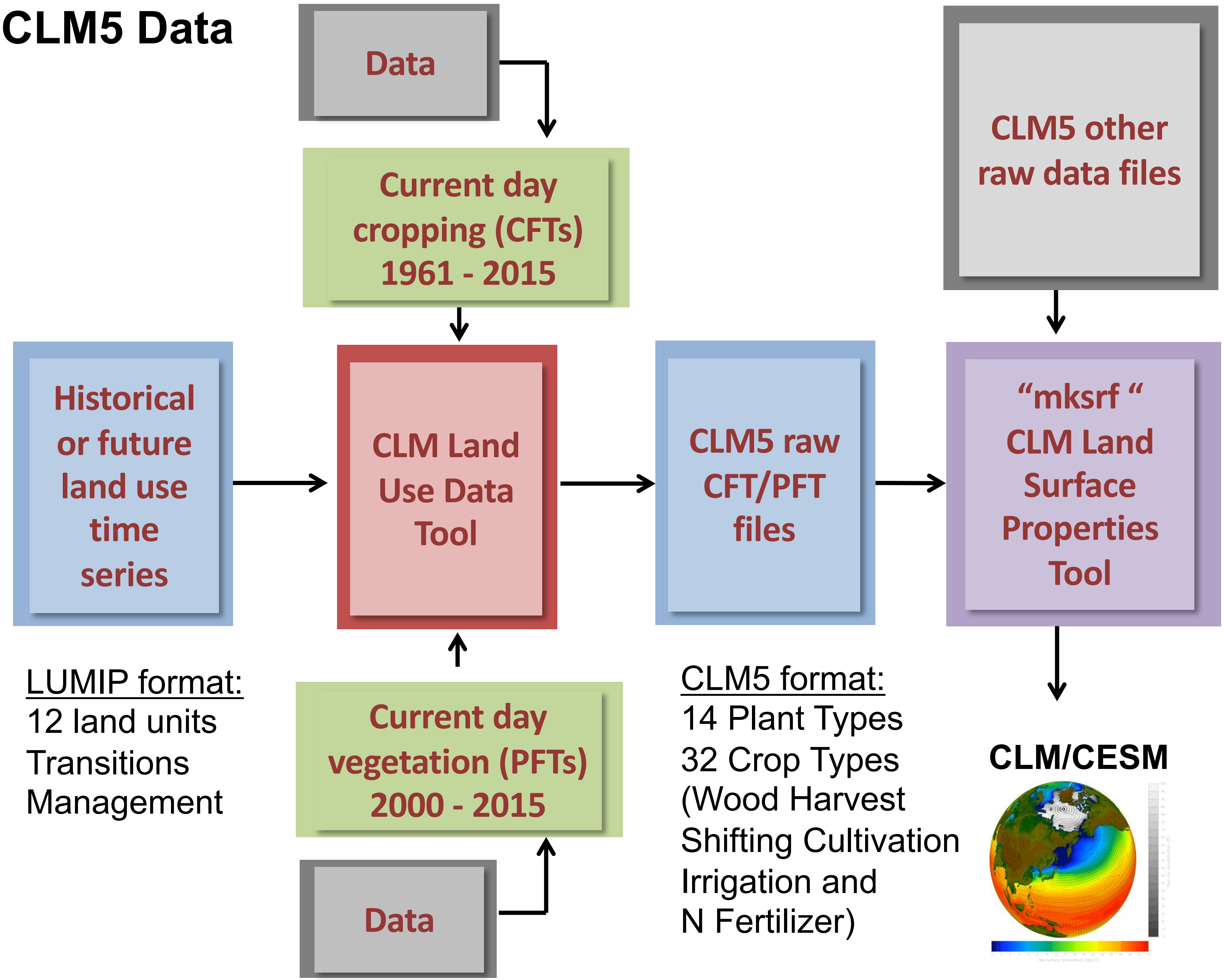
CLM5 Percent Crop 2005



CLM5 Average Crop N Fertilizer kg/ha 2005



8. CLM5 Data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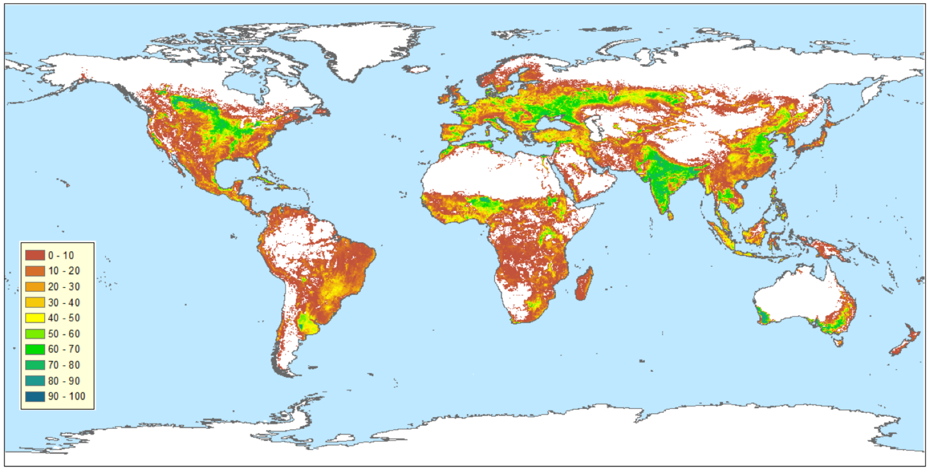
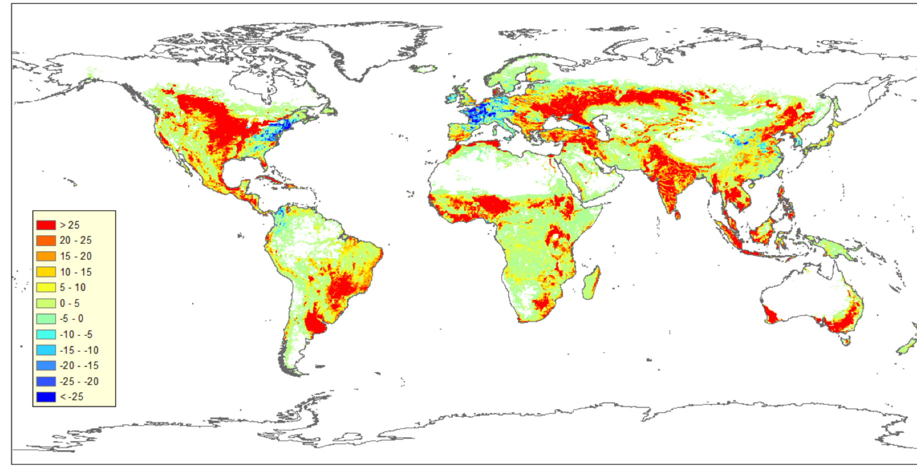
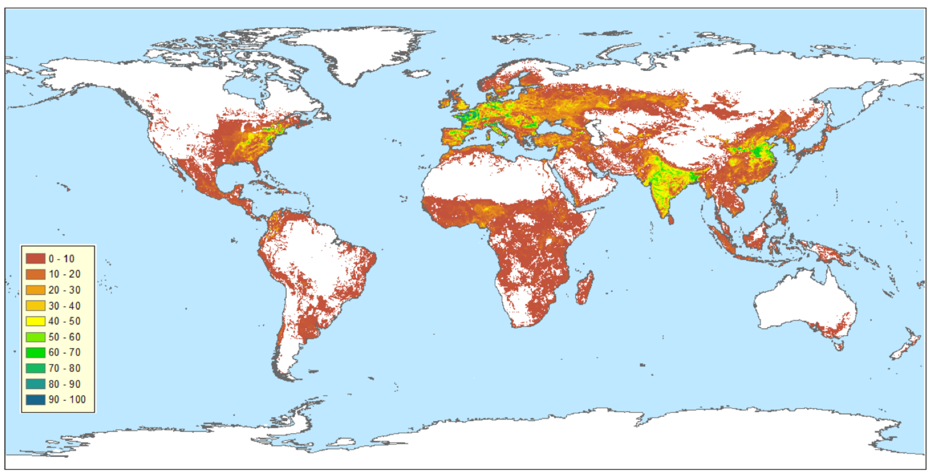
CLM5 Percent Crop 2005

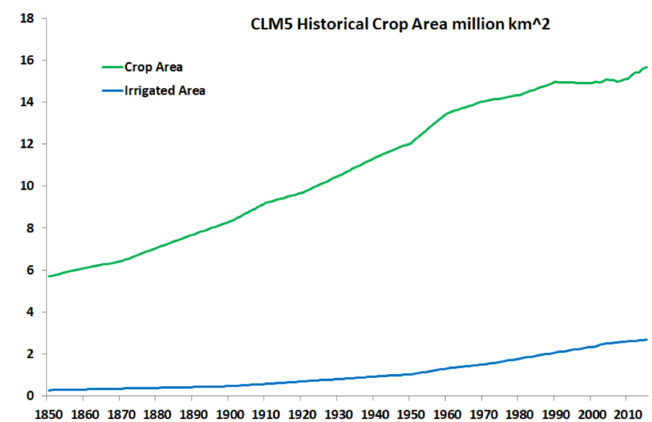


CLM5 Percent Crop Difference 2005 - 1850

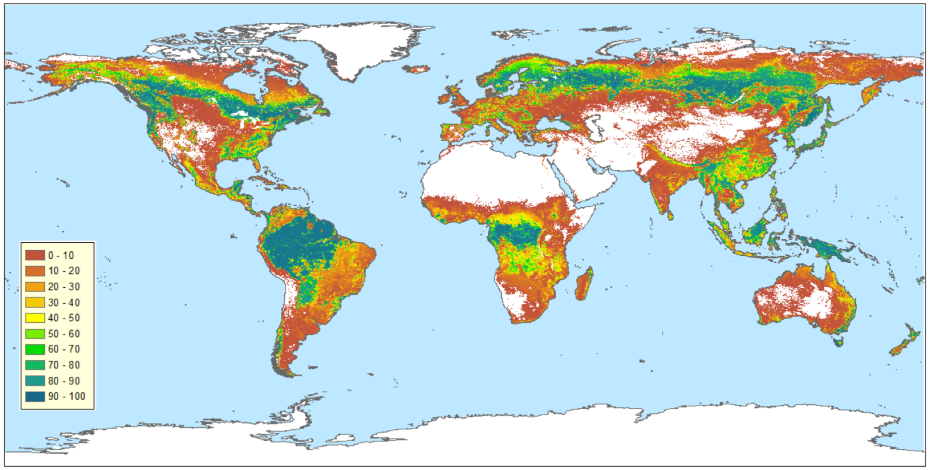


CLM5 Percent Crop 1850

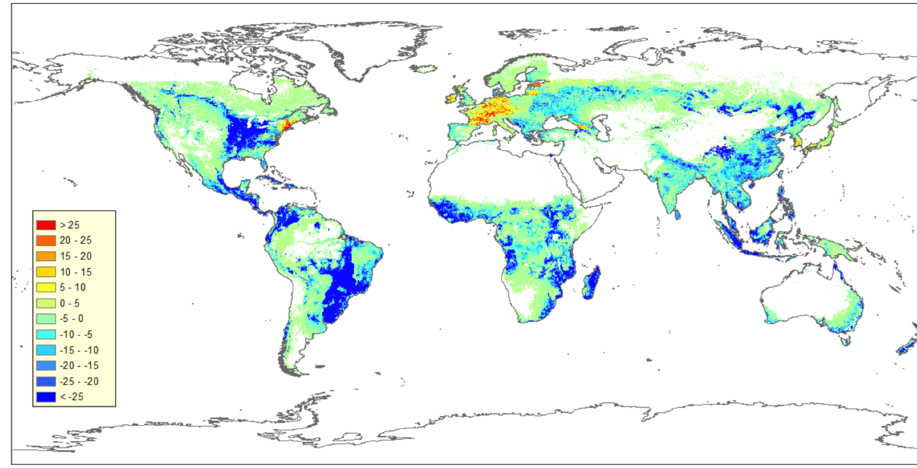




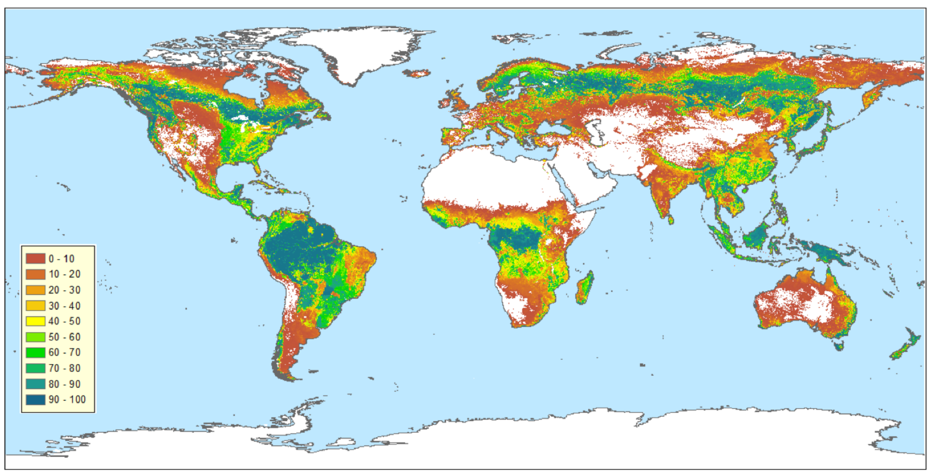
CLM5 Percent Tree 2005

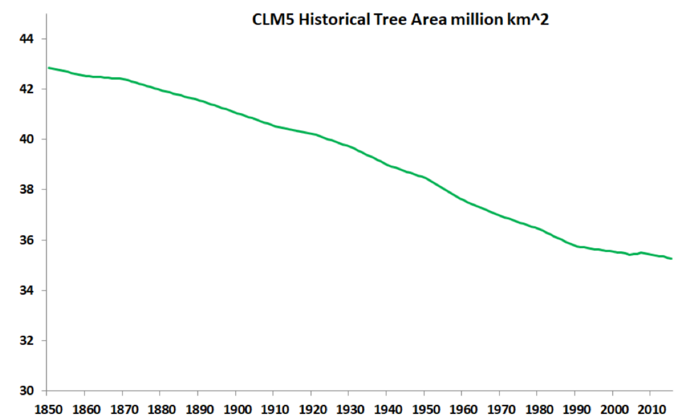


CLM5 Percent Crop Difference 2005 - 1850



CLM5 Percent Tree 1850





CLM5 LUMIP Carbon impacts of Land Use Land Cover Change

1. We can assess the LUMIP Carbon Cycle responses to Land Use Land Cover Change (LULCC) in CLM5 for a given period under changing climate and CO_2.

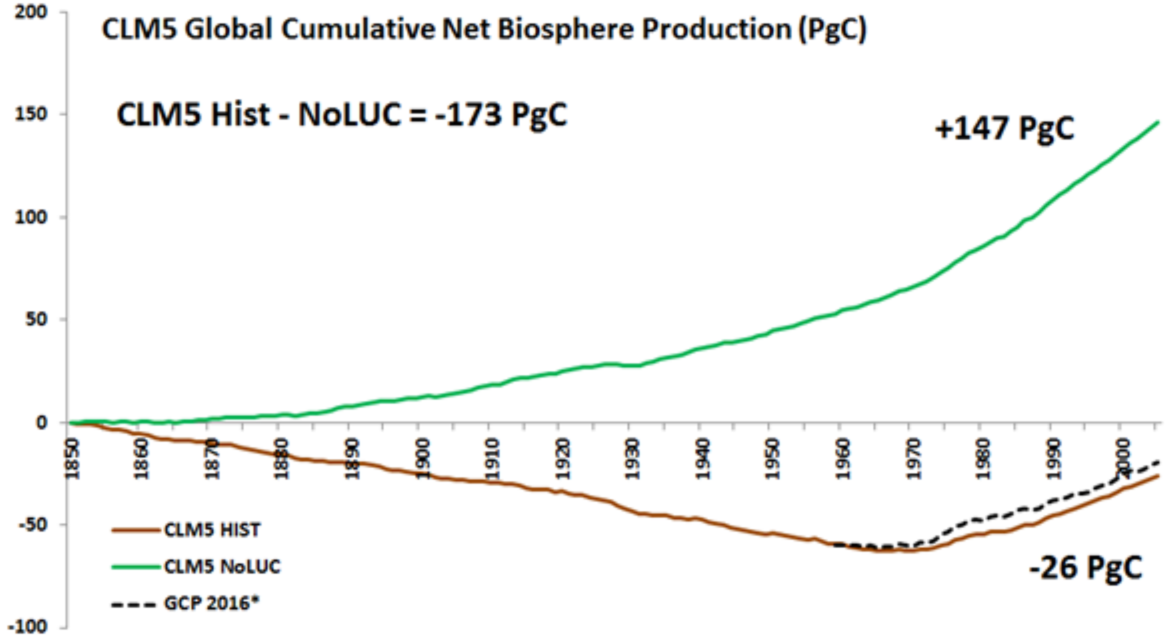
2. To do this we run CLM5 simulations with changing or transient LULCC compared to the same simulations performed without the LULCC.

3. The CLM5 LULCC impacts are assessed through looking at differences between the simulations.

4. All experiments here use 1850 – 2010 GSWP3 Prescribed Meteorology which has been shown to provide the best forcing and transient model response

5. There are no larger scale climate feedbacks in these studies as Meteorology is prescribed.

New CLM5 LUMIP LULCC vs no LULCC – NBP Carbon

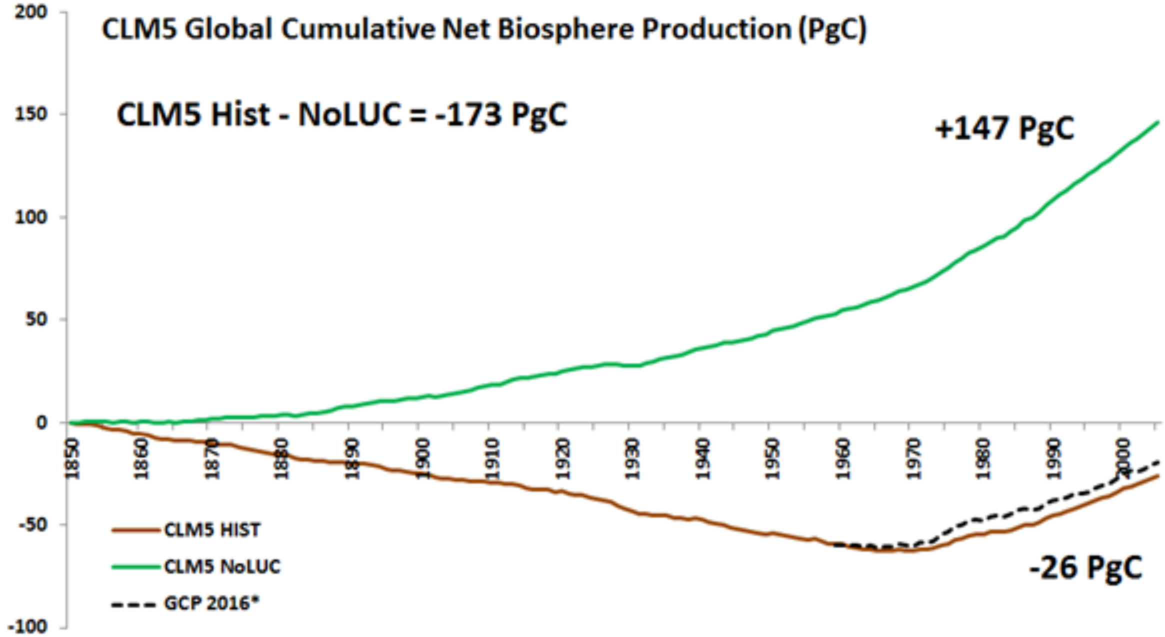


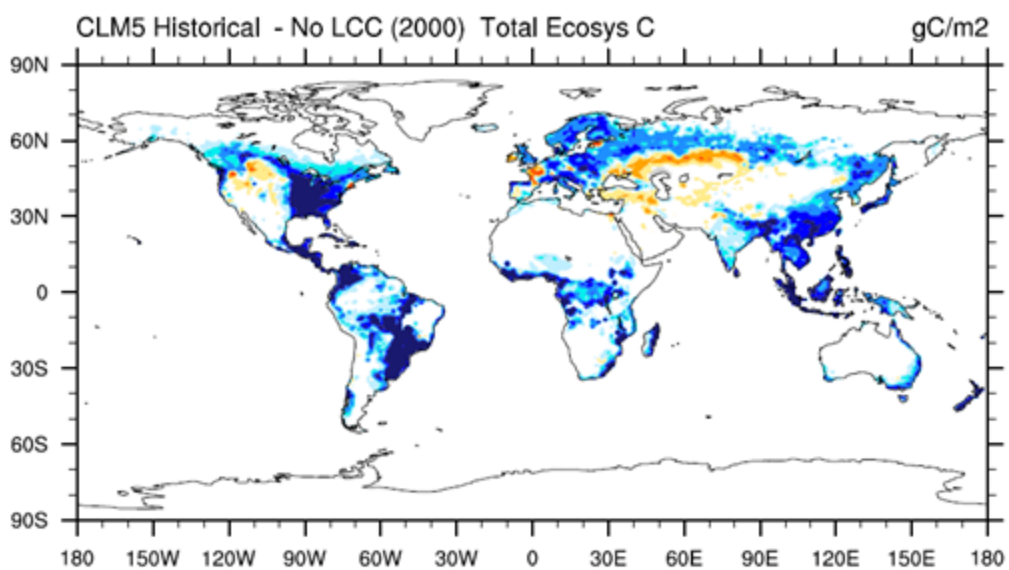
CLM5 NoLUC had large uptake of carbon from CO_2 fertilization, Climate and N Deposition CLM5 +147 PgC

This is offset by LULCC in CLM5 = 173 PgC
Global Estimates ~160 PgC

*Global Carbon Project Land Sink - LULCC 1959 – 2016

CLM5 LUMIP LULCC vs no LULCC – NBP Carbon



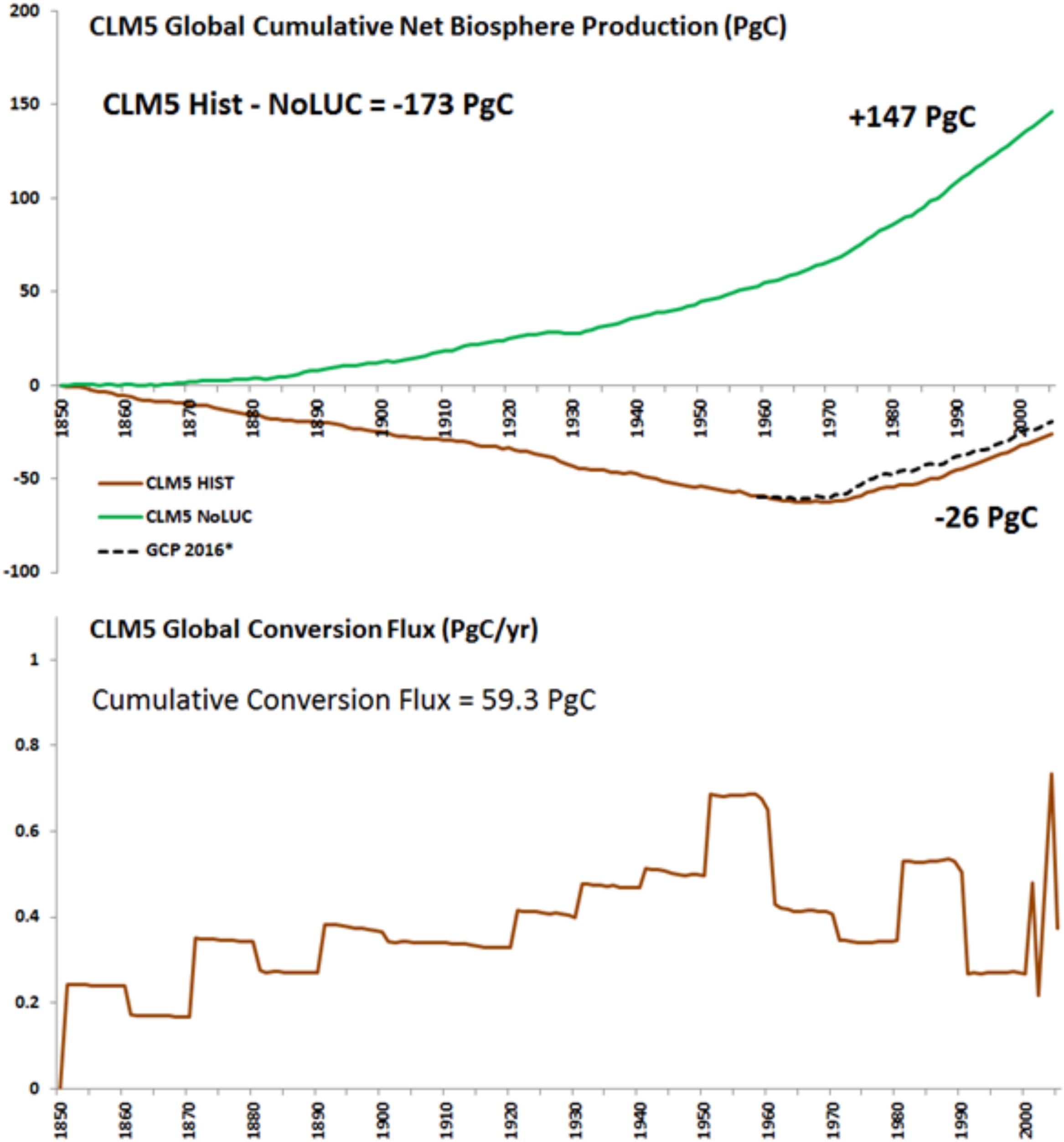


CLM5 NoLUC had large uptake of carbon from CO_2 fertilization, Climate and N Deposition
CLM5 +147 PgC

This is offset by LULCC in CLM5 = 173 PgC
Global Estimates ~160 PgC

*Global Carbon Project
Land Sink - LULCC
1959 – 2016

CLM5 LUMIP LULCC vs no LULCC – Conversion Flux



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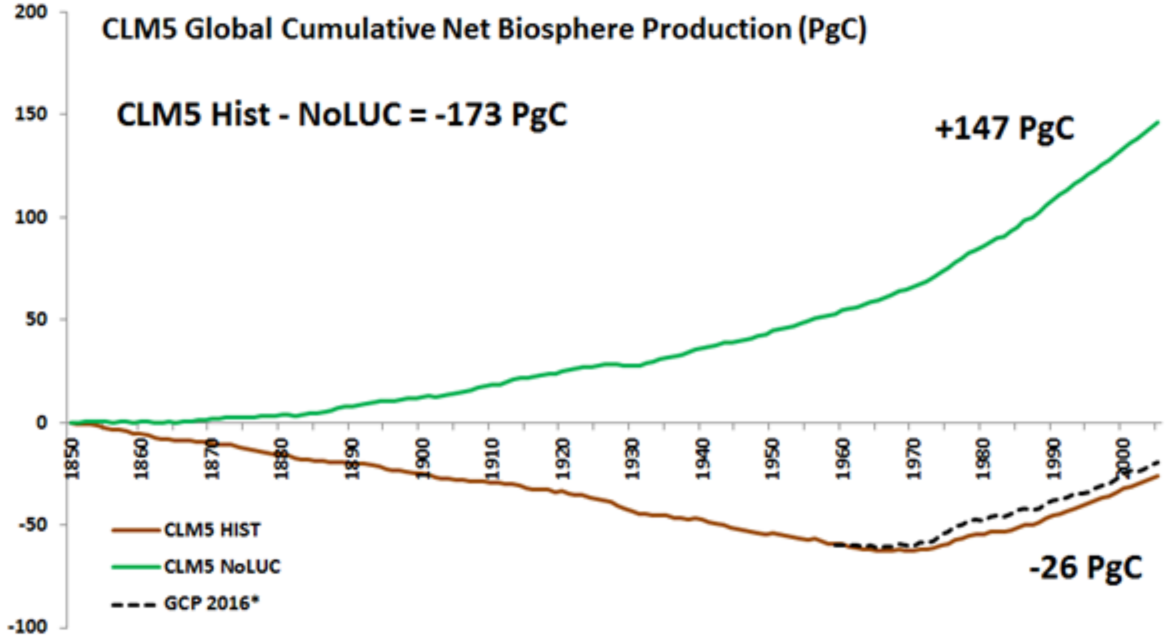
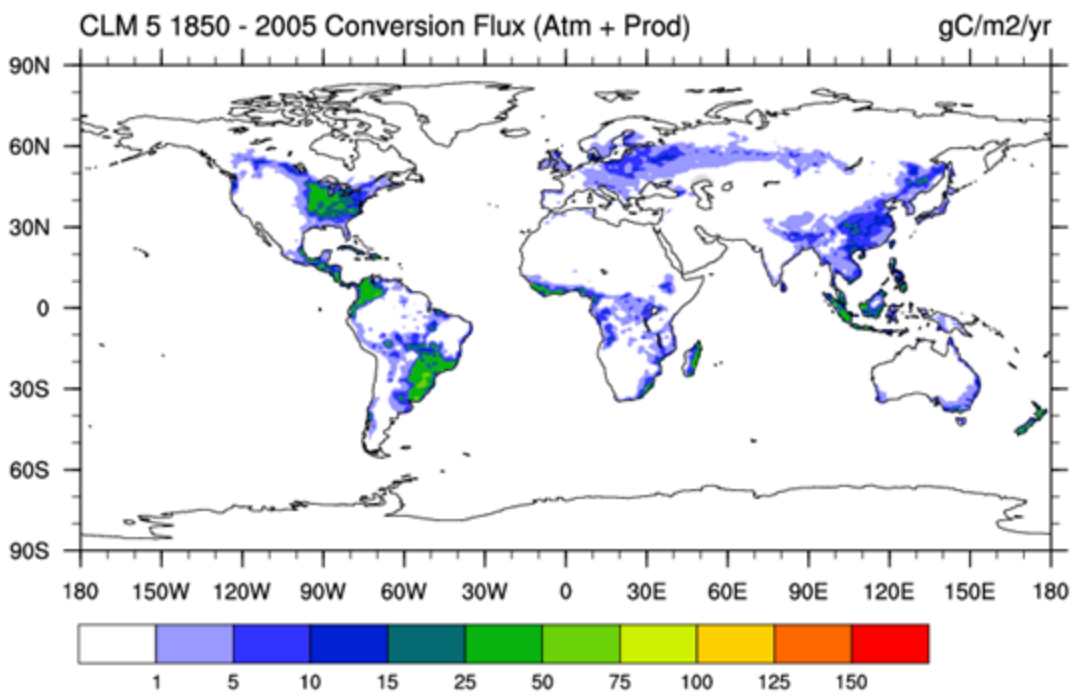
*Global Carbon Project Land Sink - LULCC 1959 – 2016

CLM5 conversion of PFTs and CFTs results in a cumulative loss of 59.3 PgC

CLM5 LUMIP LULCC vs no LULCC – Conversion Flux





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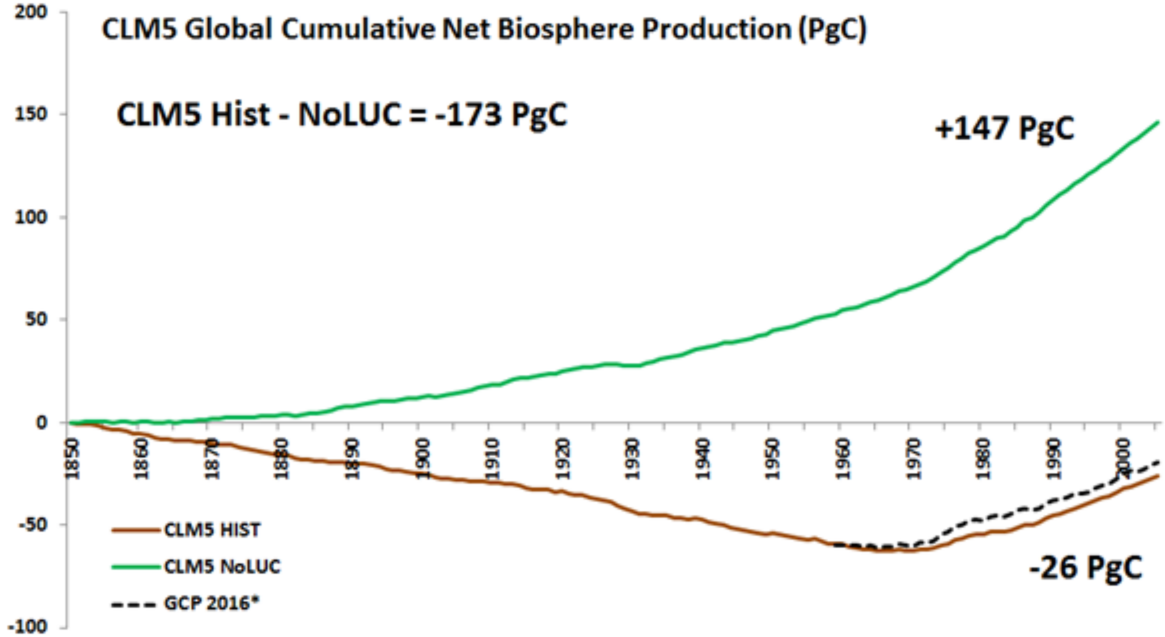
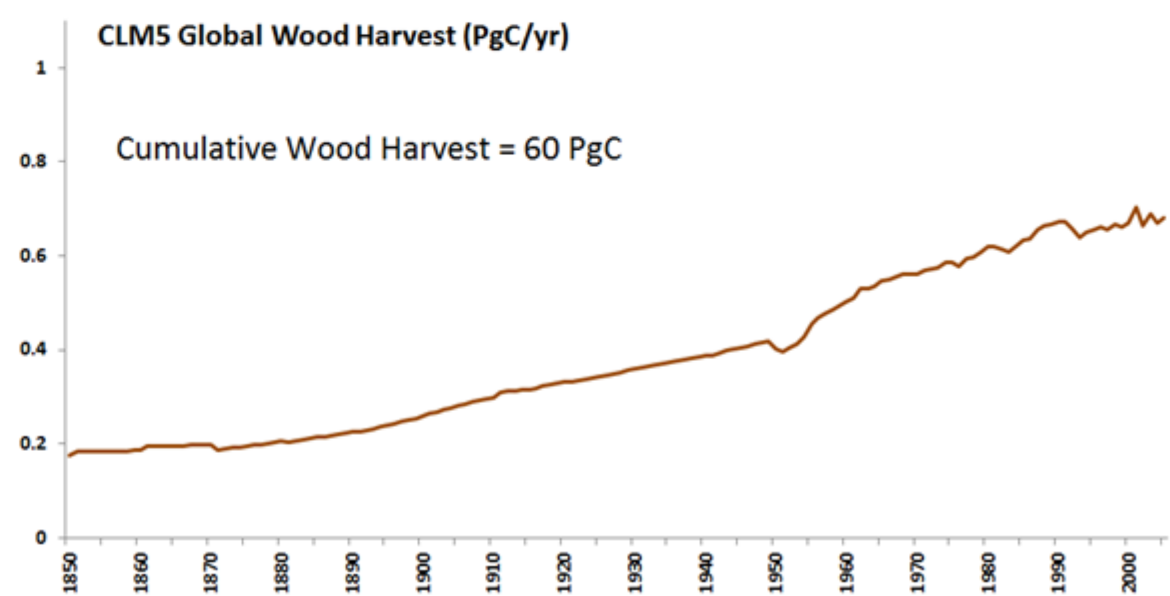
CLM5 conversion of PFTs and CFTs results in a cumulative loss of 59.3 PgC

CLM5 LUMIP LULCC vs no LULCC – Wood Harvest





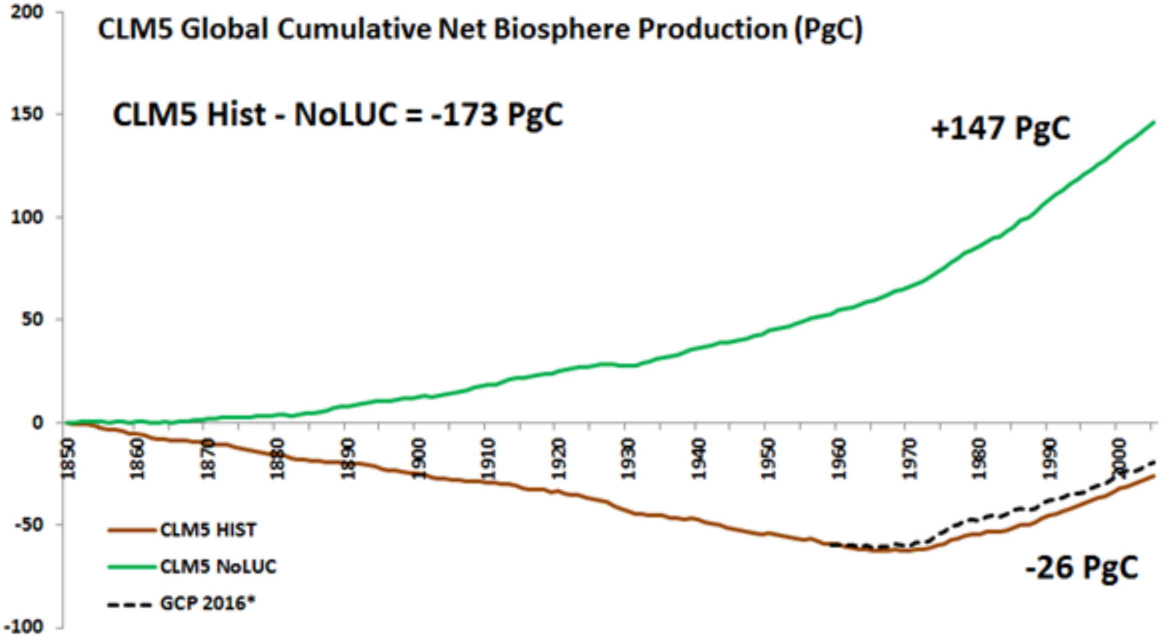
CLM5 NoLUC had large uptake of carbon from CO_2 fertilization, Climate and N Deposition CLM5 +147 PgC

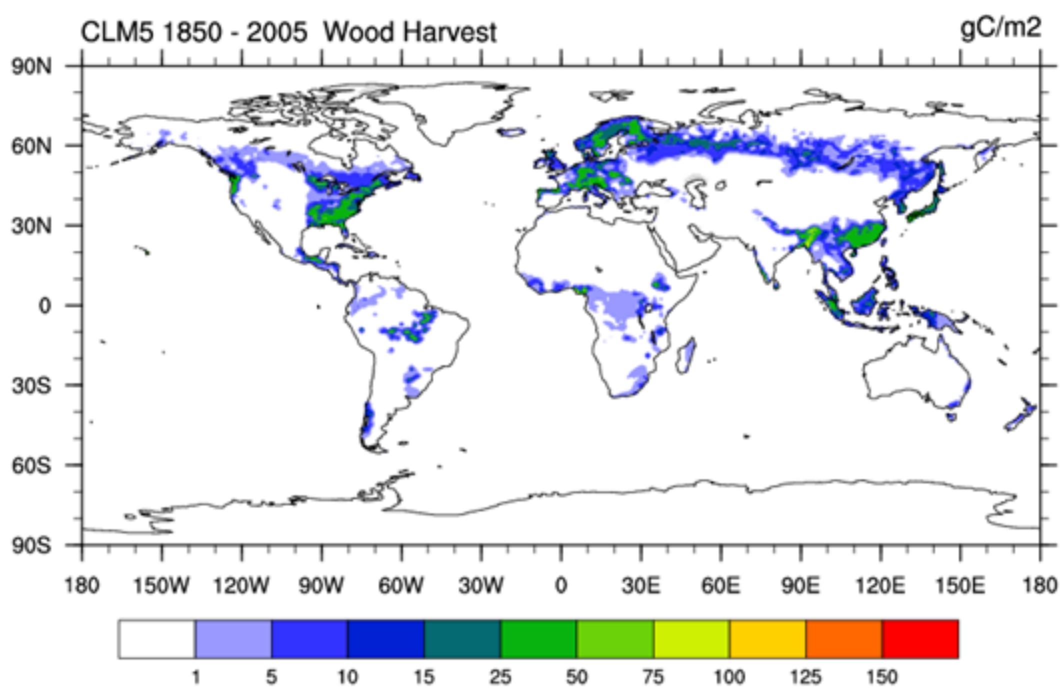
This is offset by LULCC in CLM5 = 173 PgC
Global Estimates ~160 PgC

*Global Carbon Project Land Sink - LULCC 1959 – 2016

CLM5 wood harvest of tree PFTs results in a cumulative loss of 60 PgC over the period.

CLM5 LUMIP LULCC vs no LULCC – Wood Harvest





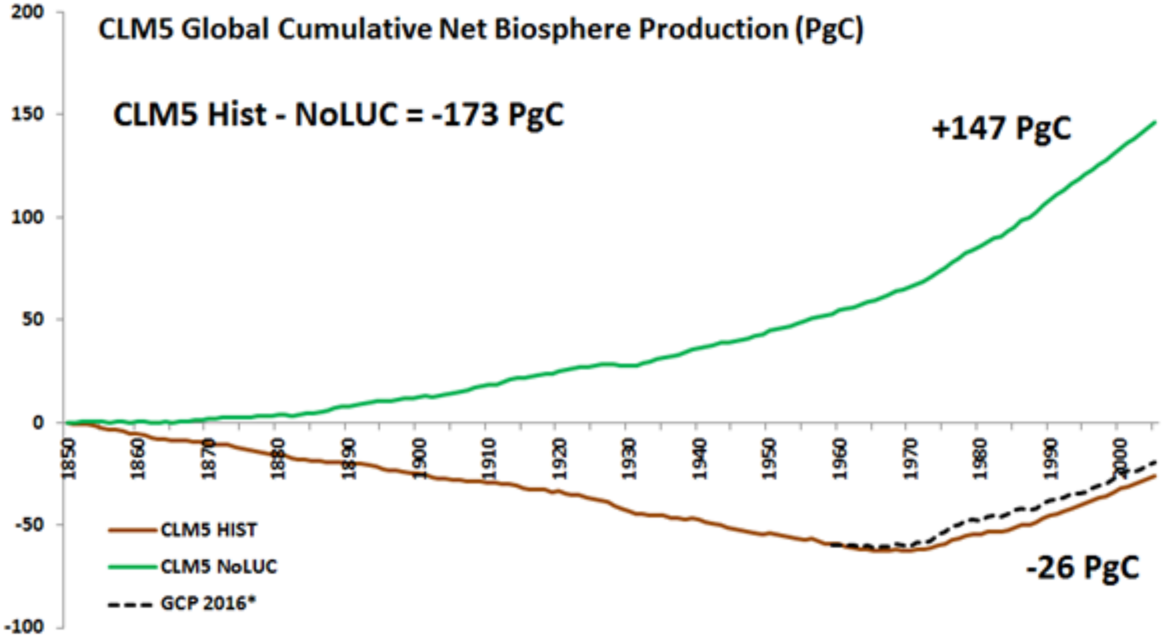
CLM5 NoLUC had large uptake of carbon from CO_2 fertilization, Climate and N Deposition CLM5 +147 PgC

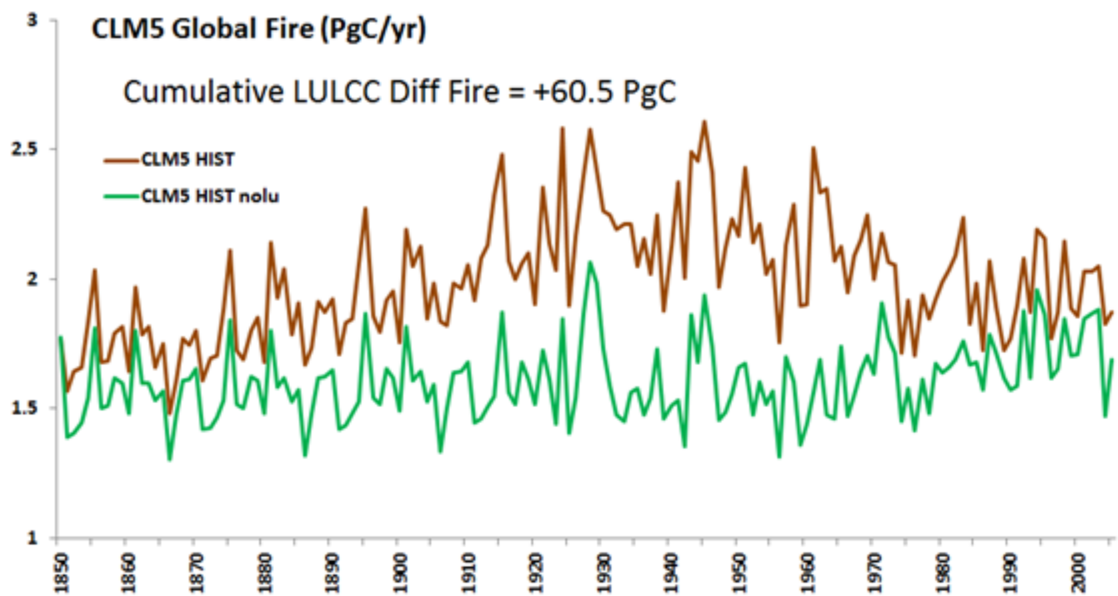
This is offset by LULCC in CLM5 = 173 PgC
Global Estimates ~160 PgC

*Global Carbon Project Land Sink - LULCC 1959 – 2016

CLM5 wood harvest of tree PFTs results in a cumulative loss of 60 PgC over the period.

CLM5 LUMIP LULCC vs no LULCC – Wildfire Flux





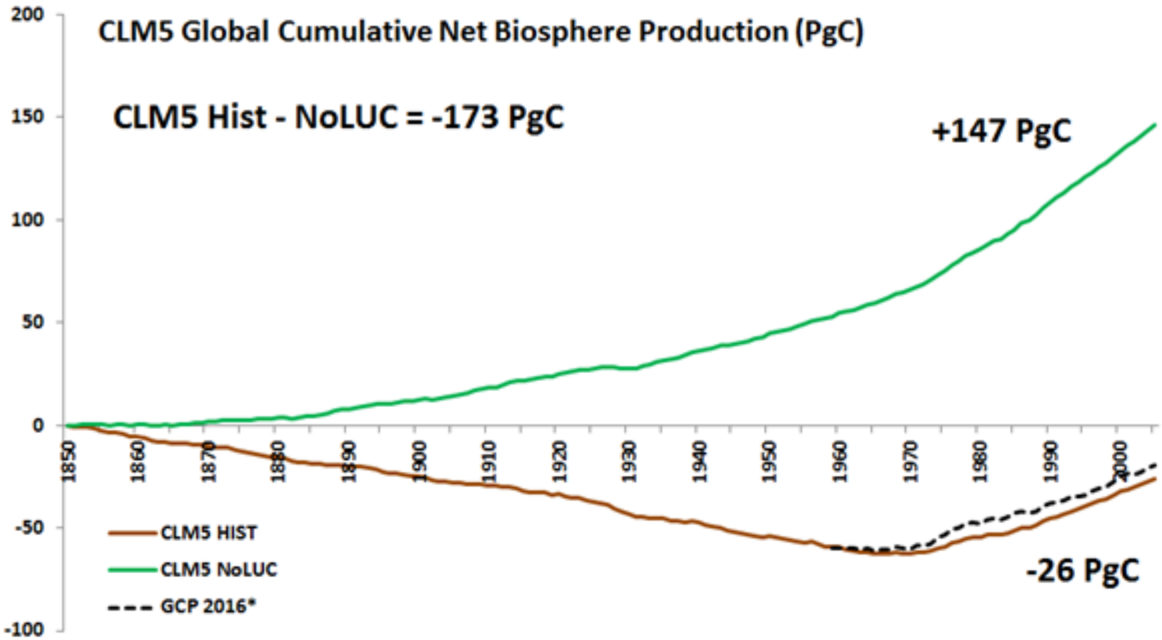
CLM5 NoLUC had large uptake of carbon from CO_2 fertilization, Climate and N Deposition CLM5 +147 PgC

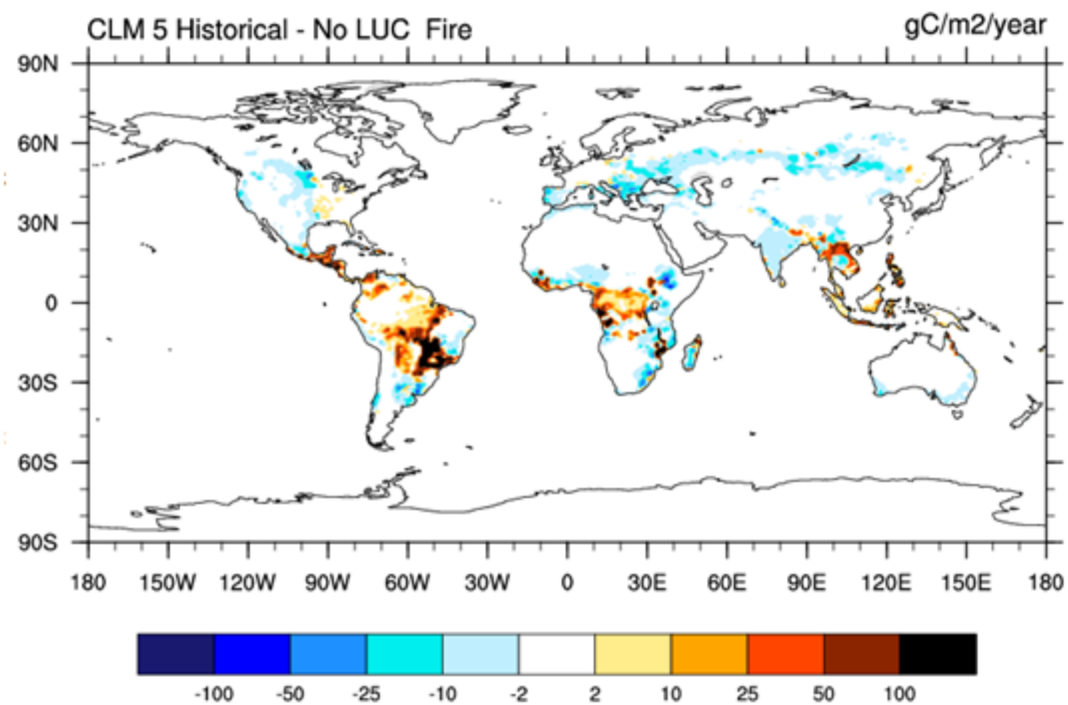
This is offset by LULCC in CLM5 = 173 PgC
Global Estimates ~160 PgC

*Global Carbon Project Land Sink - LULCC 1959 – 2016

CLM5 LULCC results in large increase in carbon loss through increased fire of +60.5 PgC

CLM5 LUMIP LULCC vs no LULCC – Wildfire Flux





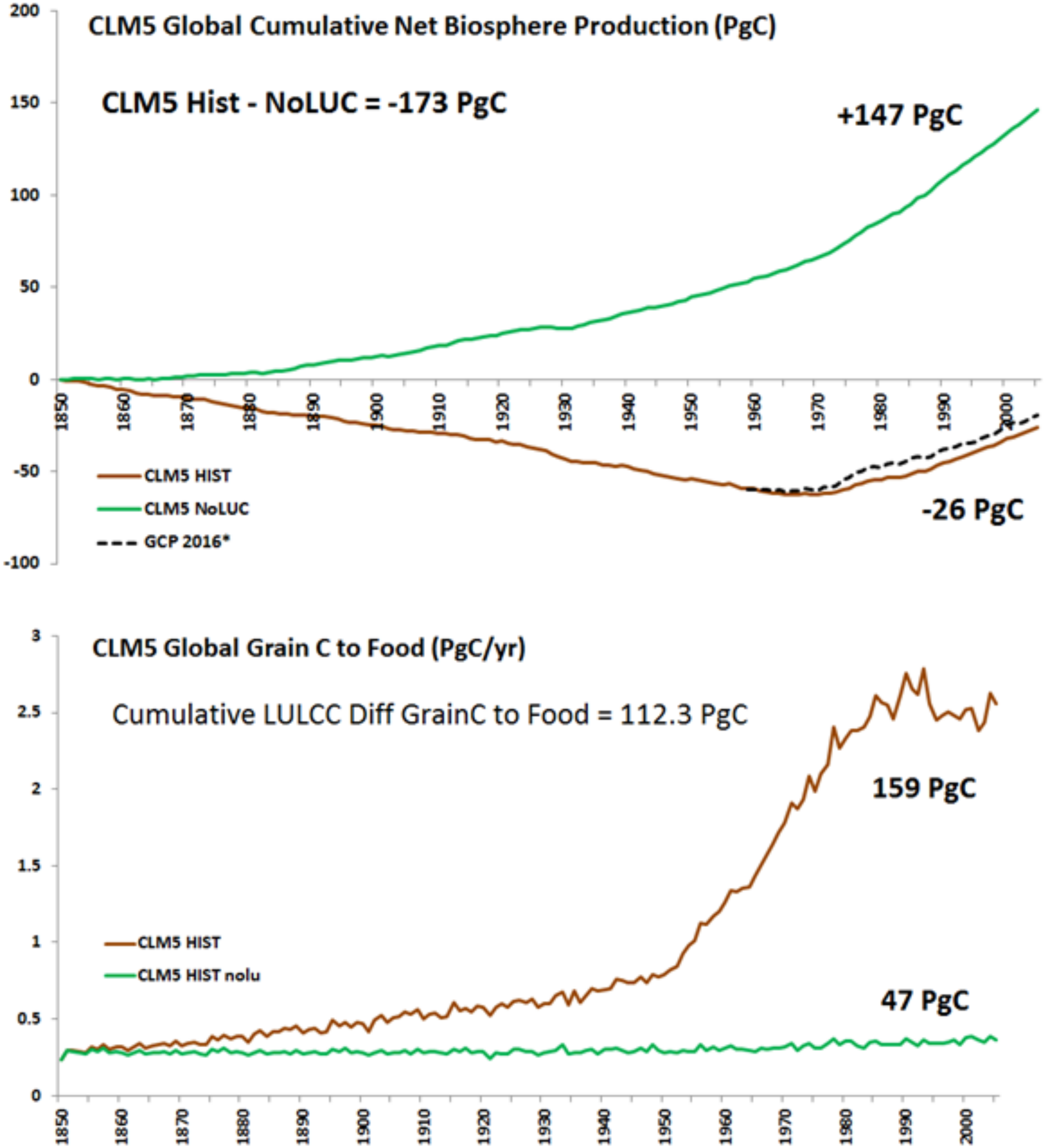
CLM5 NoLUC had large uptake of carbon from CO_2 fertilization, Climate and N Deposition CLM5 +147 PgC

This is offset by LULCC in CLM5 = 173 PgC Global Estimates ~160 PgC

*Global Carbon Project Land Sink - LULCC 1959 – 2016

CLM5 LULCC results in large increase in carbon loss through increased fire of +60.5 PgC

CLM5 LUMIP – Crop Harvest Grain Carbon



CLM5 NoLUC had large uptake of carbon from CO_2 fertilization, Climate and N Deposition CLM5 +147 PgC

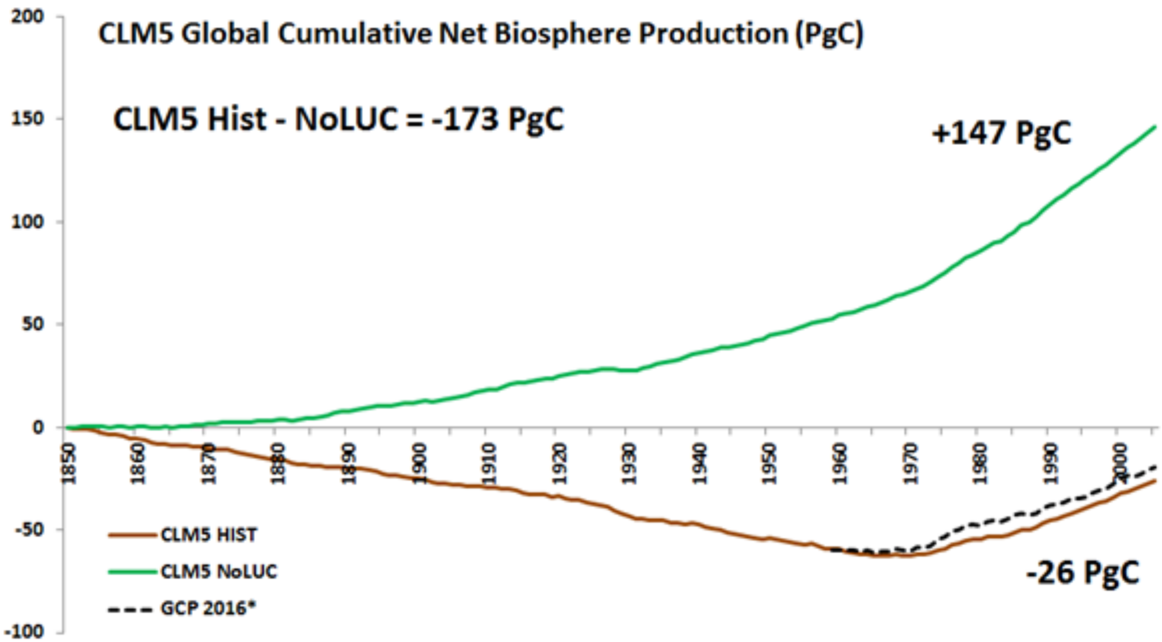
This is offset by LULCC in CLM5 = 173 PgC Global Estimates ~160 PgC

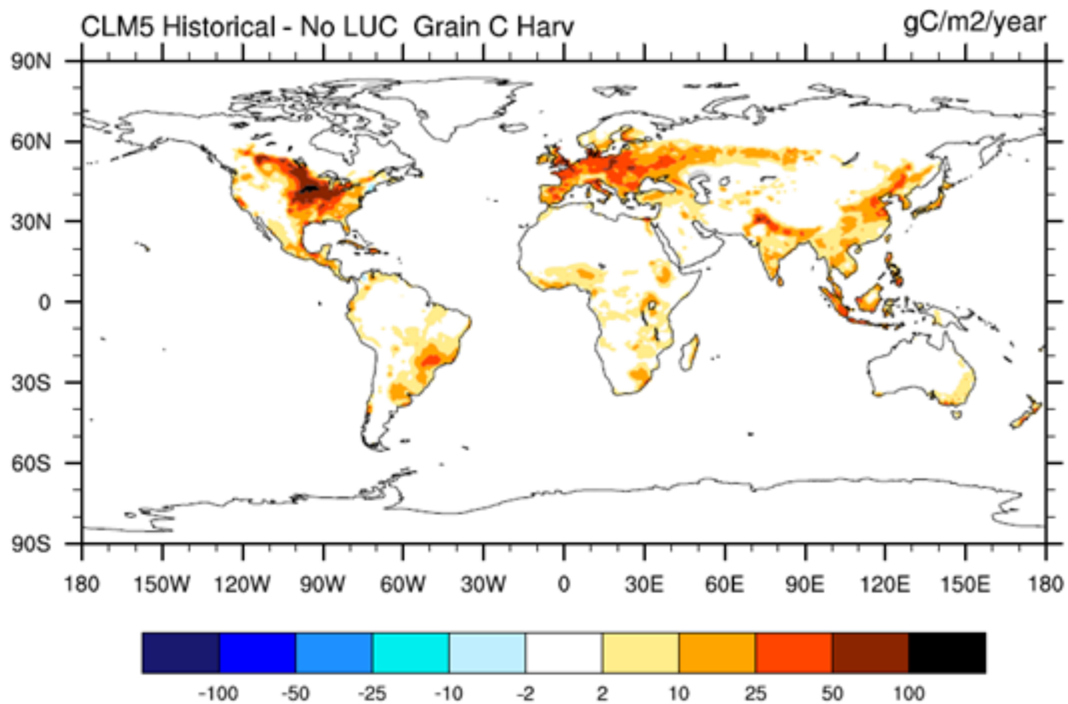
*Global Carbon Project Land Sink - LULCC 1959 – 2016

CLM5 LULCC results in large crop harvest flux out of the land of 159 PgC

Much of the crop harvest flux is offset in the LULCC simulation by higher NPP from fertilizer and lower heterotrophic respiration (organic matter decay) from harvest and residue management.

CLM5 LUMIP – Crop Harvest Grain Carbon





CLM5 NoLUC had large uptake of carbon from CO_2 fertilization, Climate and N Deposition CLM5 +147 PgC

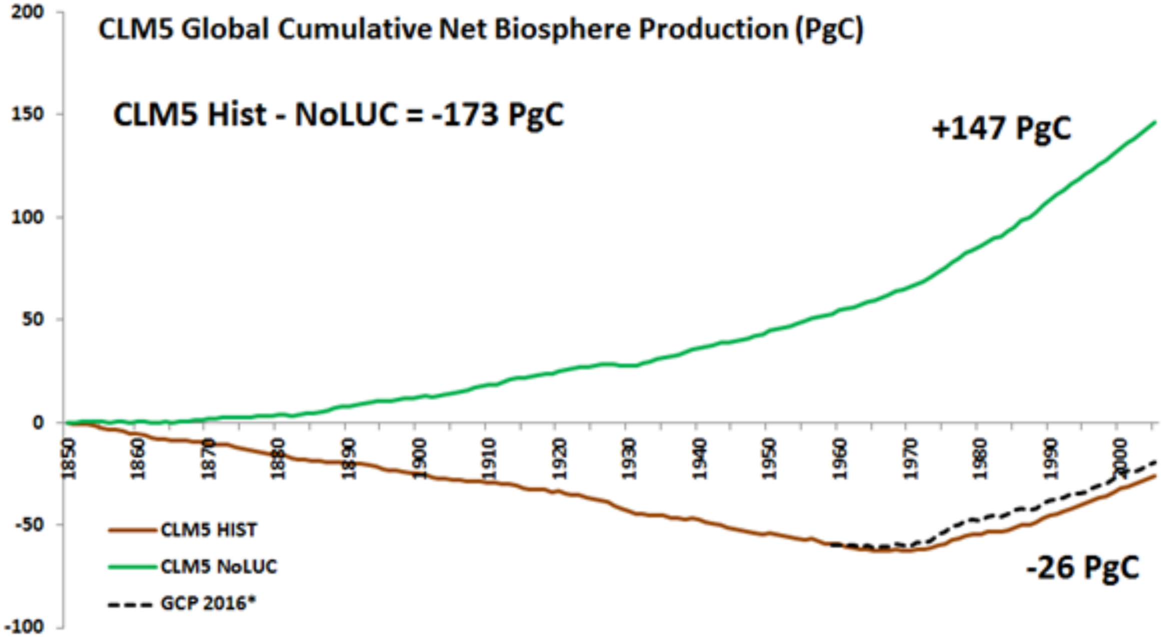
This is offset by LULCC in CLM5 = 173 PgC Global Estimates ~160 PgC

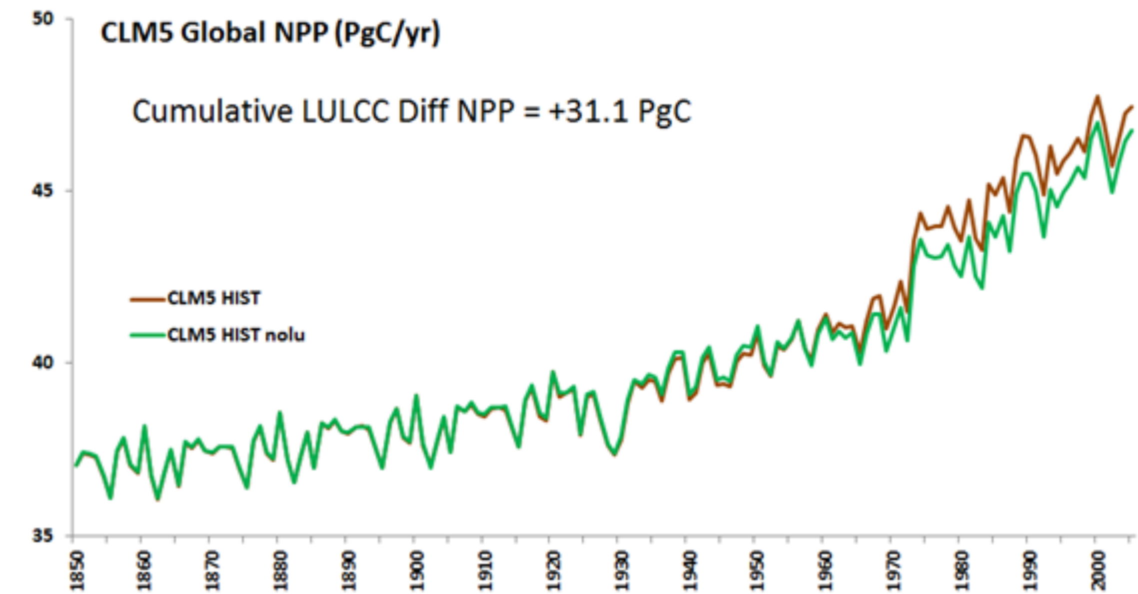
*Global Carbon Project Land Sink - LULCC 1959 – 2016

CLM5 LULCC results in large crop harvest flux out of the land of 159 PgC

Much of the crop harvest flux is offset in the LULCC simulation by higher NPP from fertilizer and lower heterotrophic respiration (organic matter decay) from harvest and residue management.

CLM5 LUMIP LULCC vs no LULCC – NPP





CLM5 NoLUC had large uptake of carbon from CO_2 fertilization, Climate and N Deposition CLM5 +147 PgC

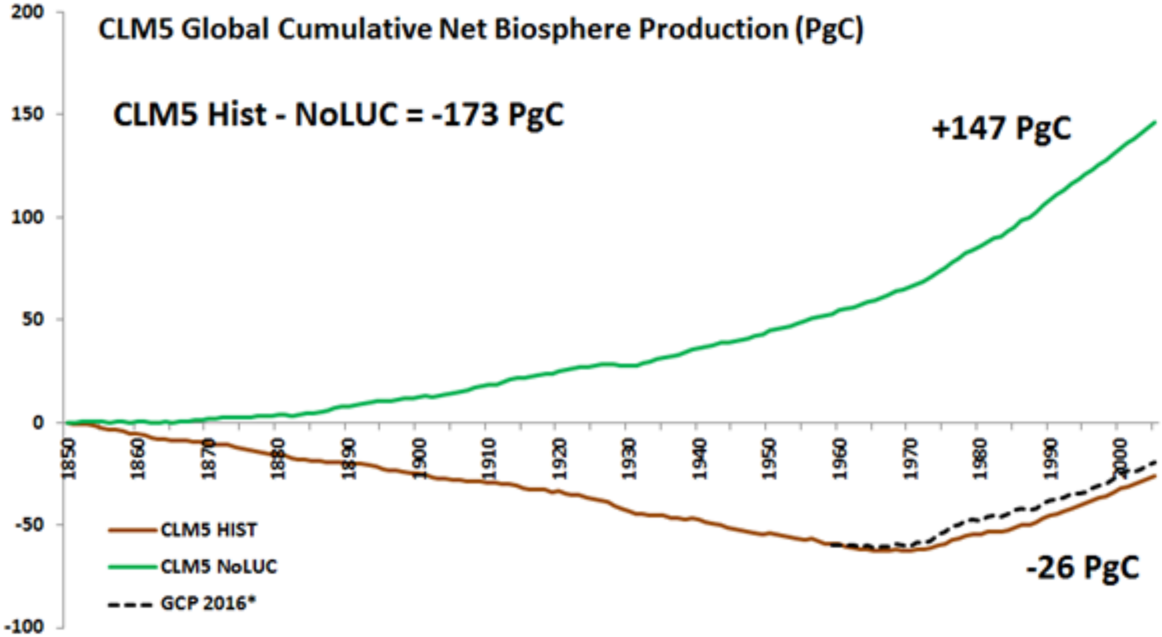
This is offset by LULCC in CLM5 = 173 PgC
Global Estimates ~160 PgC

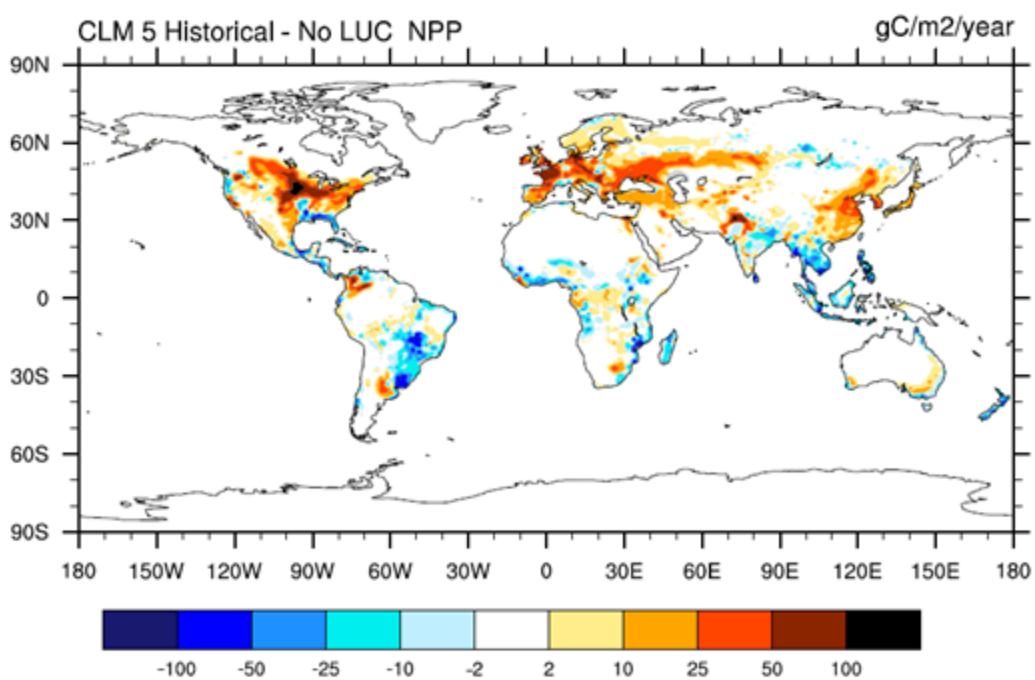
*Global Carbon Project Land Sink - LULCC 1959 – 2016

CLM5 LULCC results in Increased Net Primary Productivity uptake of carbon by the land of +31 PgC

CLM5 LULCC cropping with N fertilizer and irrigation increases NPP over previous vegetation

CLM5 LUMIP LULCC vs no LULCC – NPP





CLM5 NoLUC had large uptake of carbon from CO_2 fertilization, Climate and N Deposition CLM5 +147 PgC

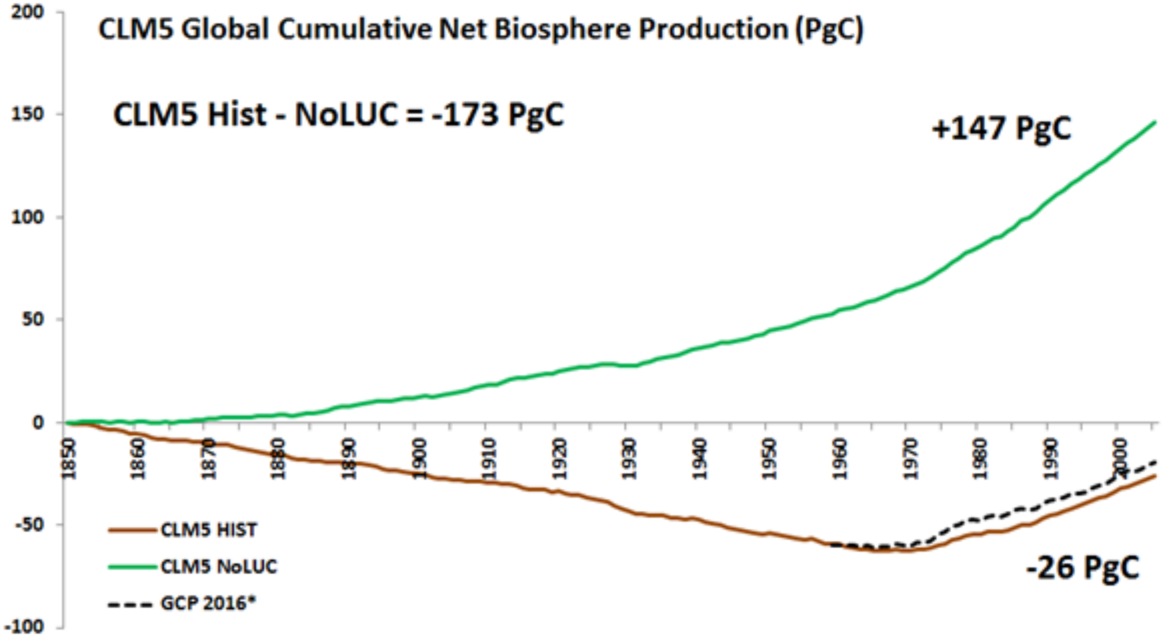
This is offset by LULCC in CLM5 = 173 PgC Global Estimates ~160 PgC

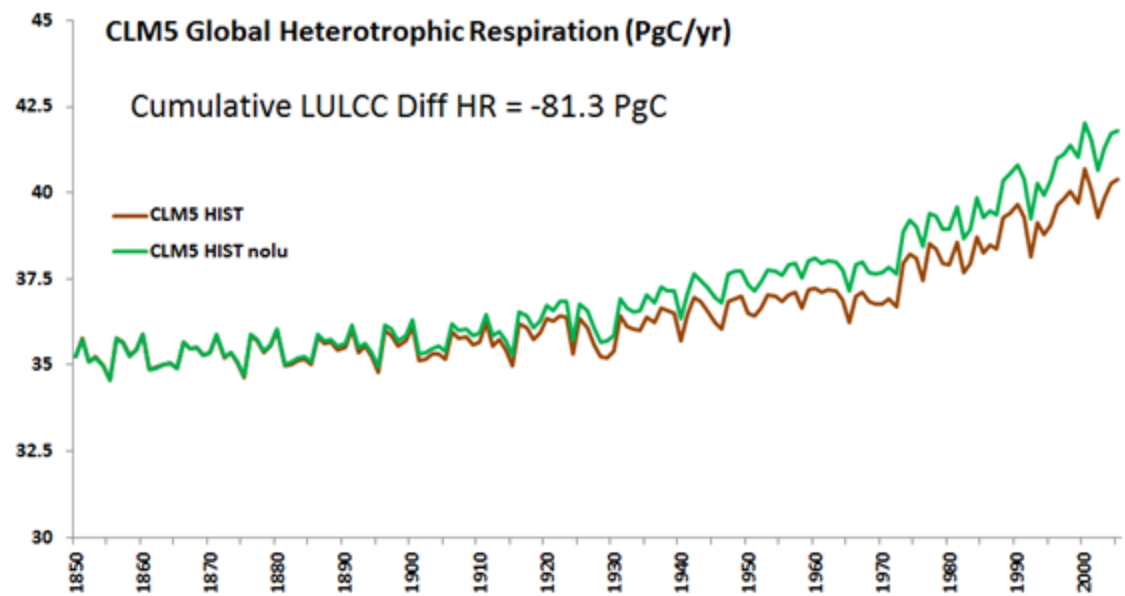
*Global Carbon Project Land Sink - LULCC 1959 – 2016

CLM5 LULCC results in Increased Net Primary Productivity uptake of carbon by the land of +31 PgC

CLM5 LULCC cropping with N fertilizer and irrigation increases NPP over previous vegetation

CLM5 LUMIP LULCC vs no LULCC – Het. Respiration





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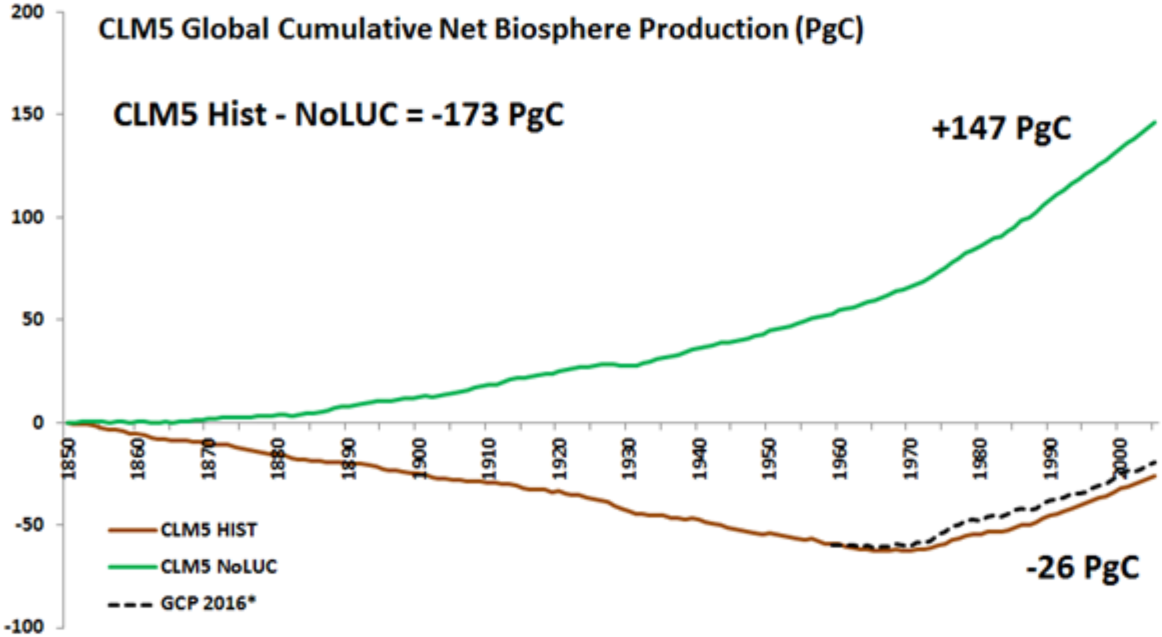
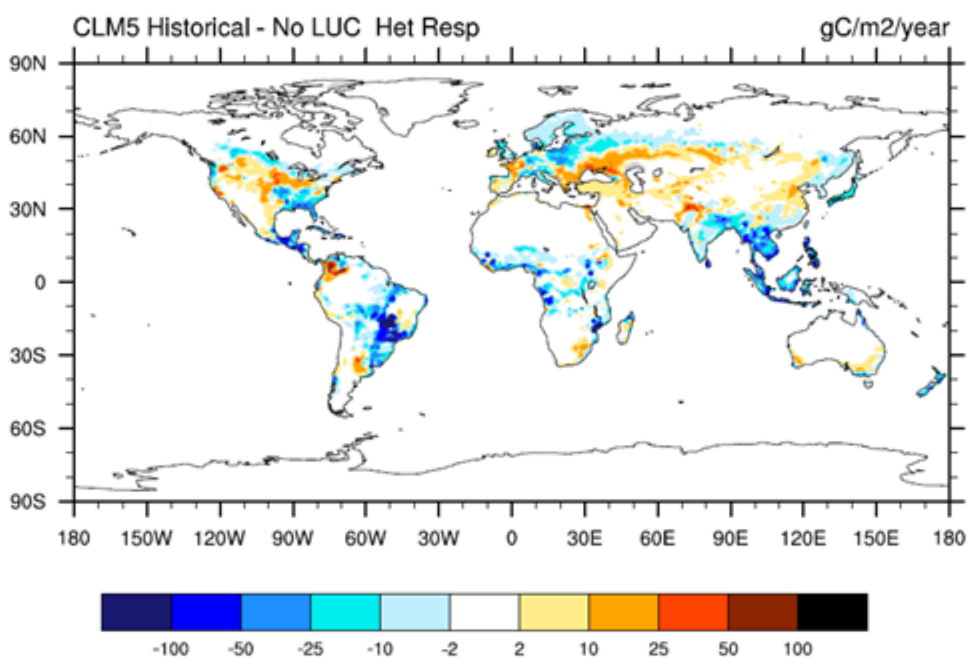
CLM5 LULCC results in Reduced Heterotrophic Respiration loss of carbon by -81.3 PgC

CLM5 LULCC deforestation, crop harvest and fire changes result in less litter, coarse woody debris and soil carbon to decay

CLM5 LUMIP LULCC vs no LULCC – Het. Respiration





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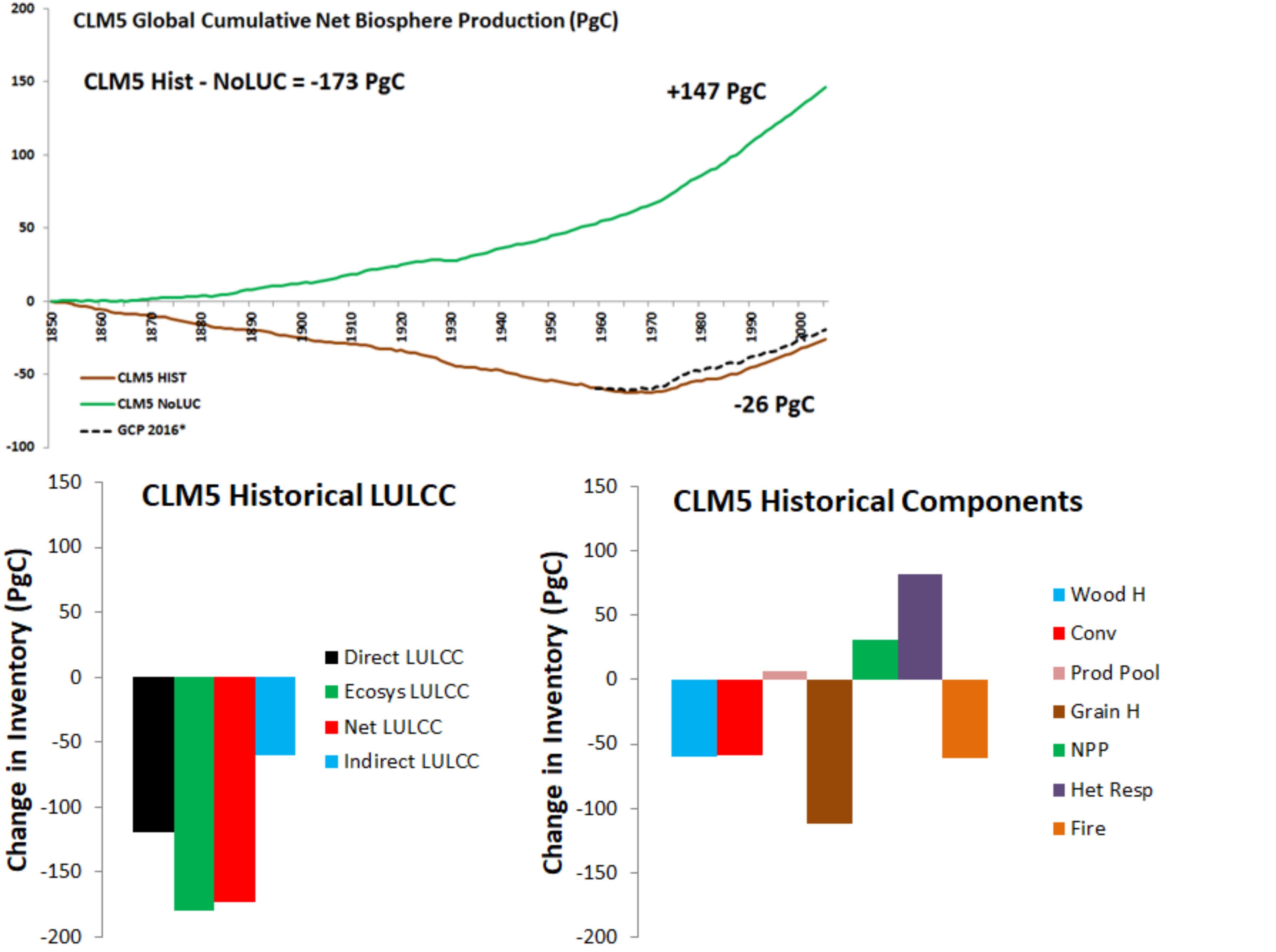
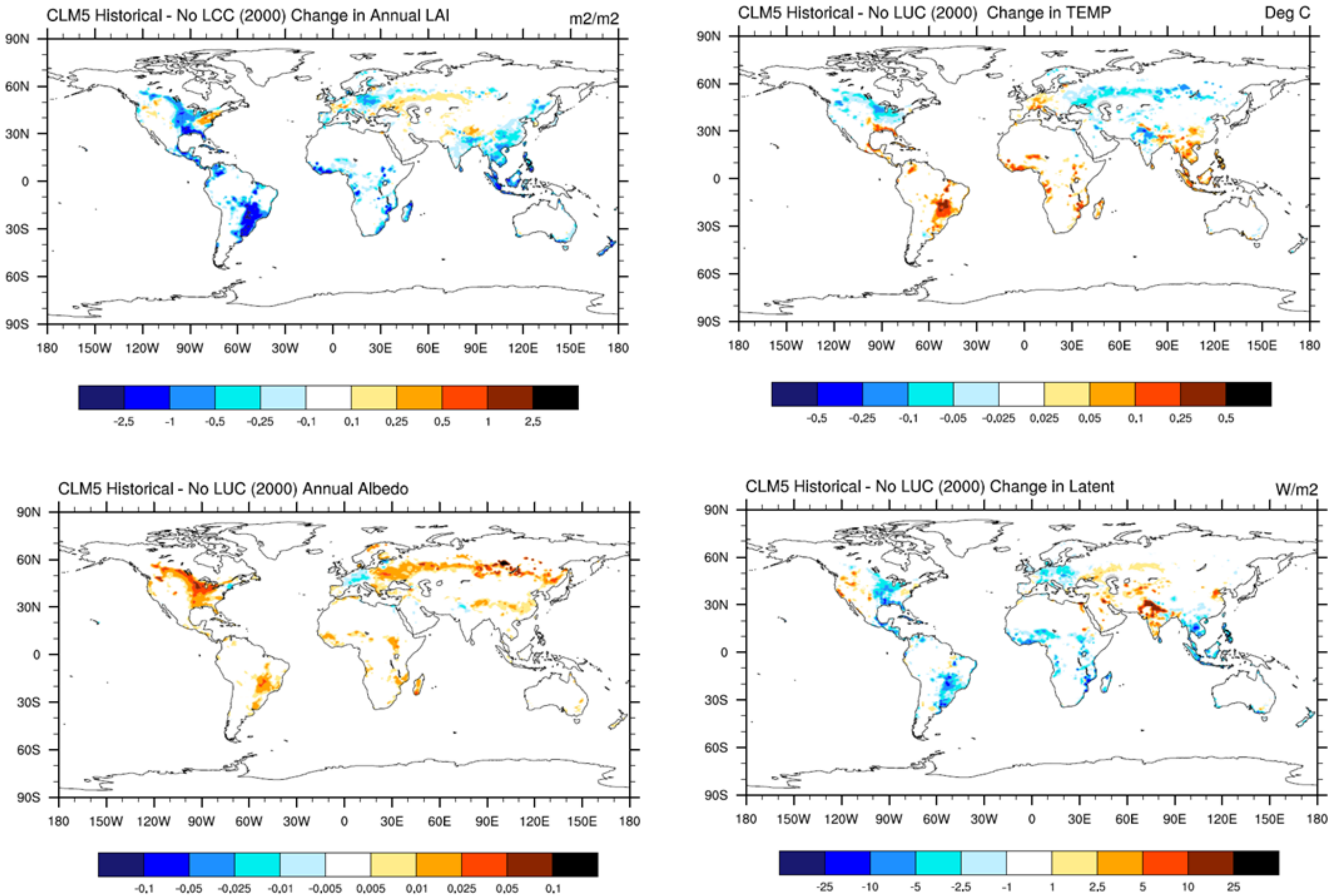
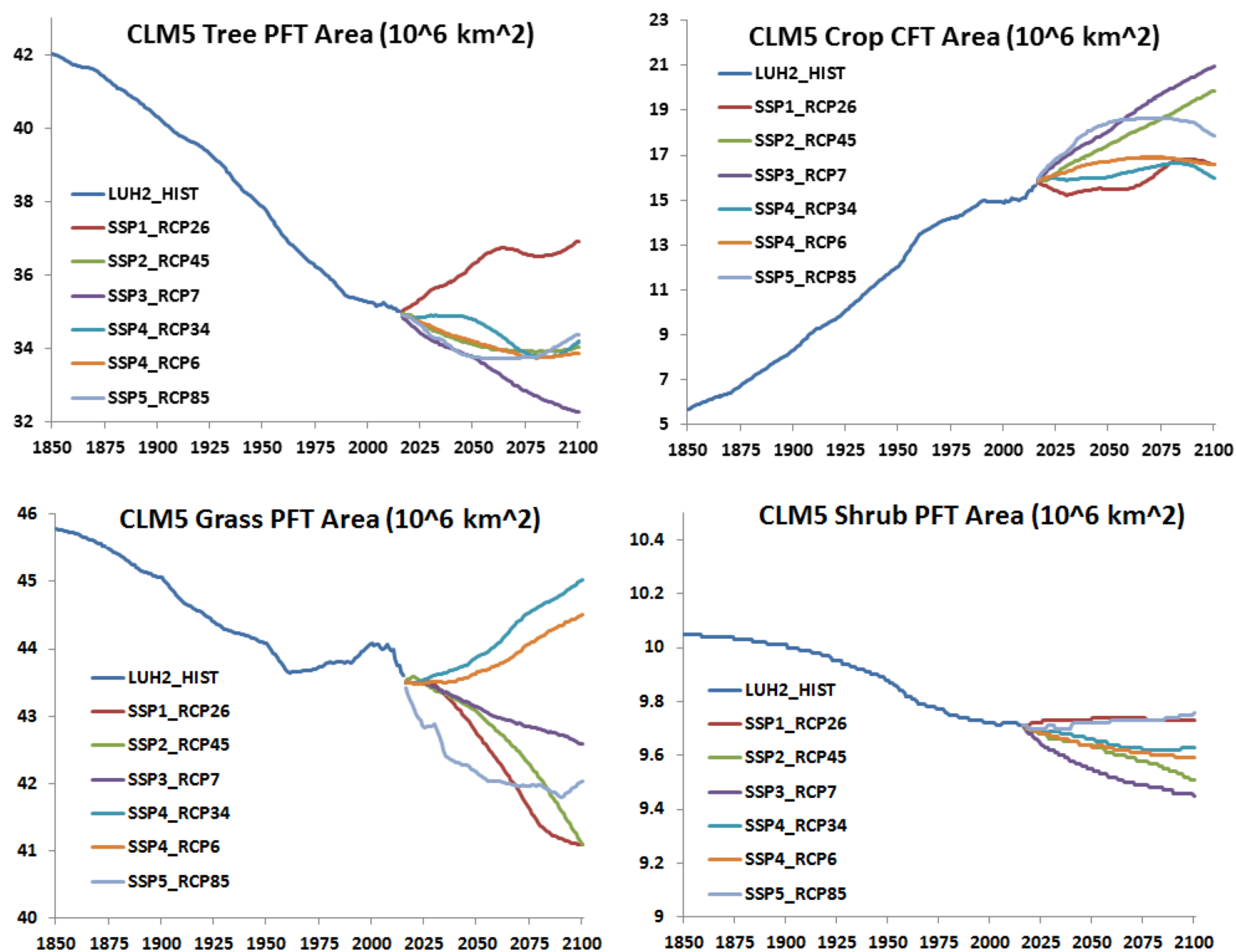
CLM5 LUMIP LULCC vs no LULCC – Cumulative



CLM5 LUMIP LULCC vs no LULCC – Biogeophysics Change



CLM5 Transient SSP RCP Land Use in 2016 – 2100



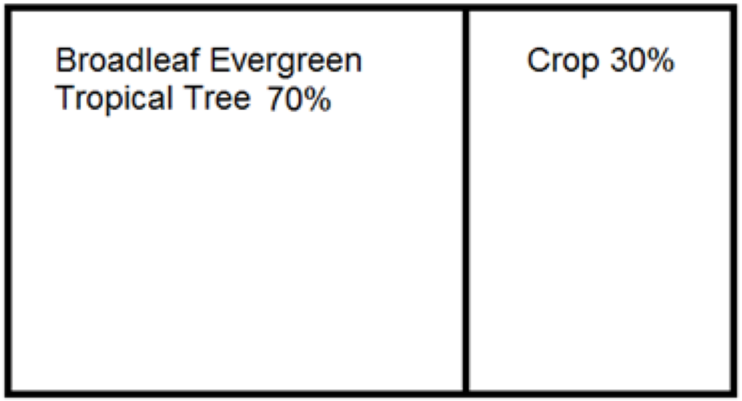
CMIP6 – CLM5 Carbon Cycle impacts of Shifting Cultivation

One element not included in the current CLM5 or CLM4 simulations is the impact of Shifting Cultivation.

In a Shifting Cultivation regime clearing of forest and abandonment of crop land can occur at the same rate so there can be no net change forest area or crop area from year to year. The state of the forest however is continually degraded.

CMIP6 Gross versus Net LULCC in CLM5 – Shifting Cultivation

Initial State Yr 1.

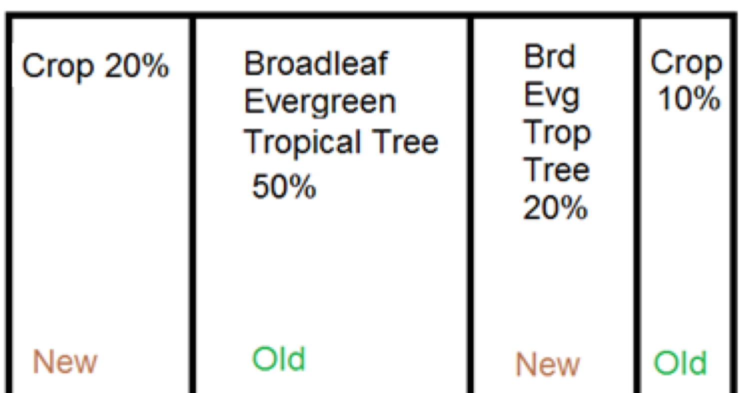


Gross Transitions
1. Broadleaf Evergreen Tropical Tree -> Crop 20%
2. Crop -> Broadleaf Evergreen Tropical Tree 20%

Net Transitions:
0% Change

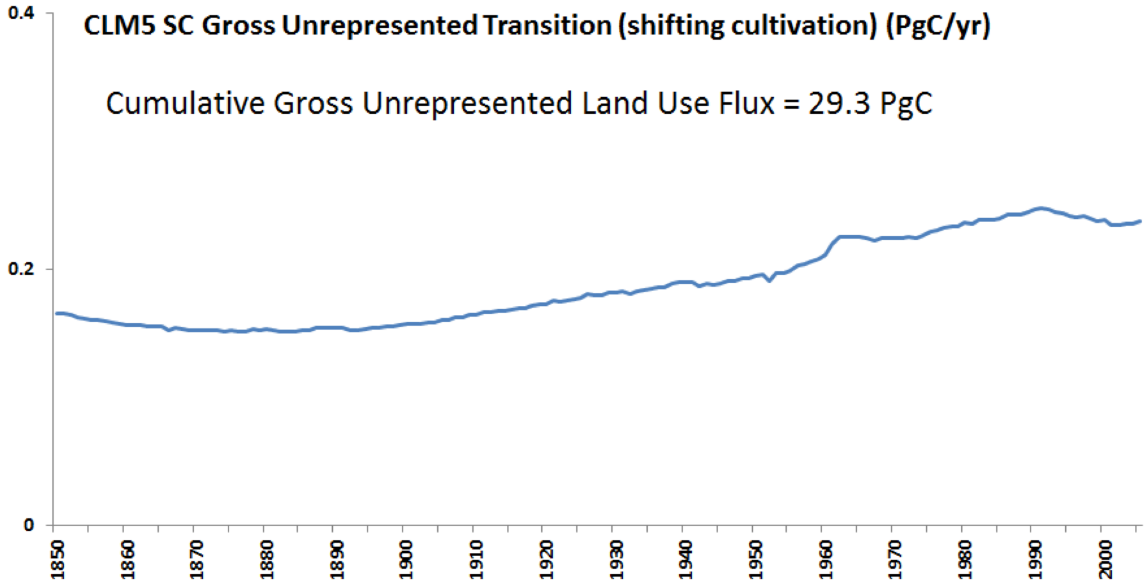
Unrepresented Gross Transitions:
BET 20% Crop 20%

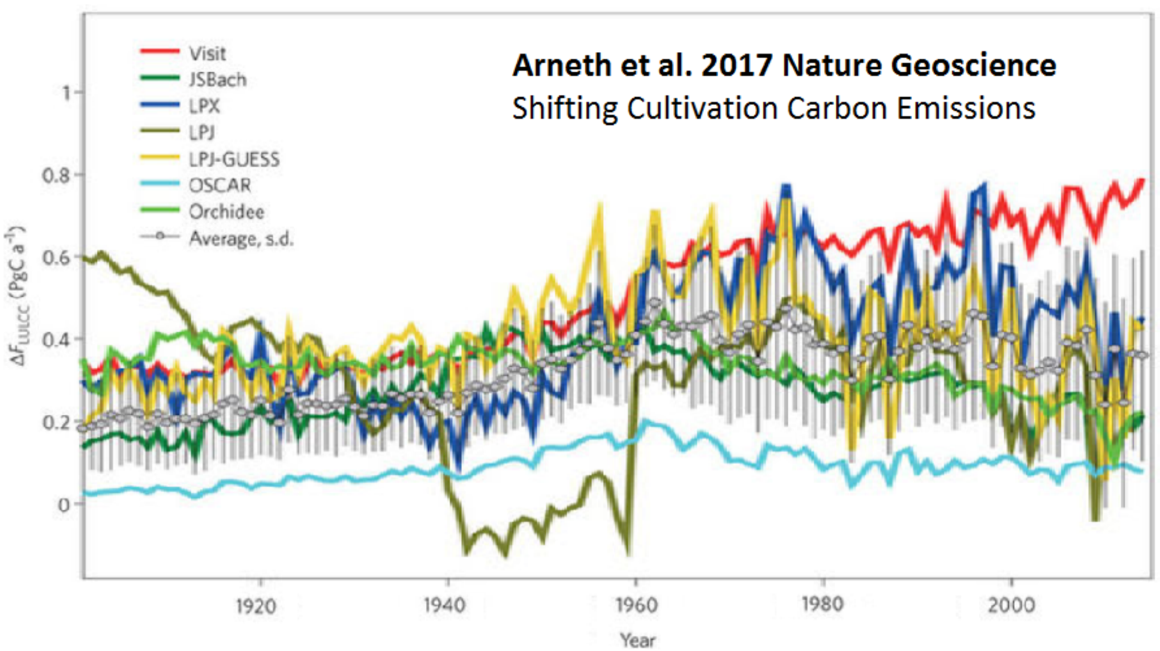
Updated State Yr 2.



Even though there are no Net Transitions we can still remove vegetation biomass for the Unrepresented Gross Transition area. Additional LULCC fluxes done in the same manner as wood harvest

CLM5 – Gross Unrepresented Land Use Carbon



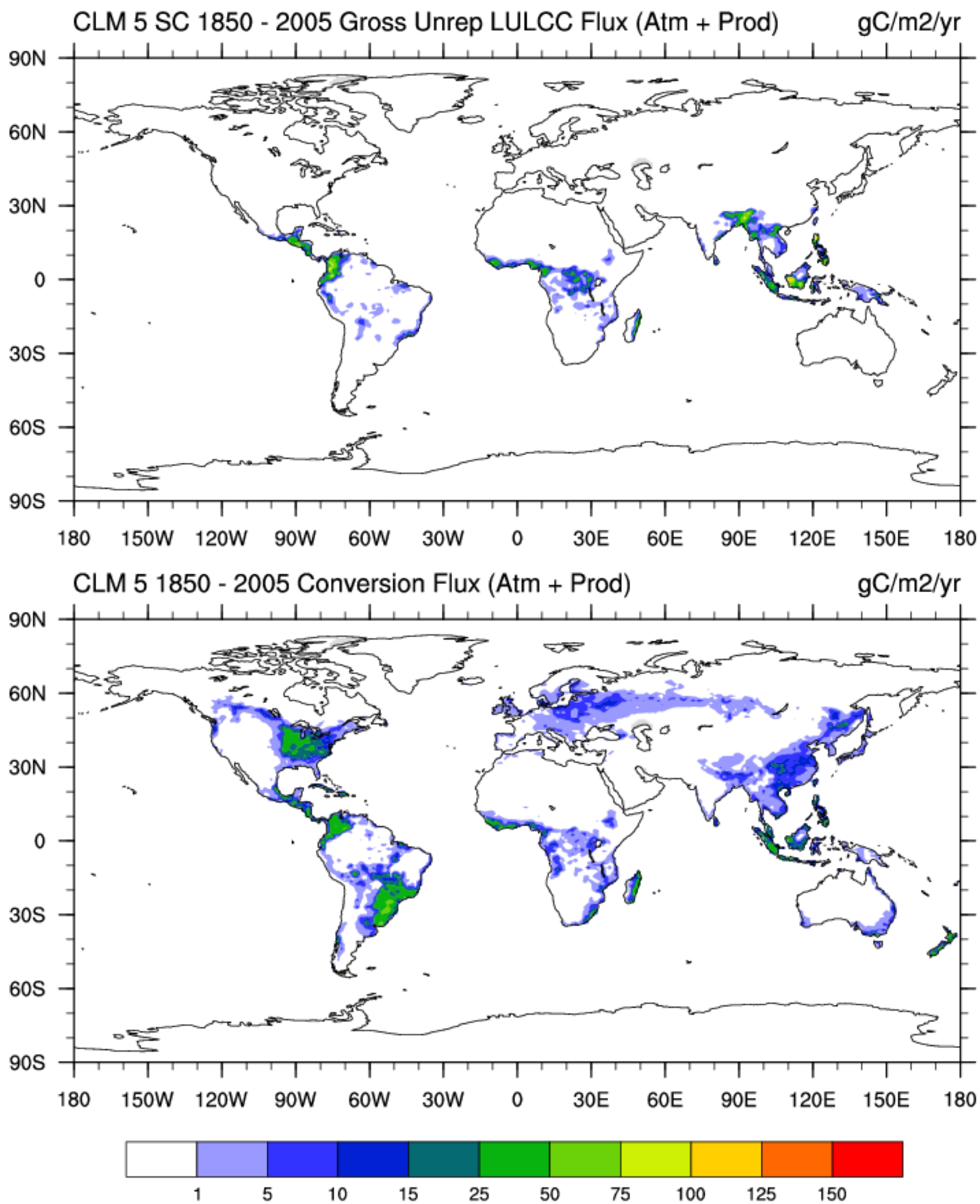


CLM5 SC Gross Unrepresented Land Use Flux results in a cumulative loss of 29.3 PgC

Compares to the CLM5 conversion flux cumulative loss of 60.4 PgC

Compares well with the model mean Shifting Cultivation flux of 0.2 – 0.3 PgC/yr found in the study by Arneth et al 2017.

CLM5 – Gross Unrepresented Land Use Carbon



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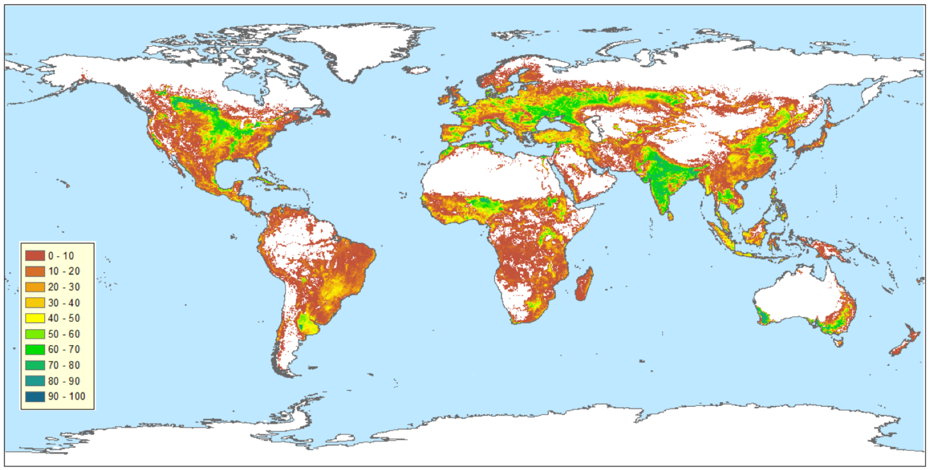
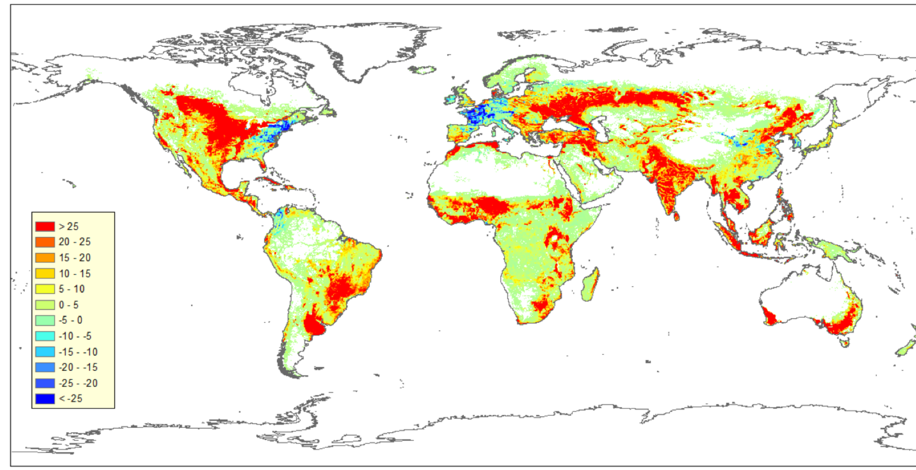
Thanks please get involved in our LULCC research. Questions?

CLM5 Percent Crop 2005



CLM5 Percent Crop Difference 2005 - 1850



CLM5 Percent Crop 1850