NCAR Earth System Laboratory NESL

Community Land Model and Land Use

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(With thanks to TSS and IAM groups for their many contributions)

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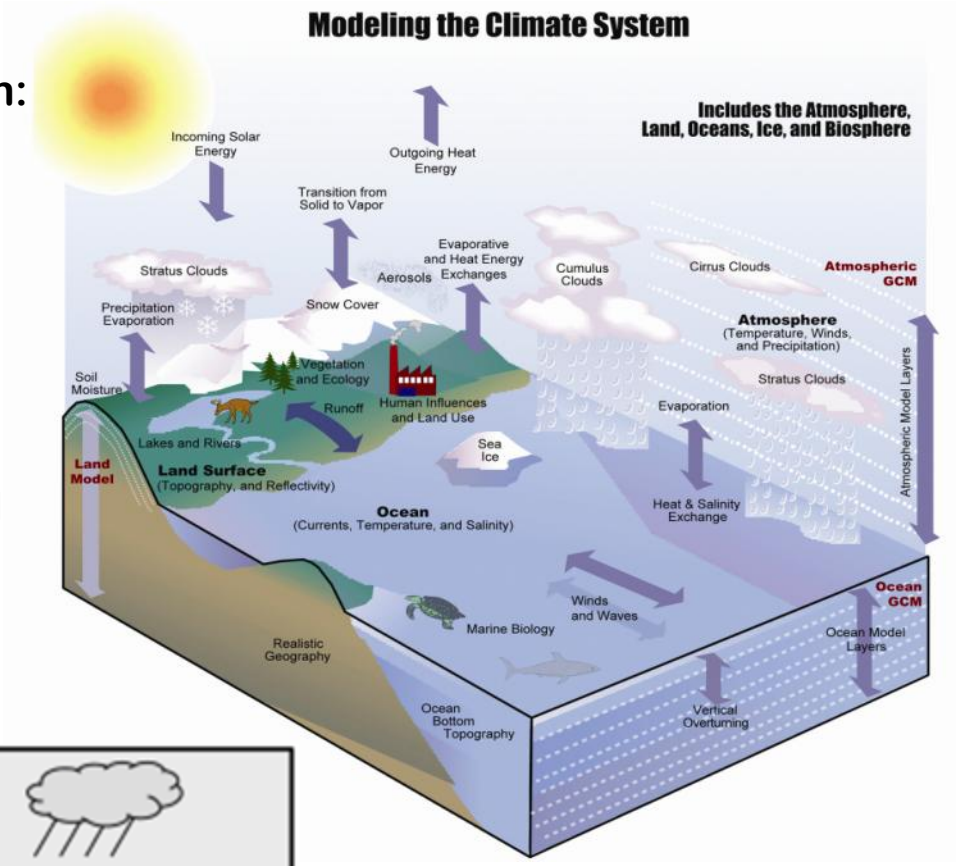
Understanding the Land Surface in the Climate System: Investigations with an Earth System Model (NCAR CESM)

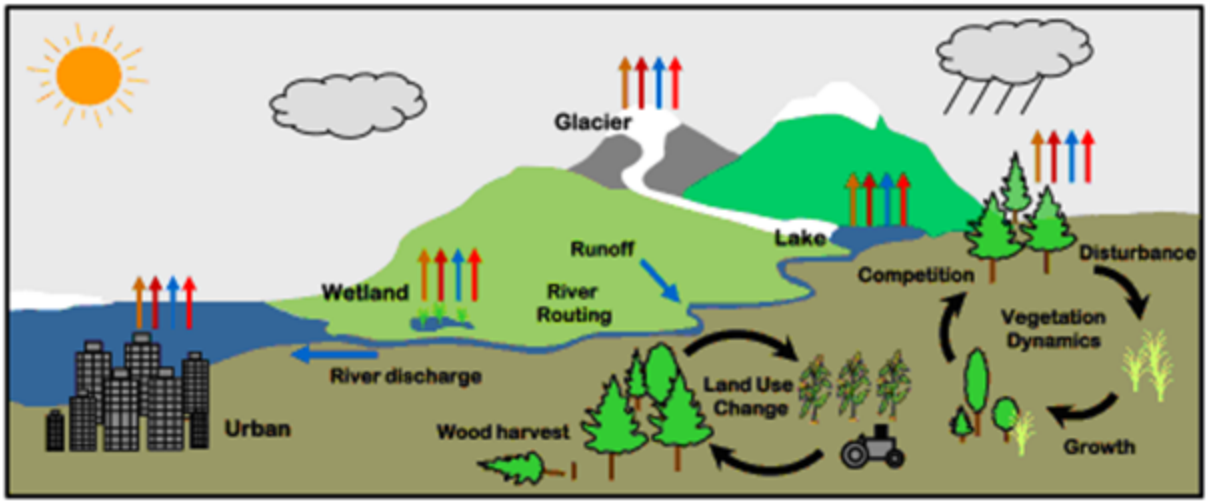
The land is a critical interface through which:

1. Climate and climate change impacts humans and ecosystems

and

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





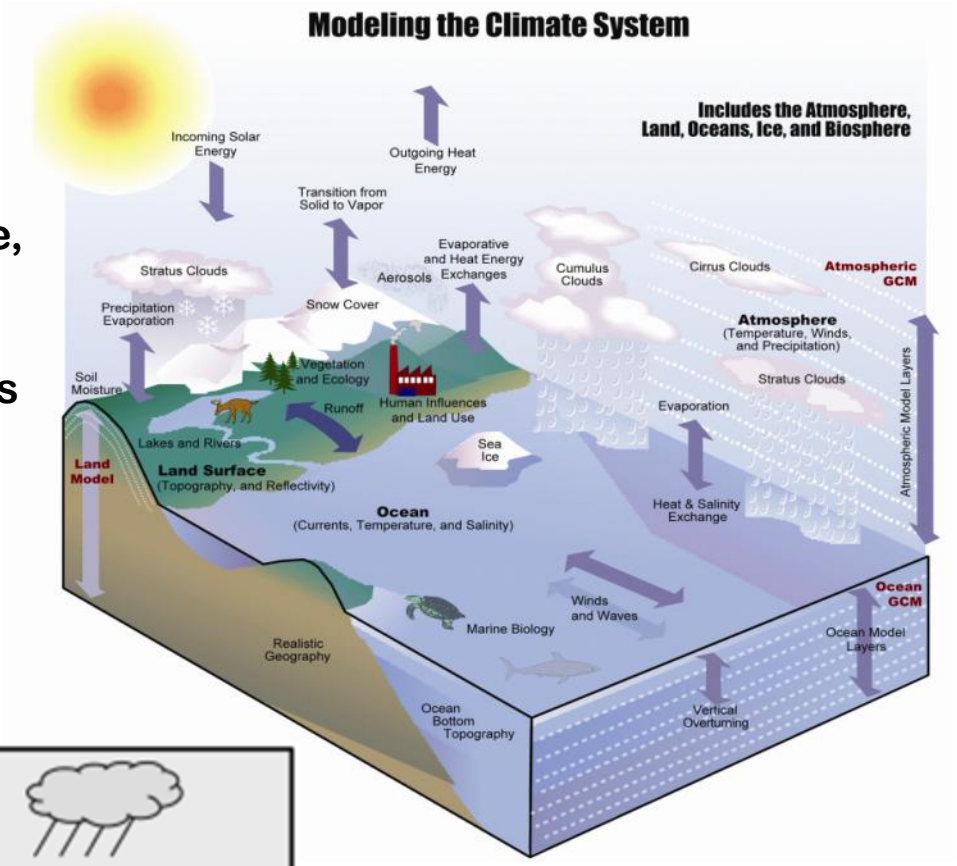
Understanding the Land Surface in the Climate System: Investigations with an Earth System Model (NCAR CESM)

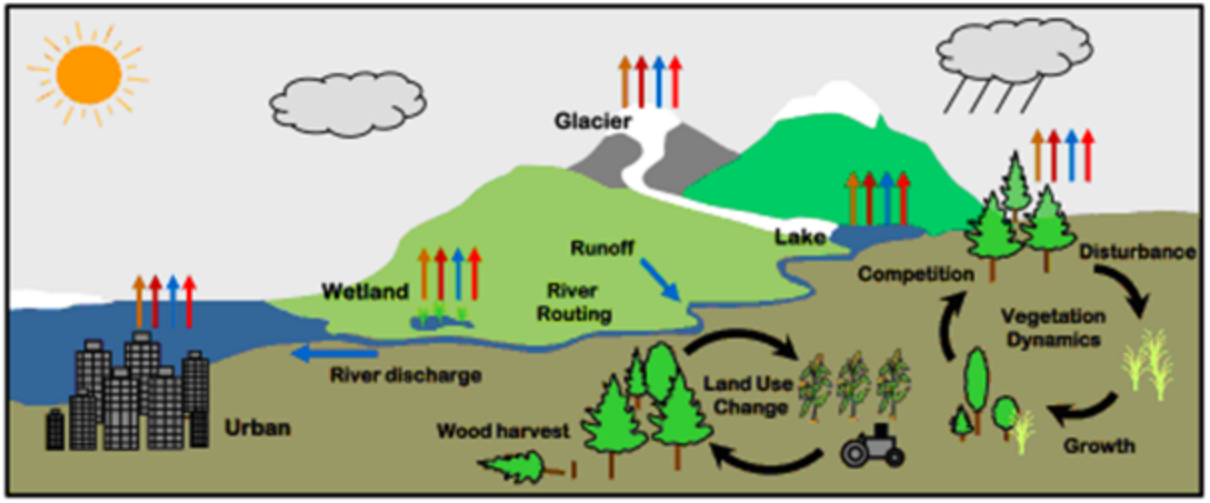
Land Management in CESM:

- **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

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

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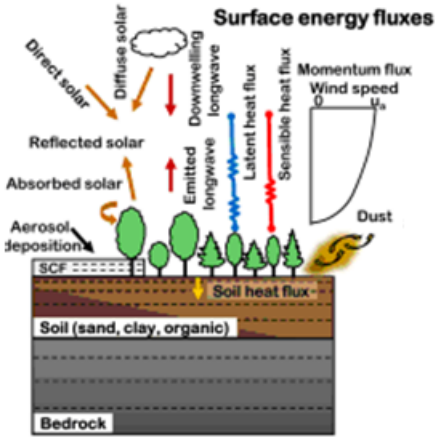
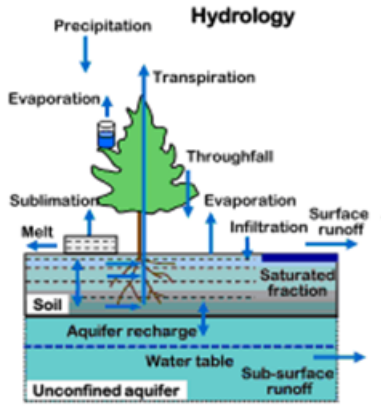
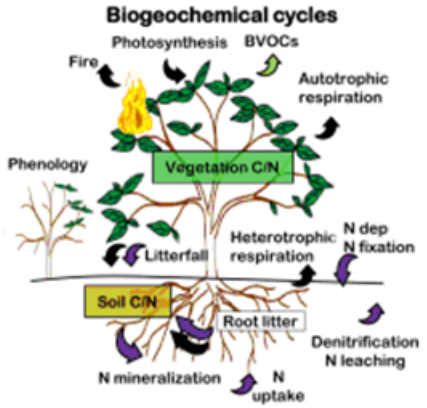
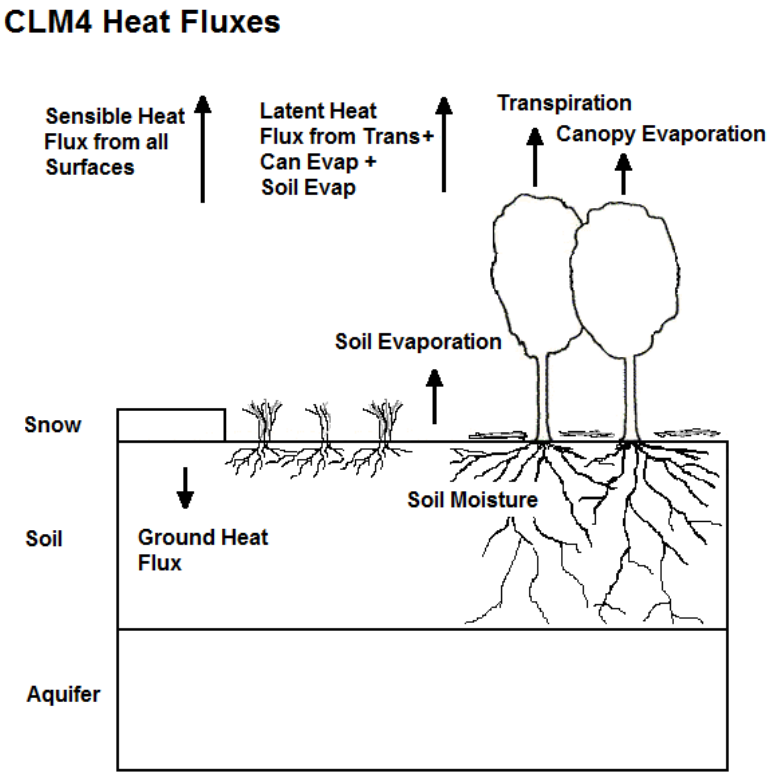
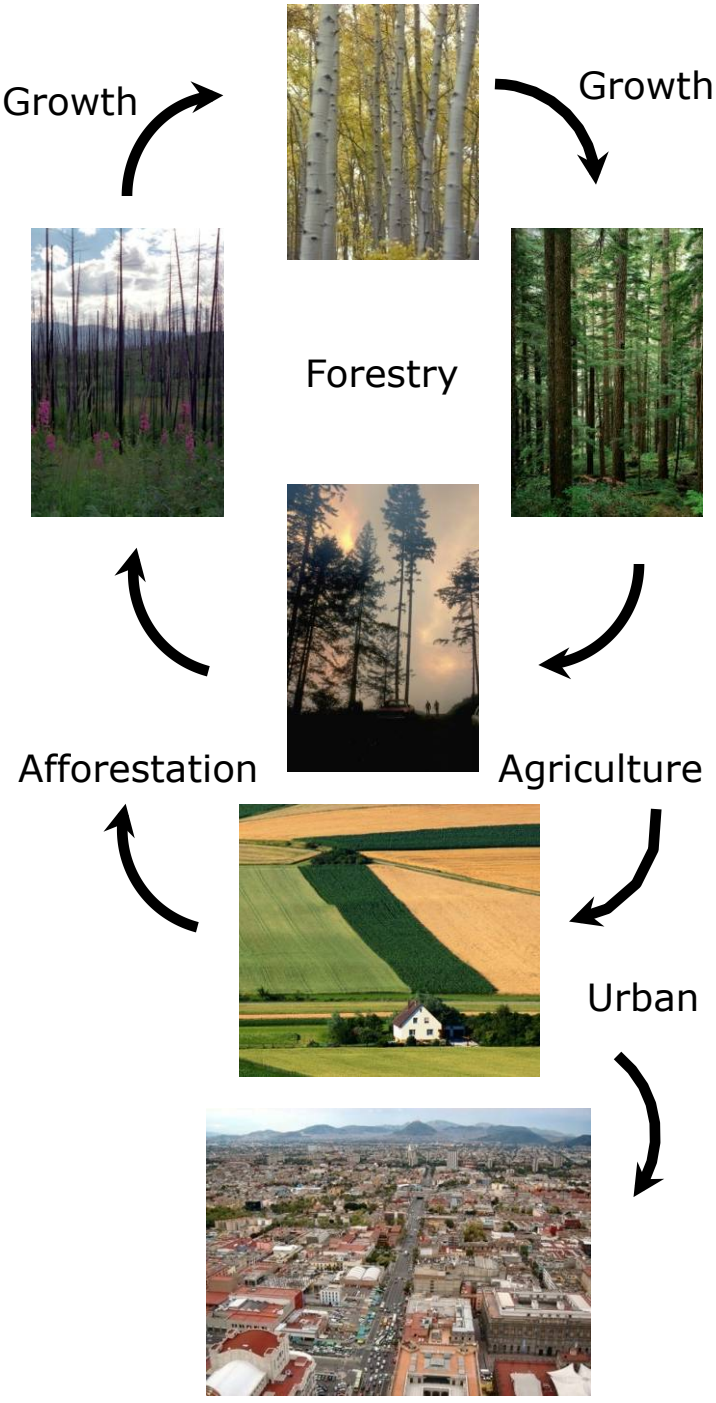






Land Cover Change Biogeophysics





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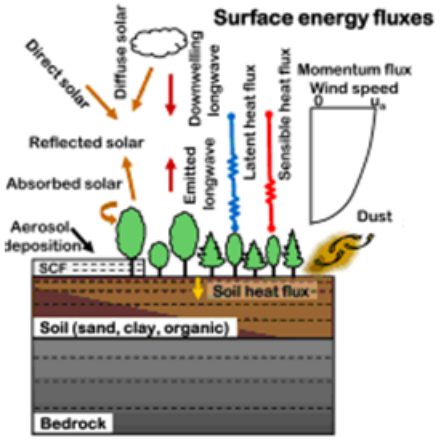

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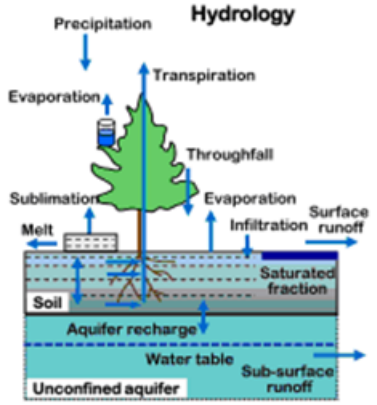

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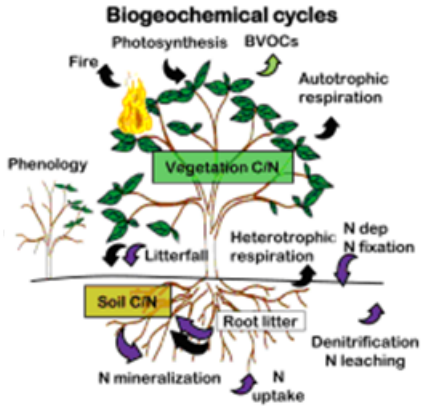

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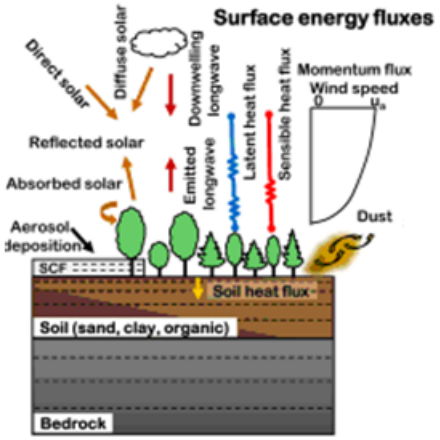
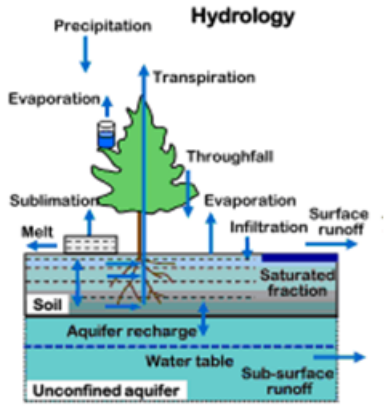
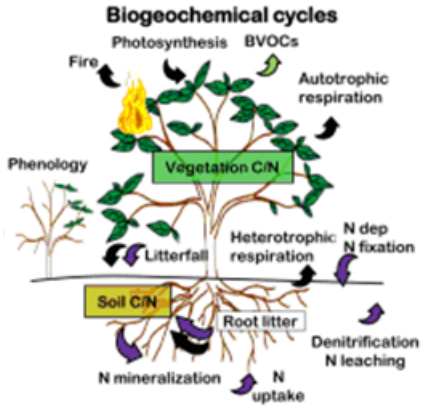
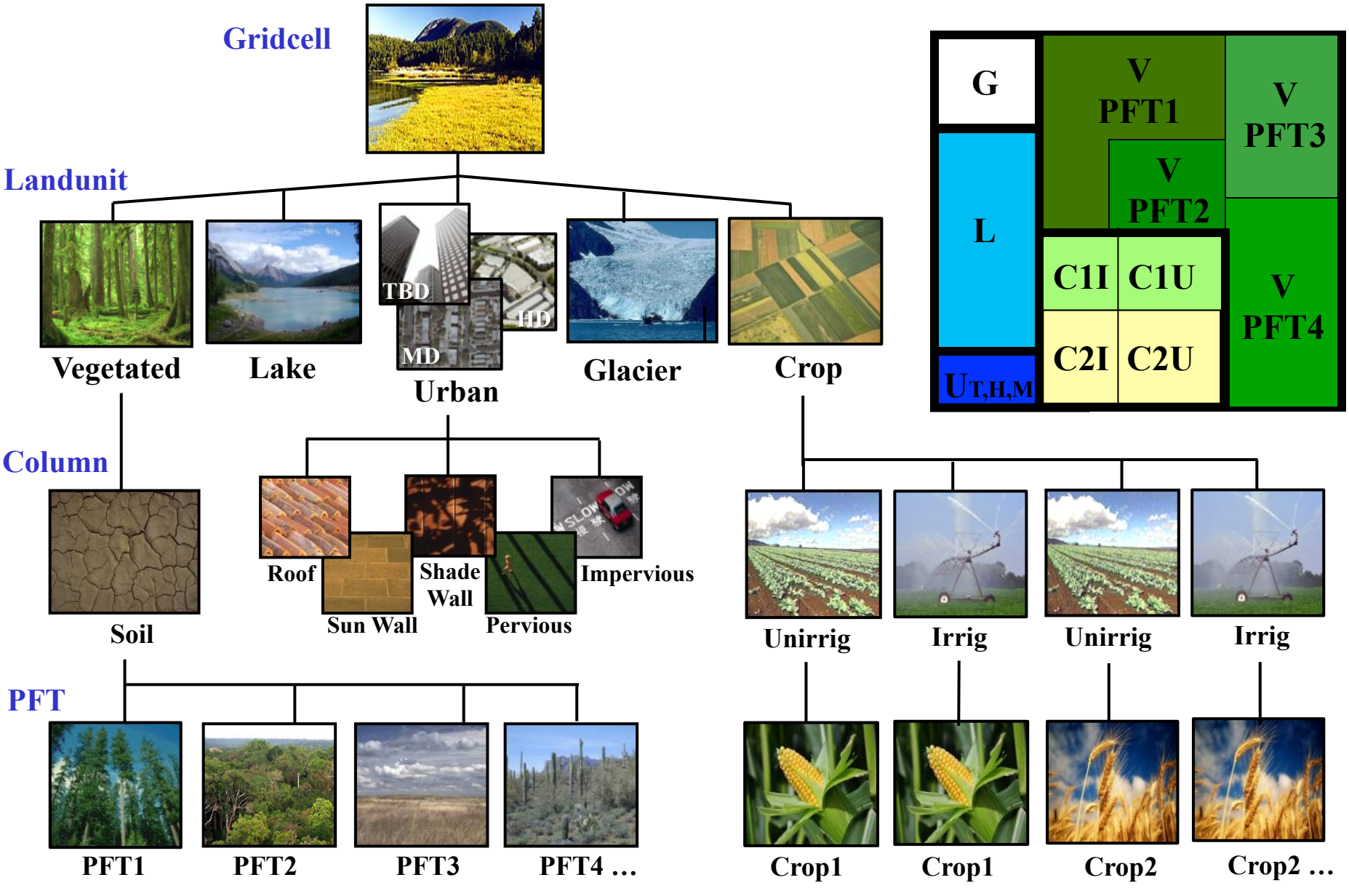






Community Land Model (CLM 4.5) subgrid tiling structure



CLM 4.5 LULCC for Natural PFT and Crop

Gridcell

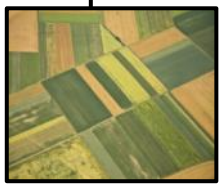
Landunit

Vegetated

Lake

Urban

Glacier



Crop

Unirrig

Irrig

Unirrig

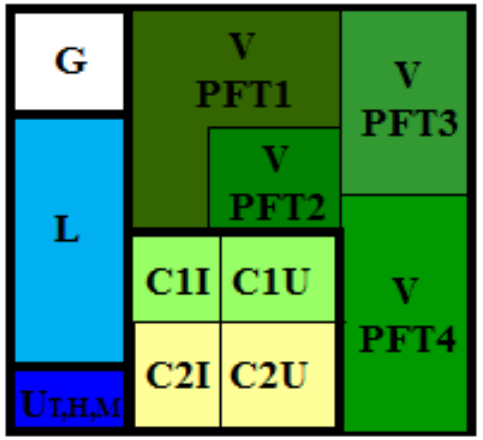
Irrig

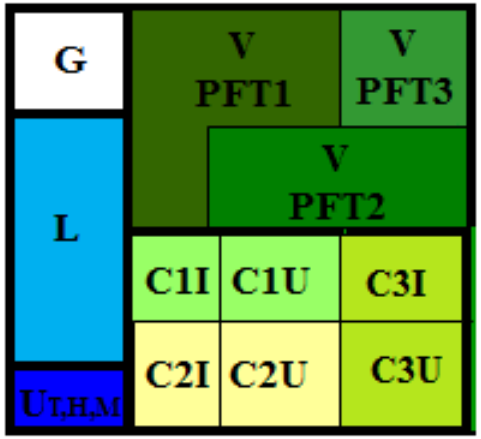
Crop1

Crop1

Crop2

Crop2 …





Ecosystem Modeling in the Coupled Model Intercomparison Project (CMIP5) – CESM modeling for IPCC AR5

1. All CMIP5 Earth system models evaluated the impacts on the global carbon cycle from changes in climate, atmospheric CO_2 and aerosols due to Fossil Fuel emissions and Land Cover Change

2. Model simulations were performed for:
   - 1850 – 2005 for the Historical period
   - 2006 – 2100 Representative Concentration Pathways (RCPs)

3. For each Historical and RCP period land use and land cover change are described through annual changes in four basic land units:

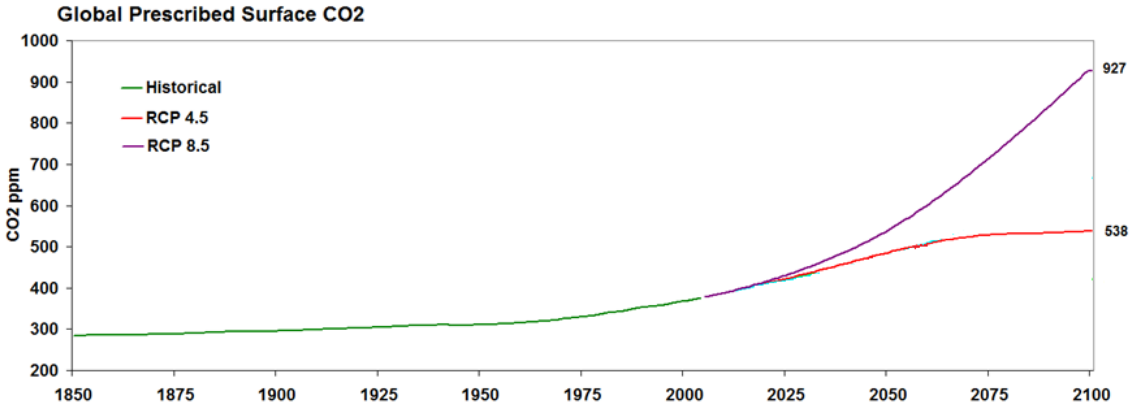
   - Primary Vegetation (Prior to Human Disturbance)
   - Secondary Vegetation (Disturbed then abandoned or managed)
   - Cropping
   - Pasture (Grazing Lands)

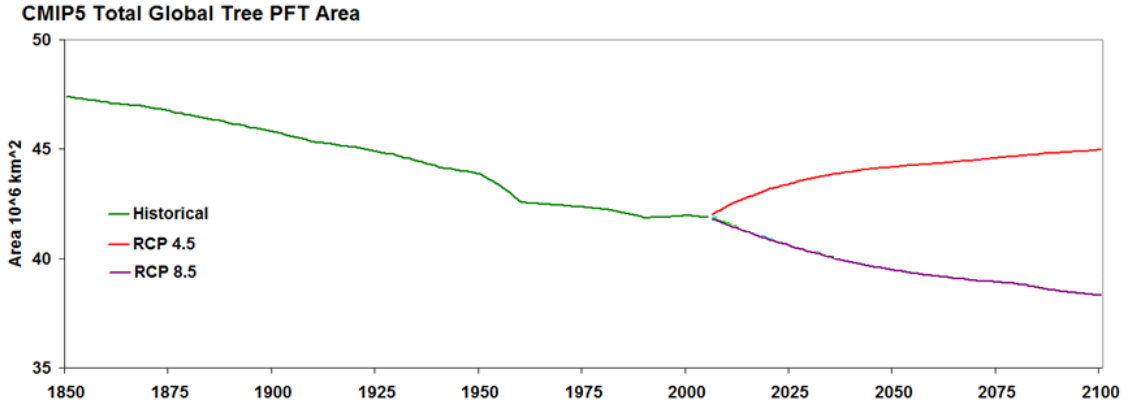
4. Harvesting of biomass is also prescribed for both primary and secondary vegetation land units

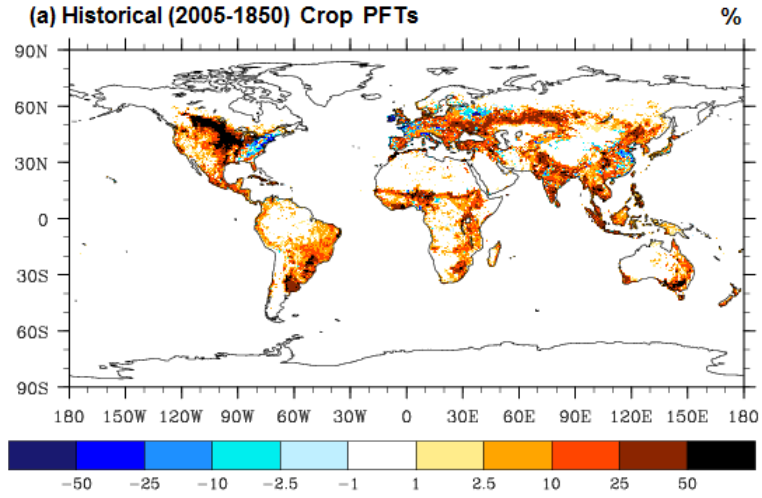
Ecosystems in CMIP5 Historical and RCP CO_2 and LULCC

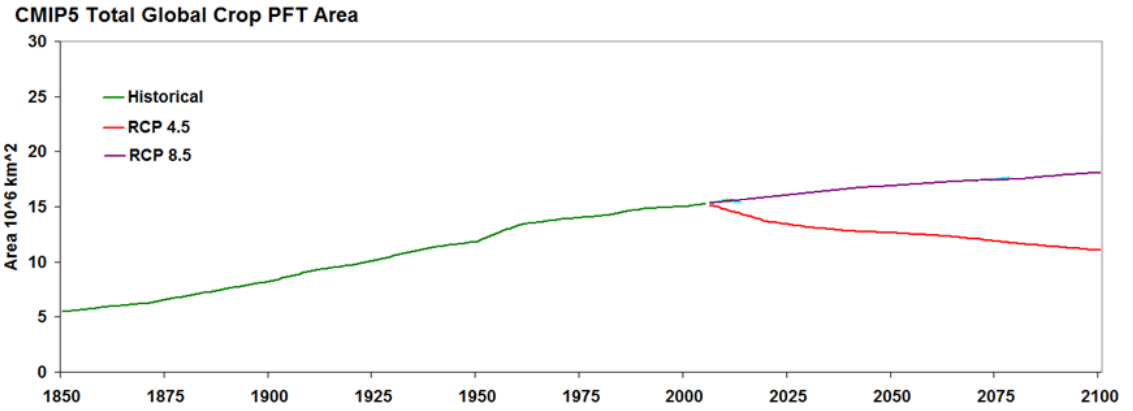
1. Changes in Atmospheric CO_2:
   - Historical (1850 – 2005): 285 – 379ppm +94 ppm
   - RCP 4.5 (2006 – 2100): 380 – 538ppm +158 ppm
   - RCP 8.5 (2006 – 2100): 380 – 936ppm +556 ppm

2. Land Use and Land Cover Change:
   - Hist: Crop +9.8 ; Tree -5.5 10^6 km^2
   - RCP 4.5: Crop -4.2 ; Tree +3.0 10^6 km^2
   - RCP 8.5: Crop +2.8 ; Tree -3.5 10^6 km^2





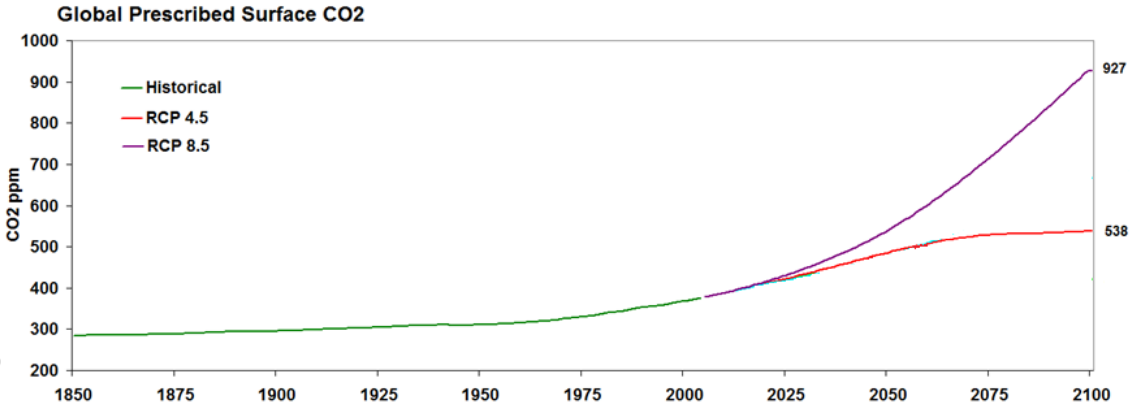


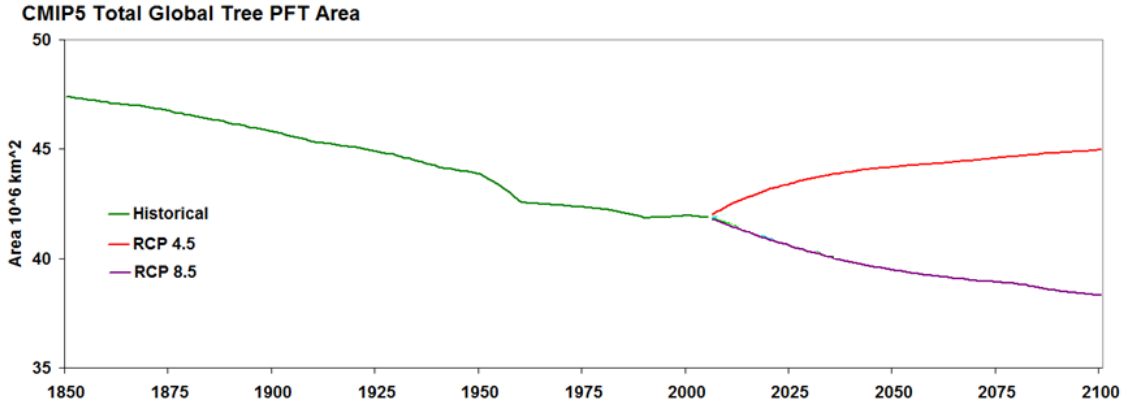


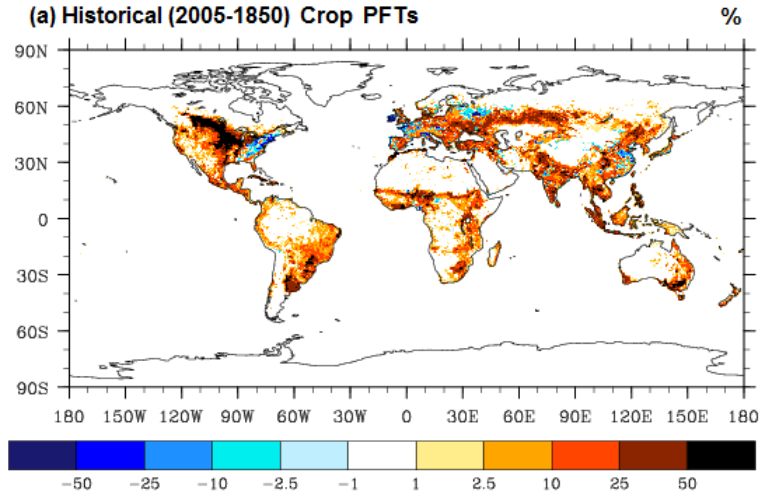
Ecosystems in CMIP5 Historical and RCP CO_2 and LULCC

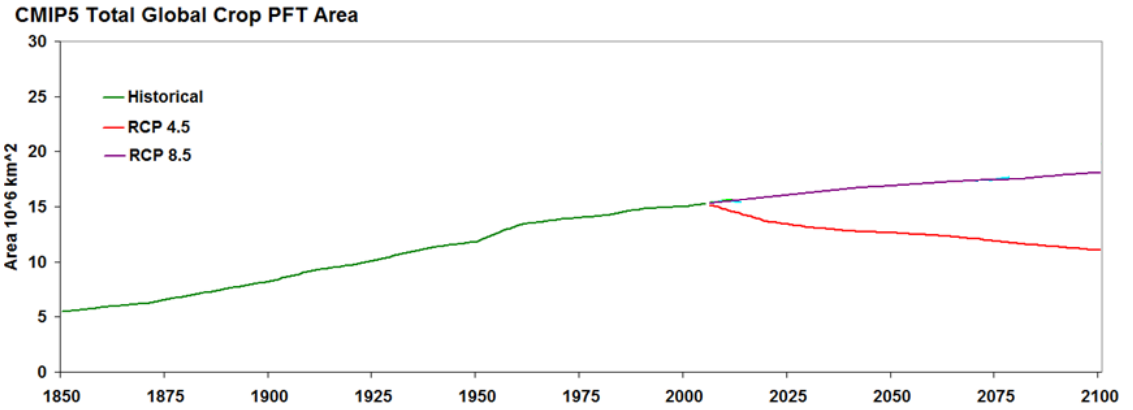
Land Use and Land Cover Change (LULCC) impact both the Biogeophysics and the Terrestrial Ecosystem Carbon Cycle in CLM.

Investigate these impacts by comparing CESM Historical and RCP simulations with LULCC against the same simulations with no LULCC







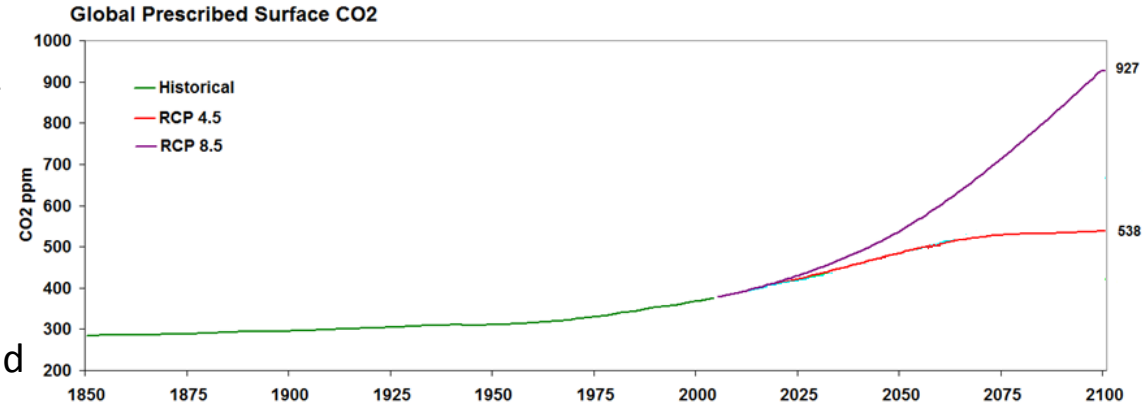


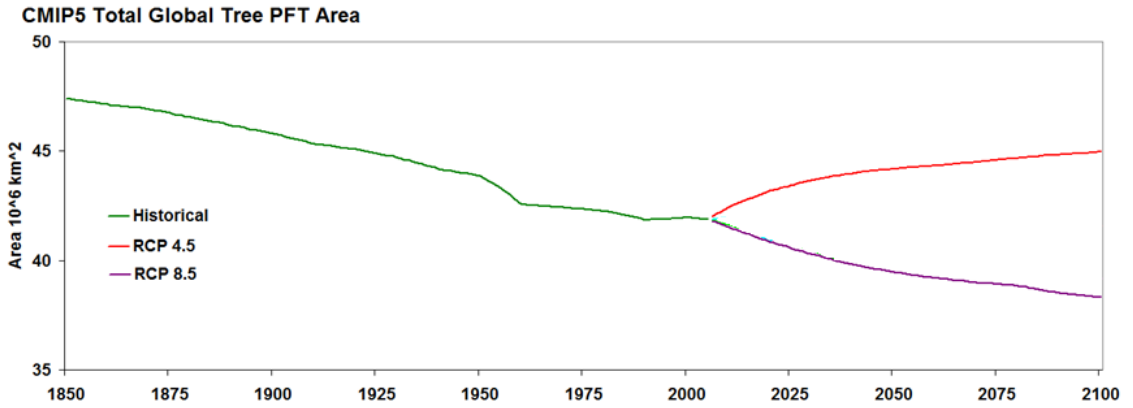
Ecosystems in CMIP5 Historical and RCP CO_2 and LULCC

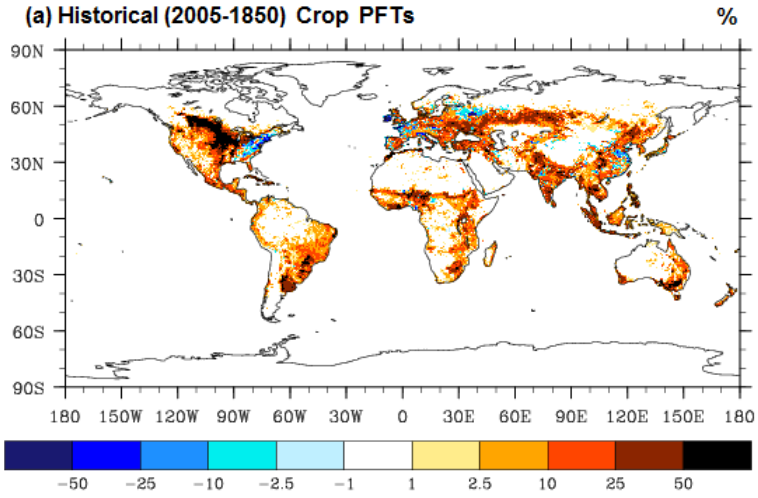
To provide statistical significance in our results we ran three ensemble members of both the LULCC and the no LULCC for each period.

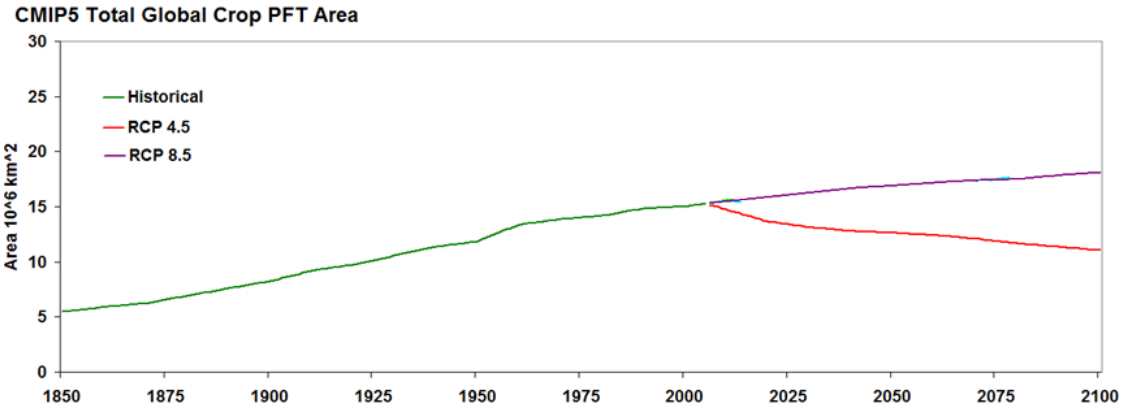
The ensembles of each simulation have the same transient forcings (CO_2 , aerosols, Land Use) but start with slightly different initial conditions.

In all simulation the atmosphere, ocean and sea ice were active with the atmospheric CO_2 concentration prescribed through time.

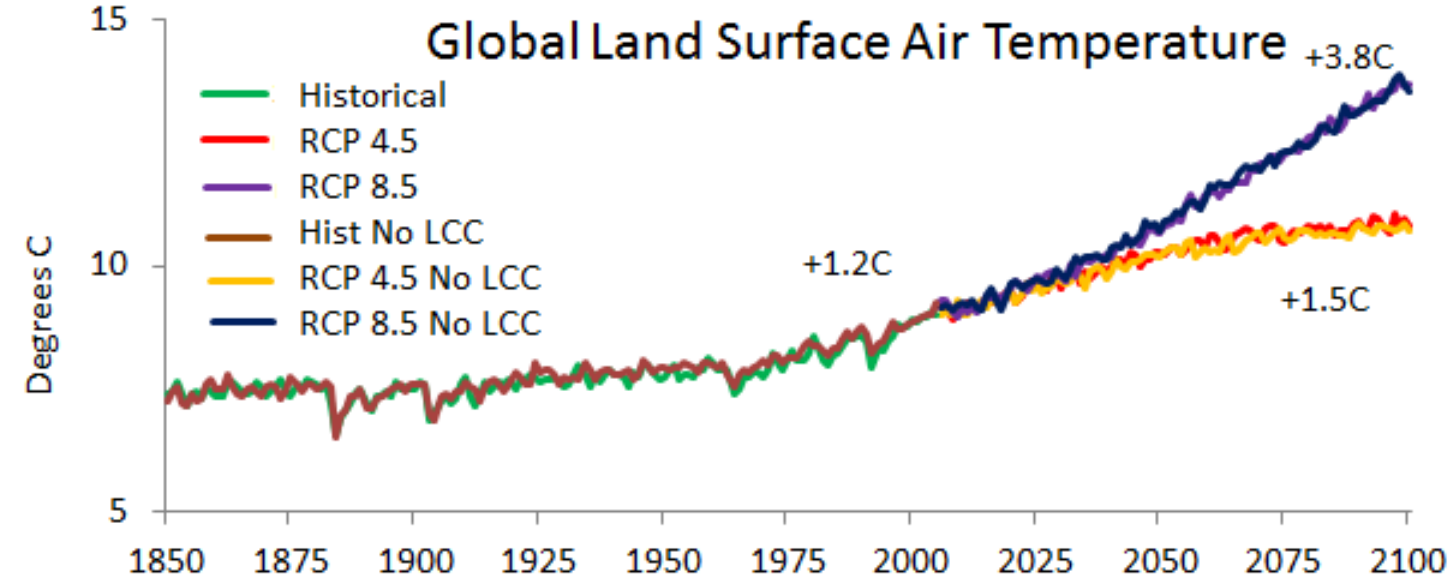


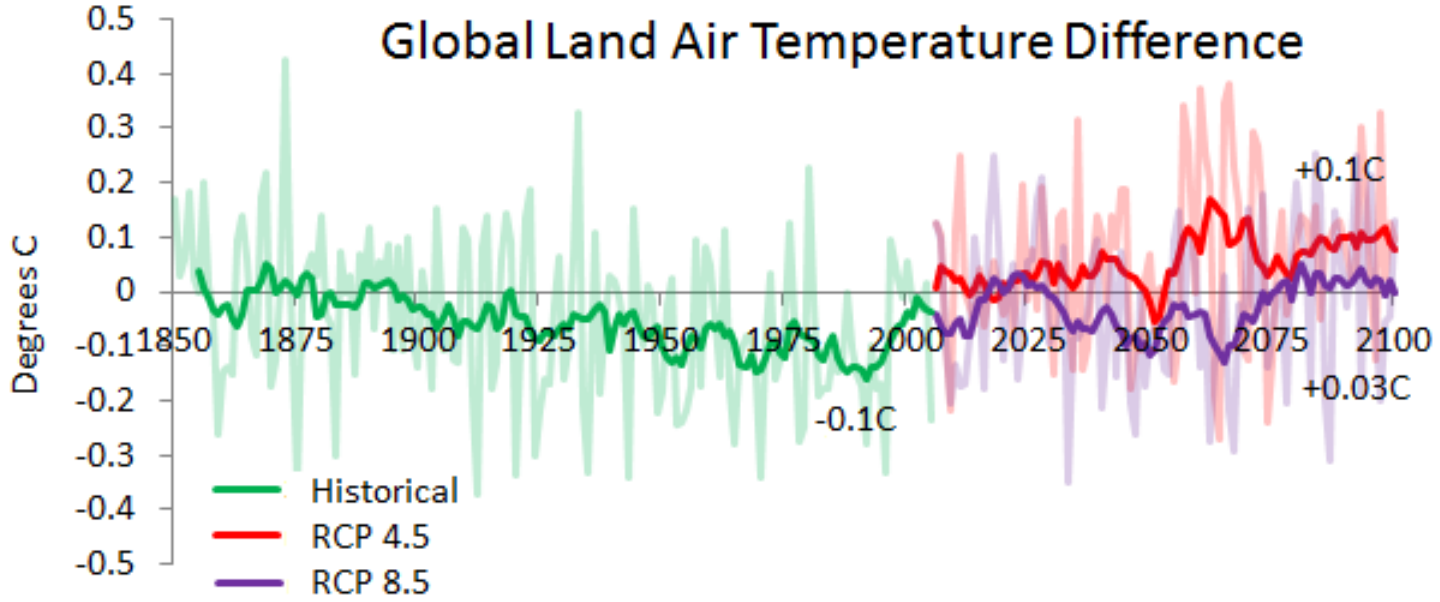






CMIP5 Land Cover Change – Land Air Temperature





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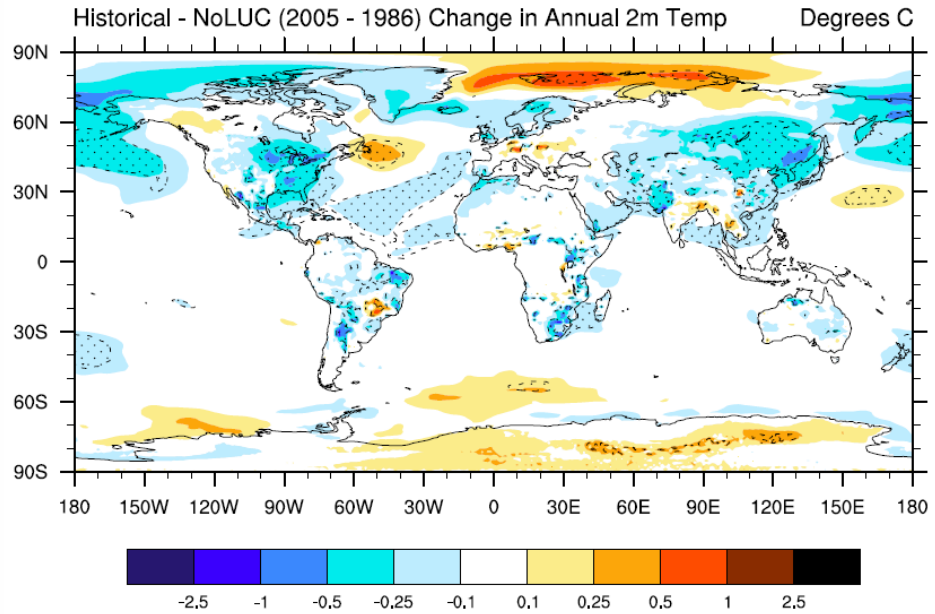
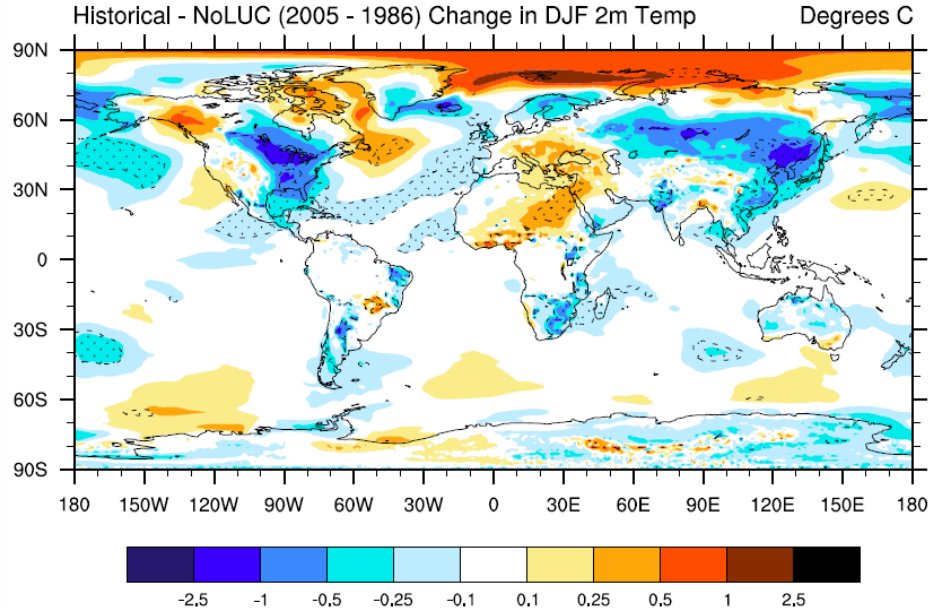
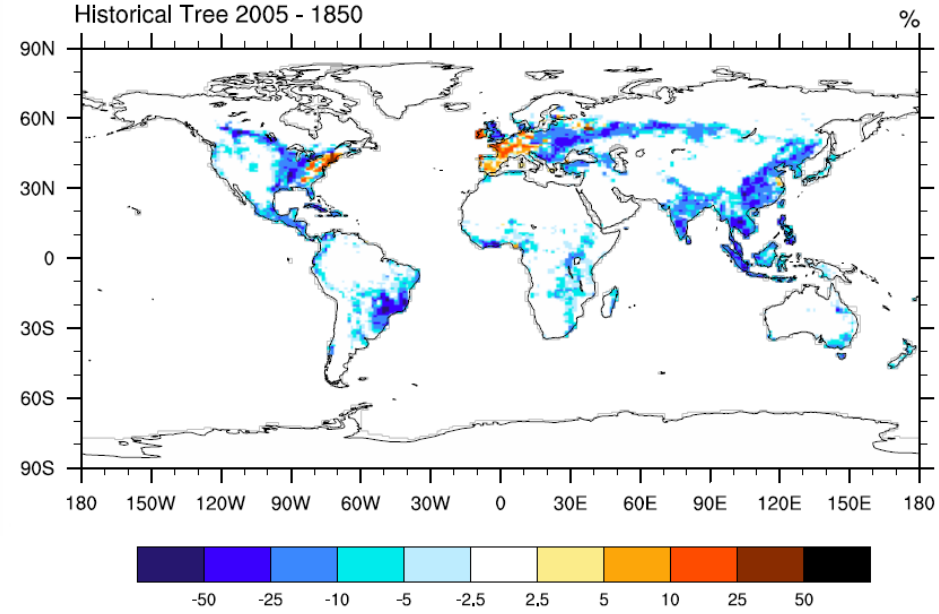
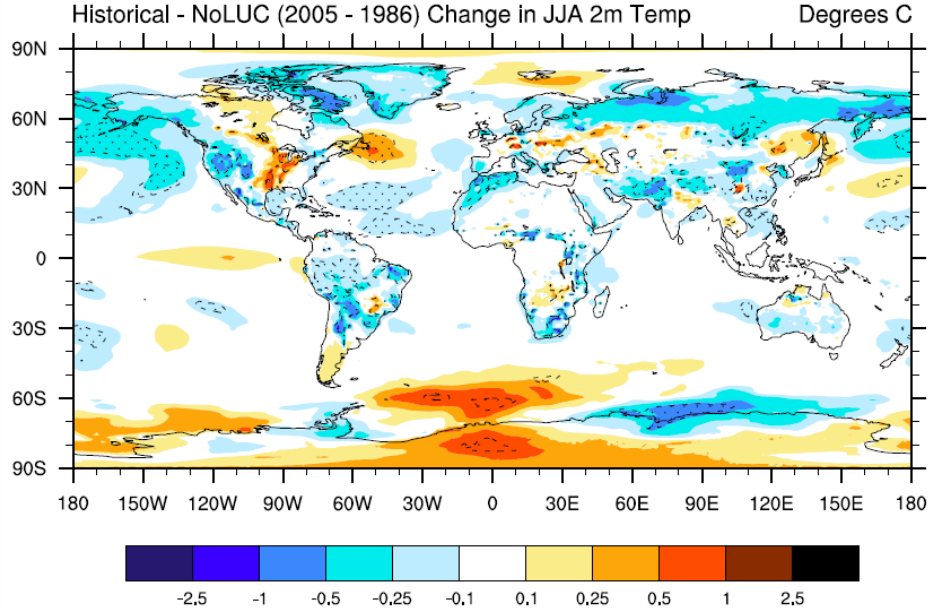
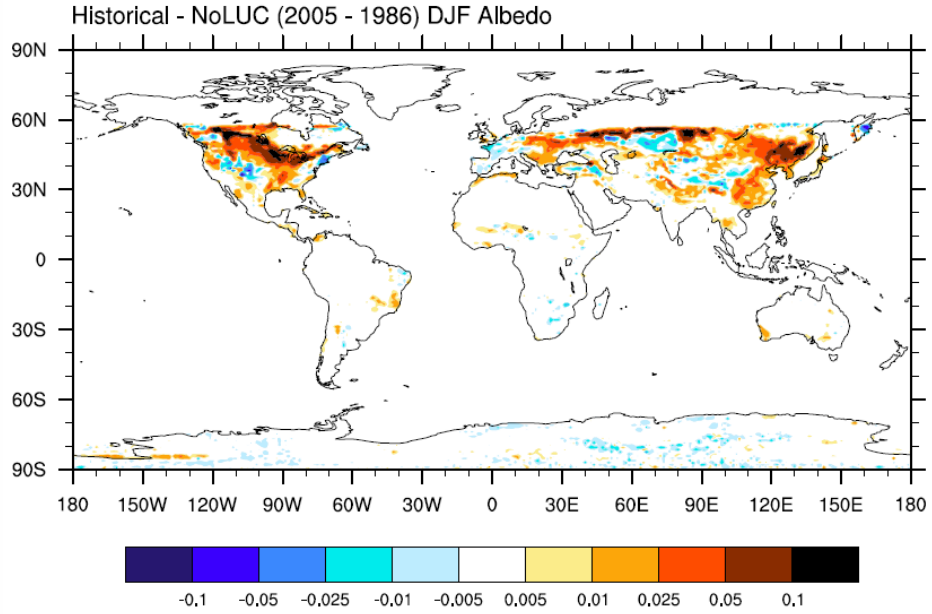


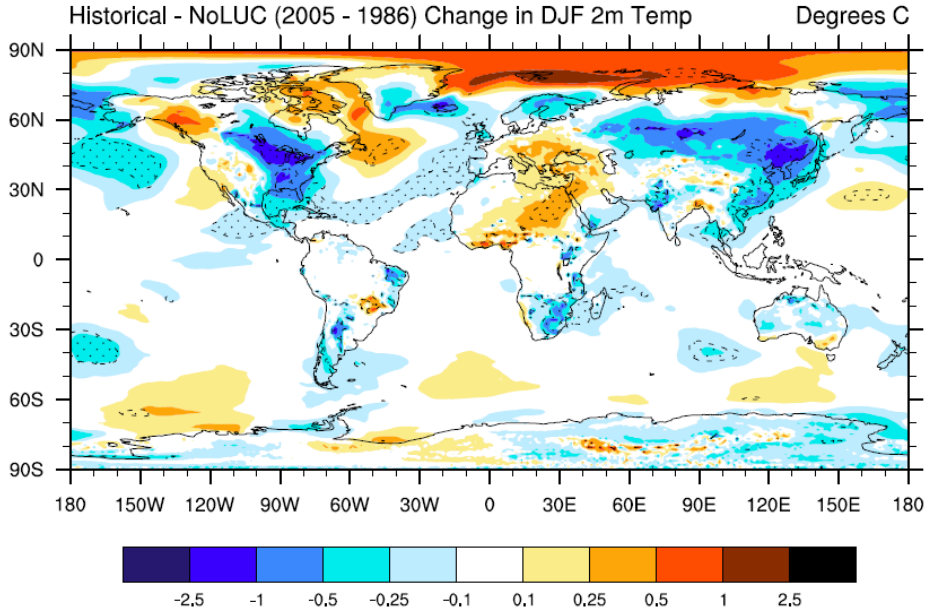


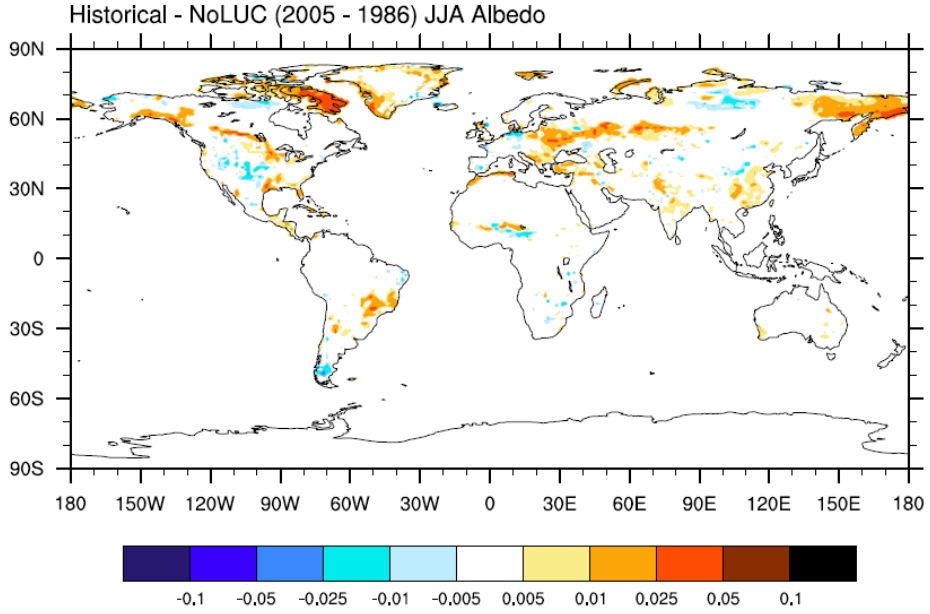


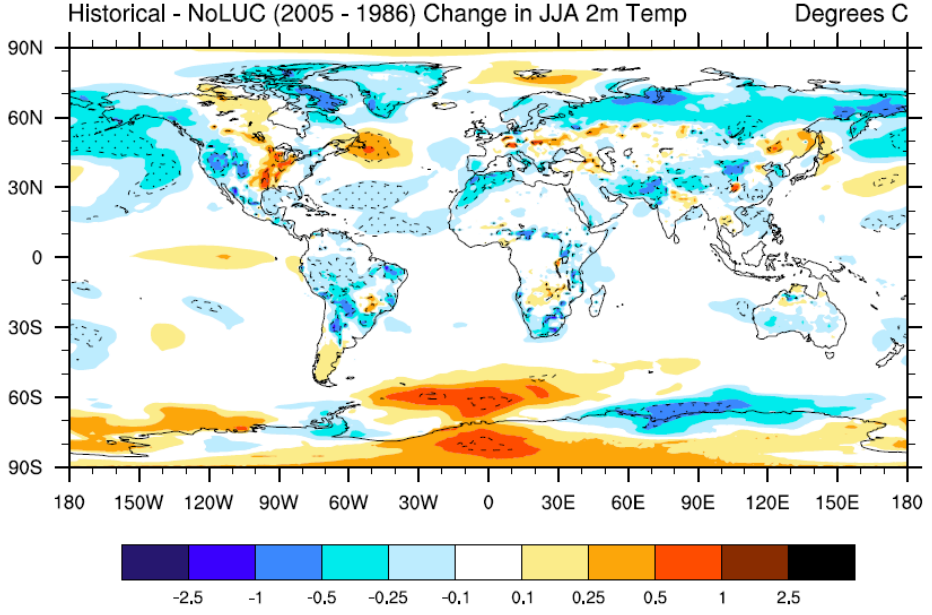


CMIP5 Land Cover Change – Albedo Land Air Temp

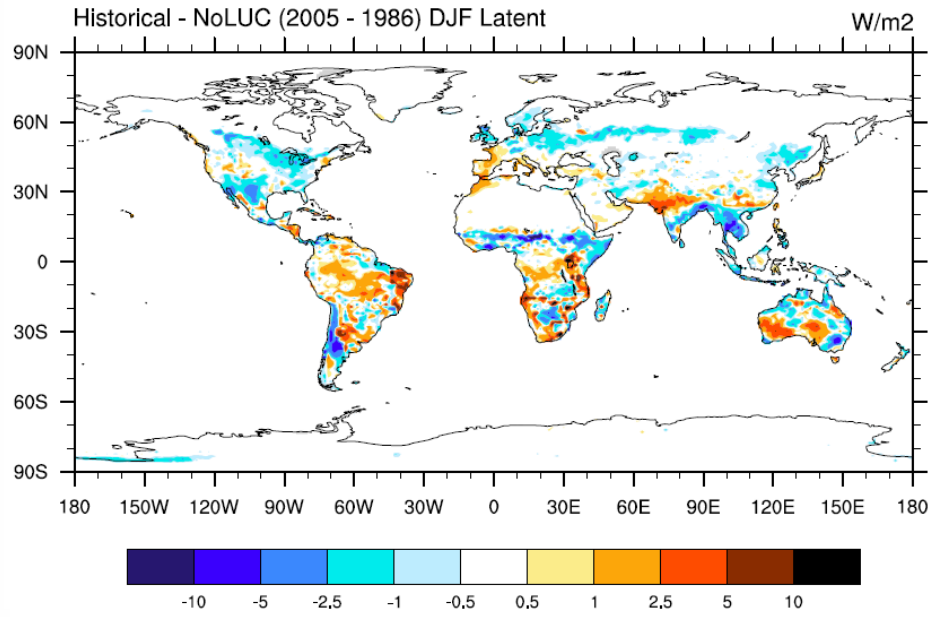


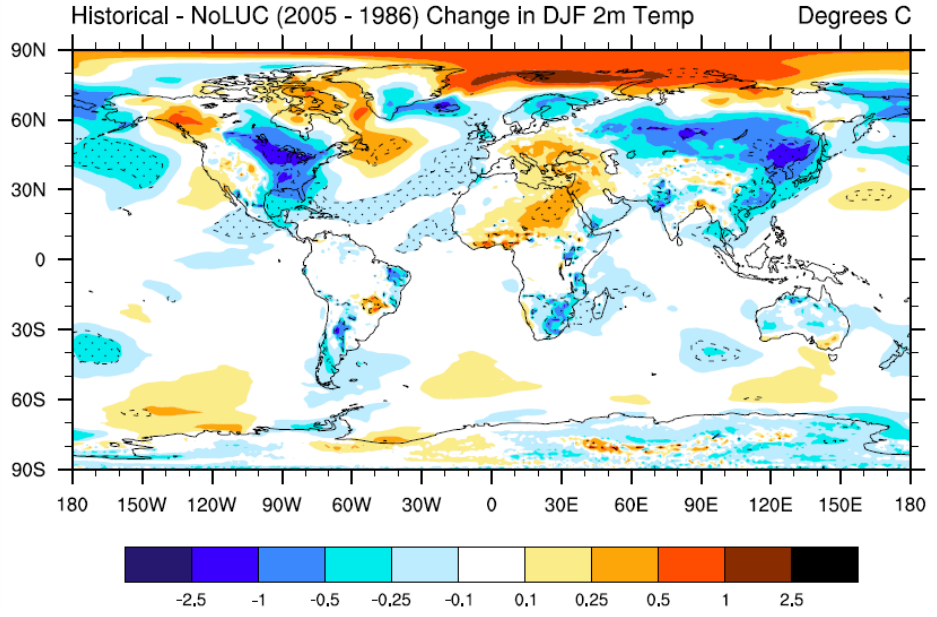


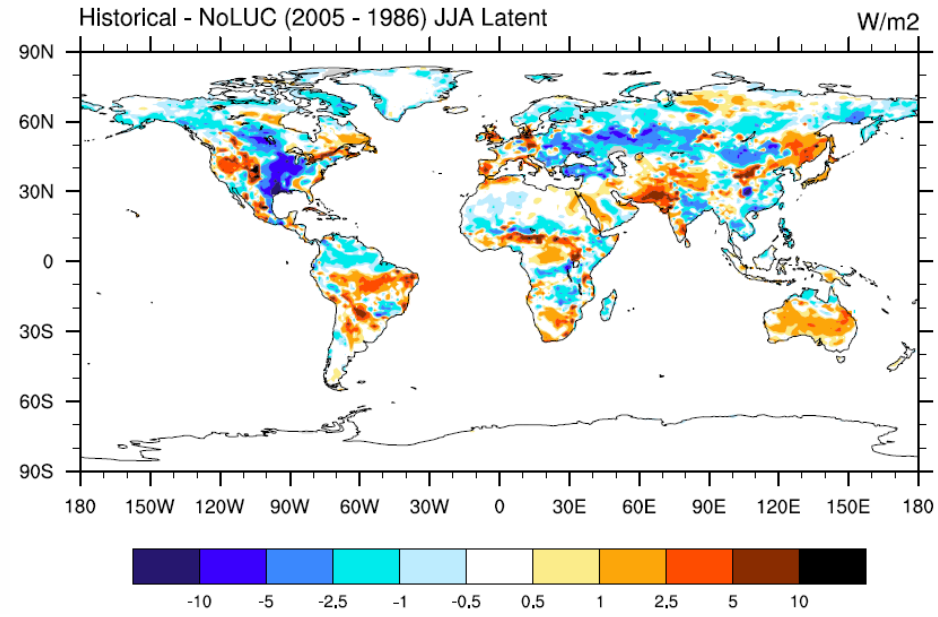


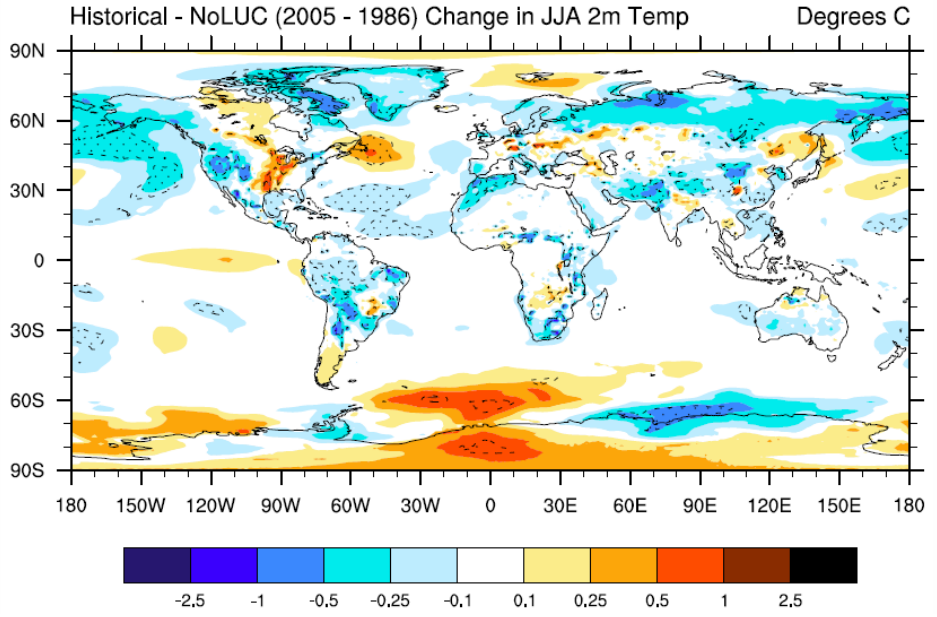


CMIP5 Land Cover Change – Latent Heat Flux Air Temp

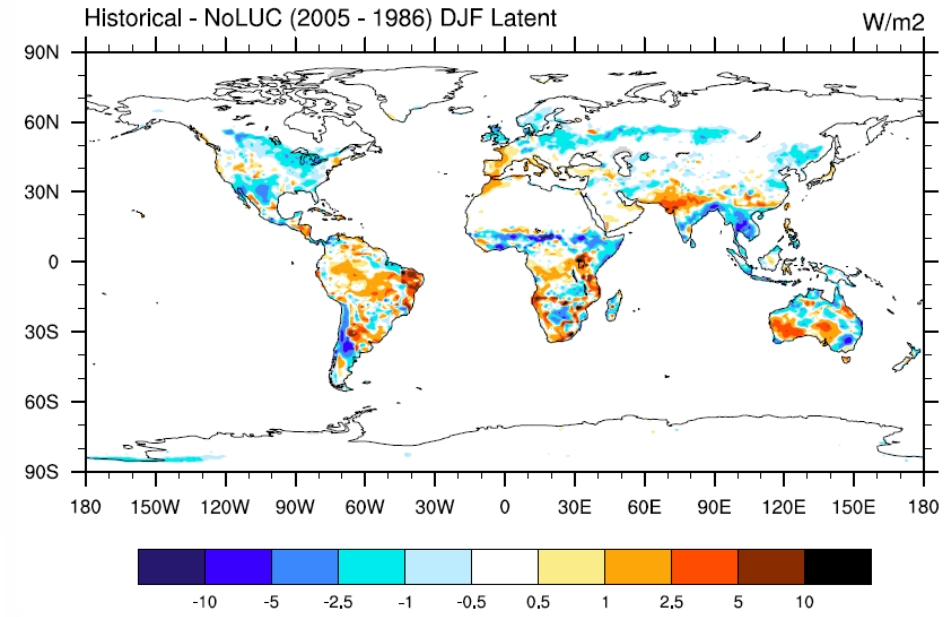


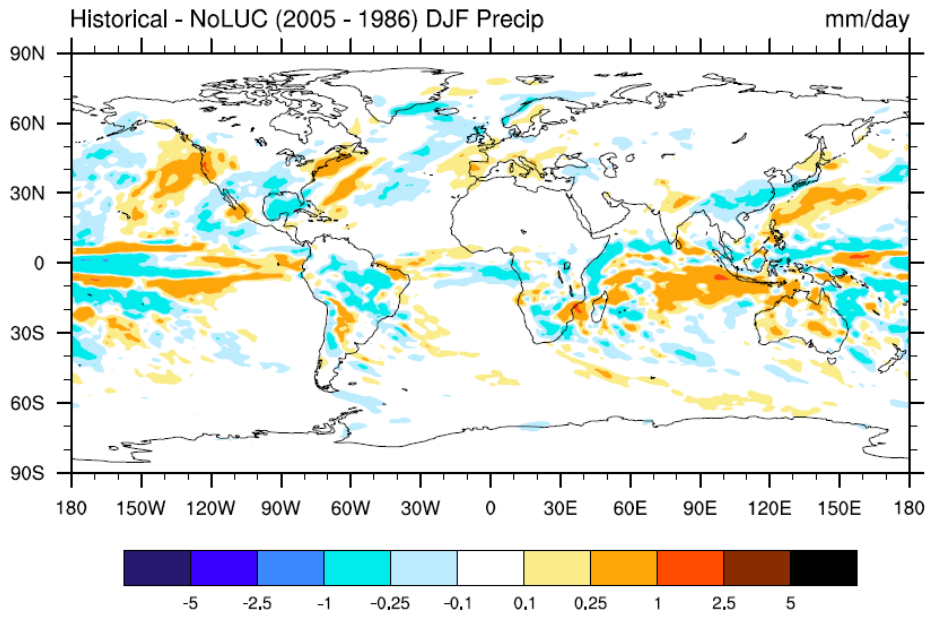


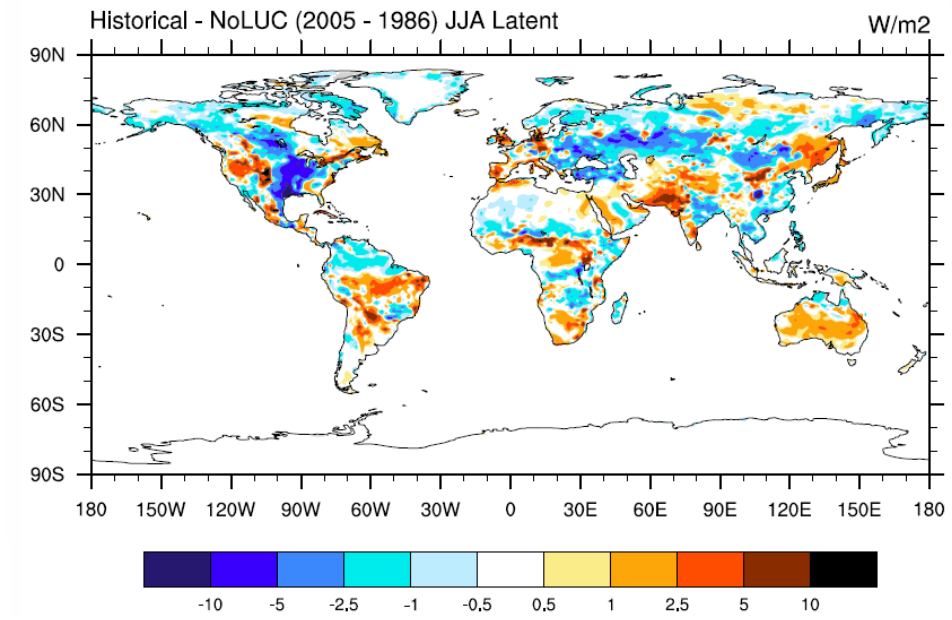


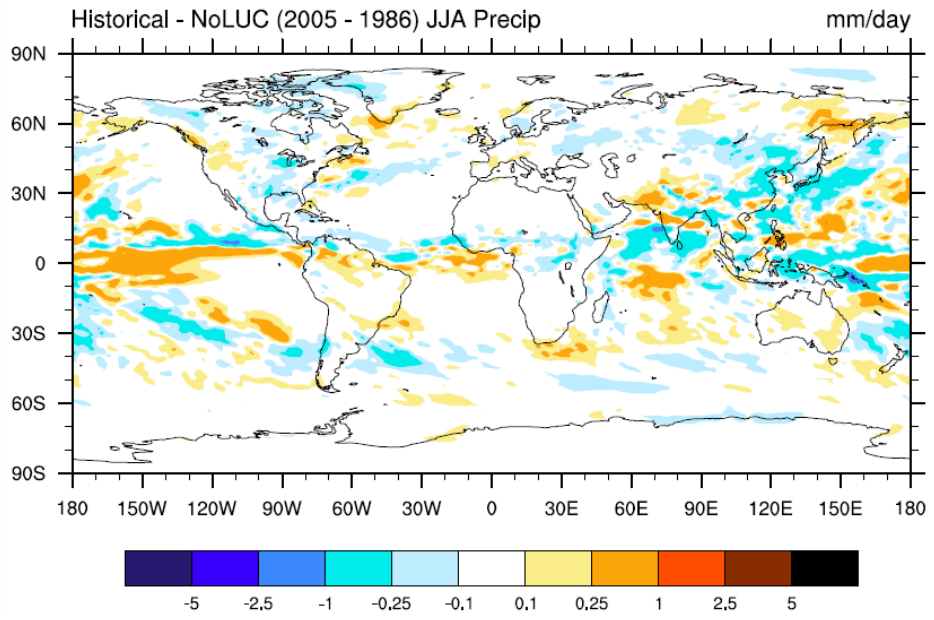


CMIP5 Land Cover Change – Latent Heat Flux Precip.

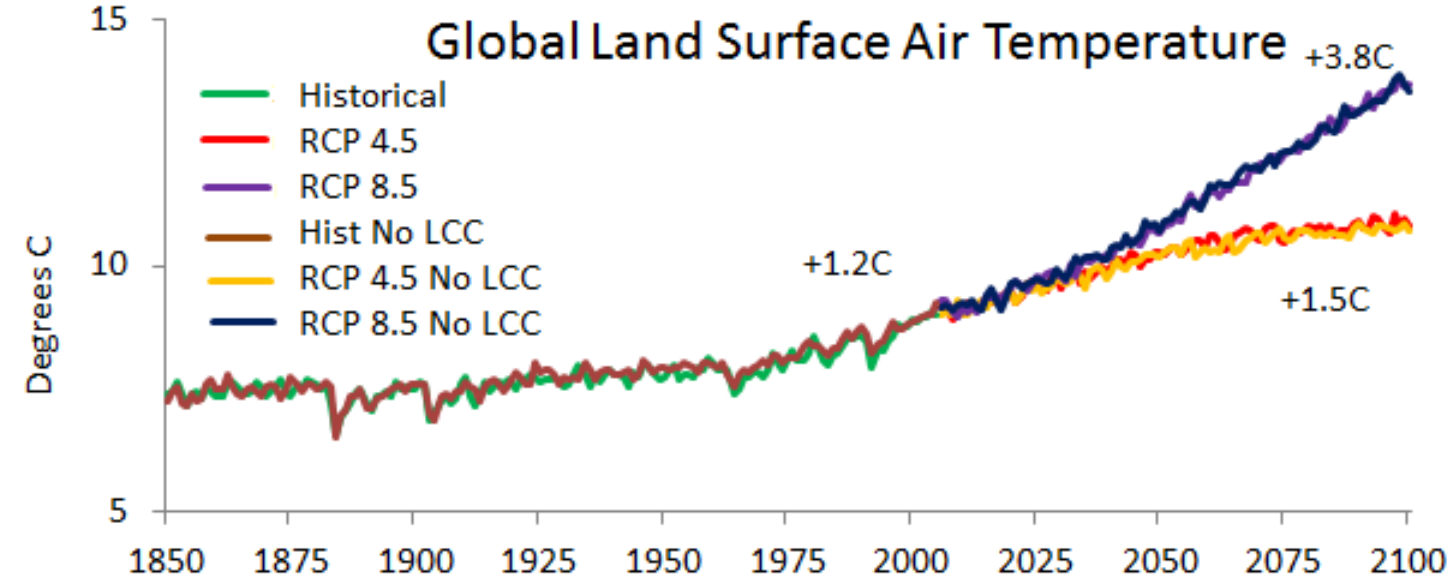


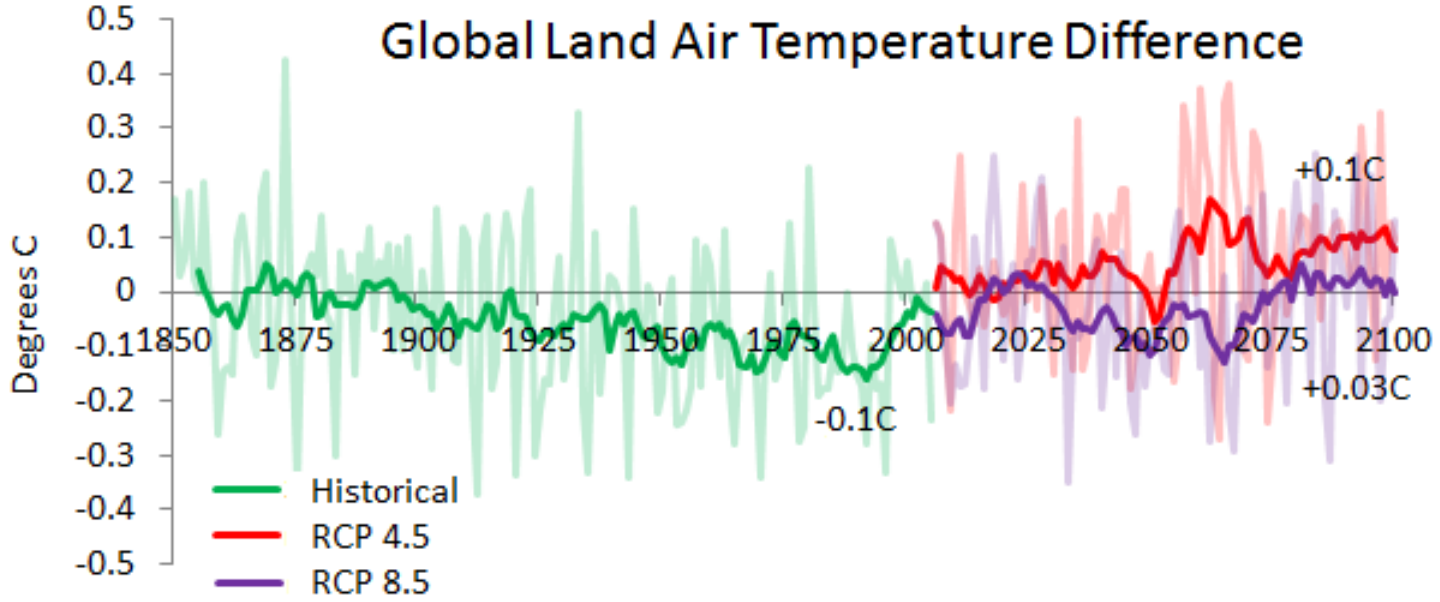




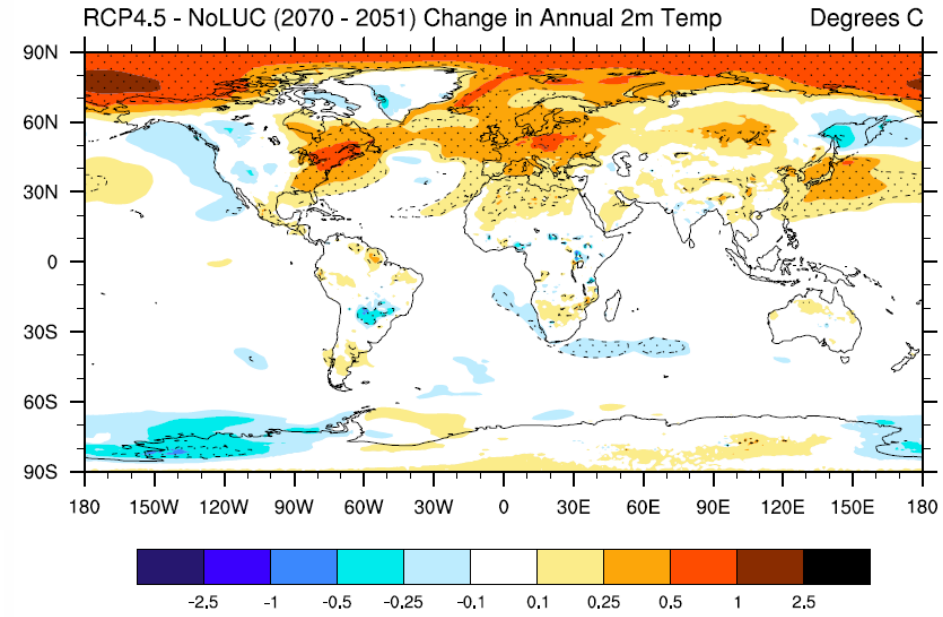


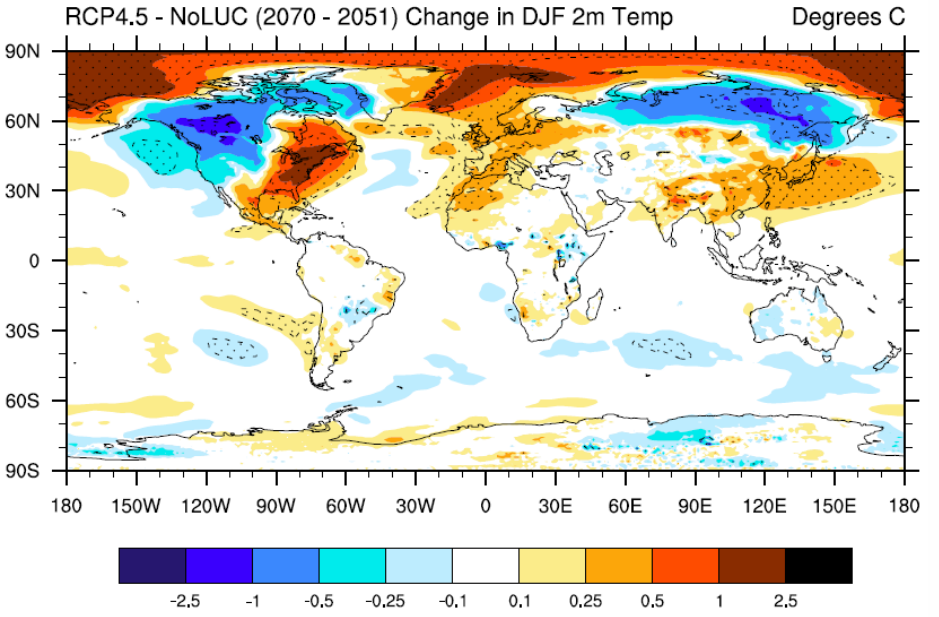
CMIP5 Land Cover Change – Land Air Temperature

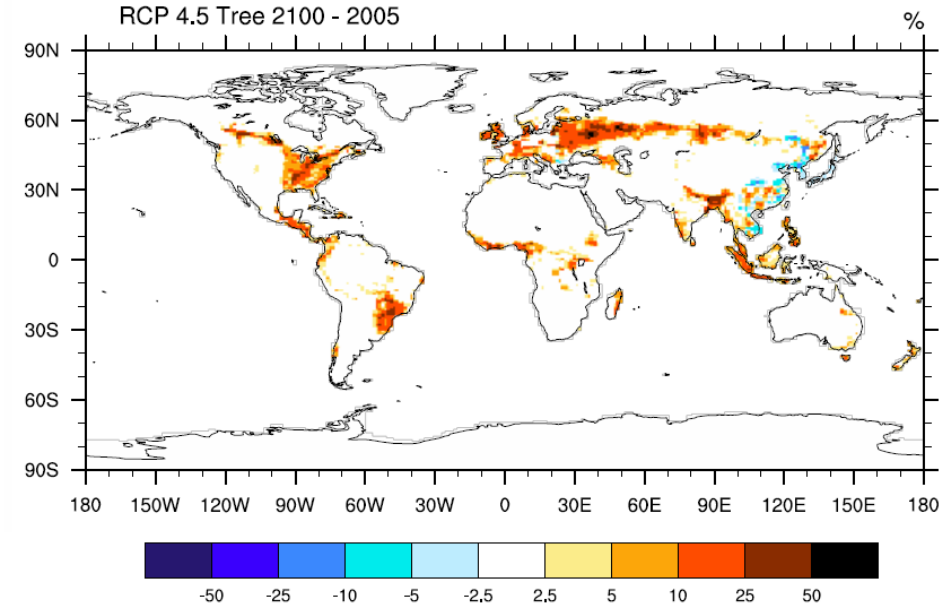


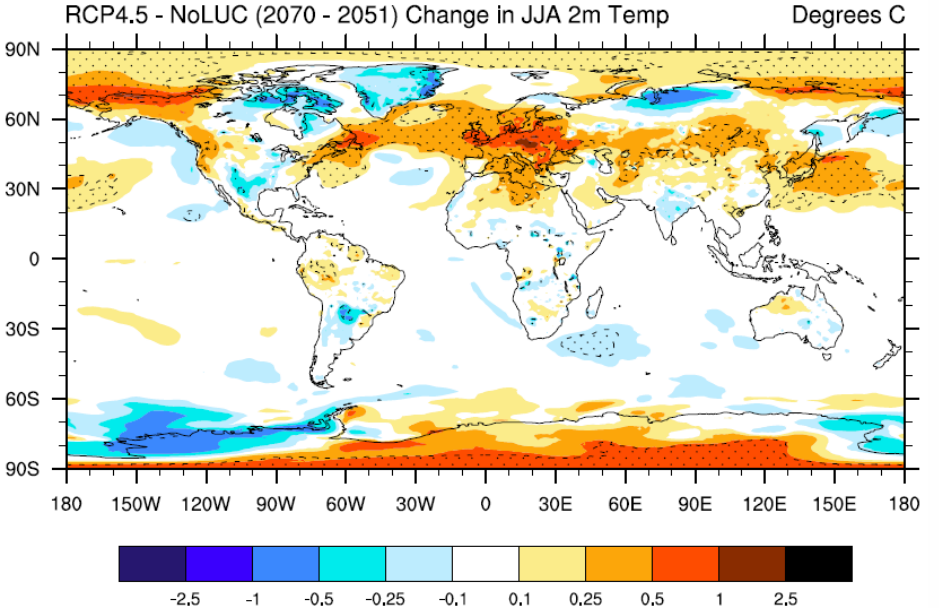


RCP 4.5 Land Cover Change – Land Air Temperature

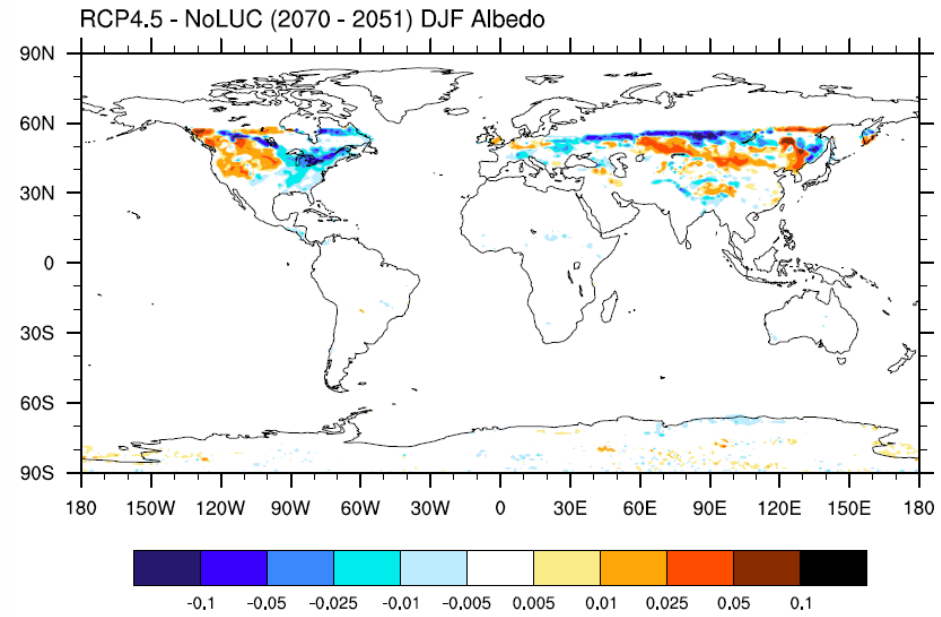


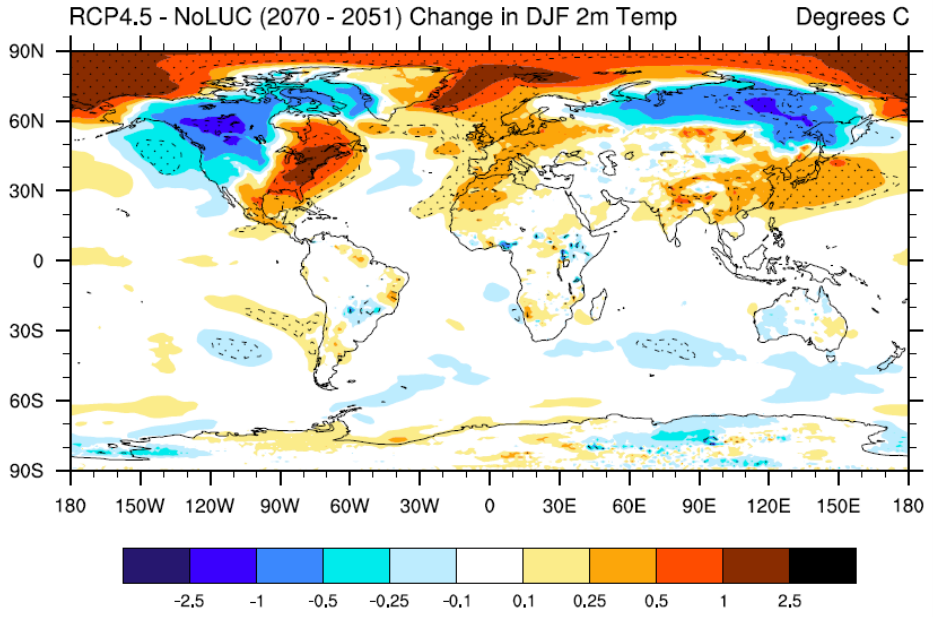


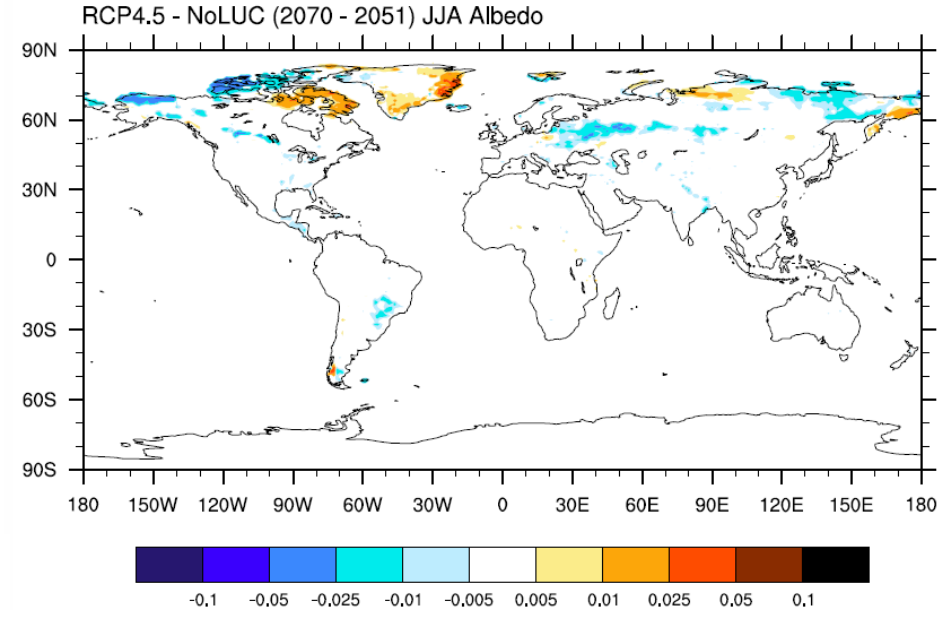


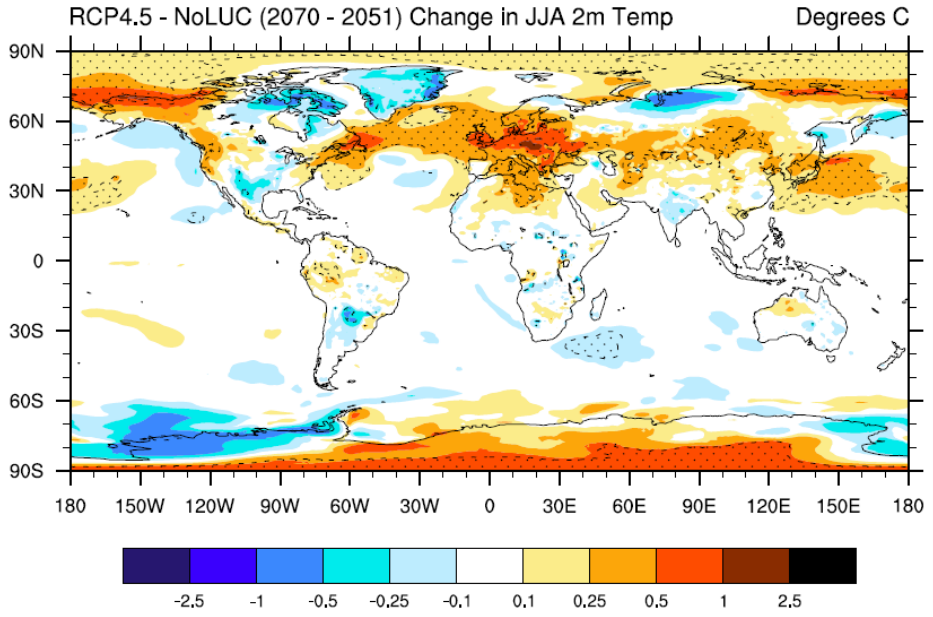


RCP 4.5 Land Cover Change – Albedo Air Temperature

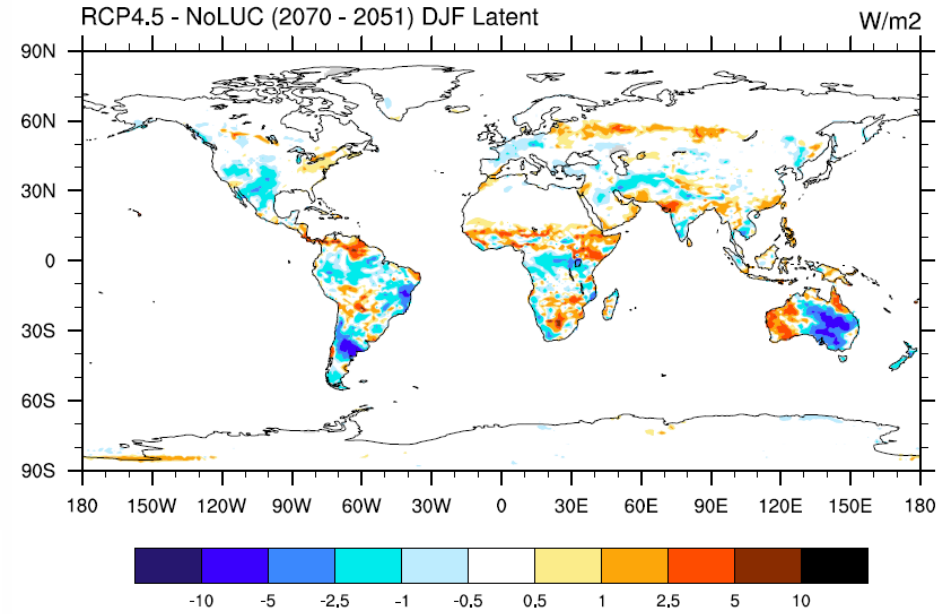


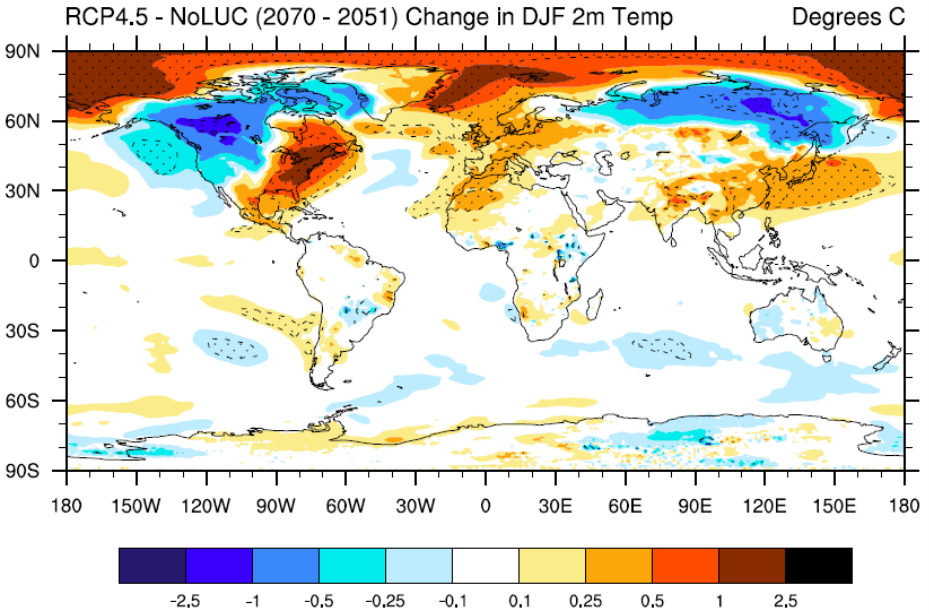


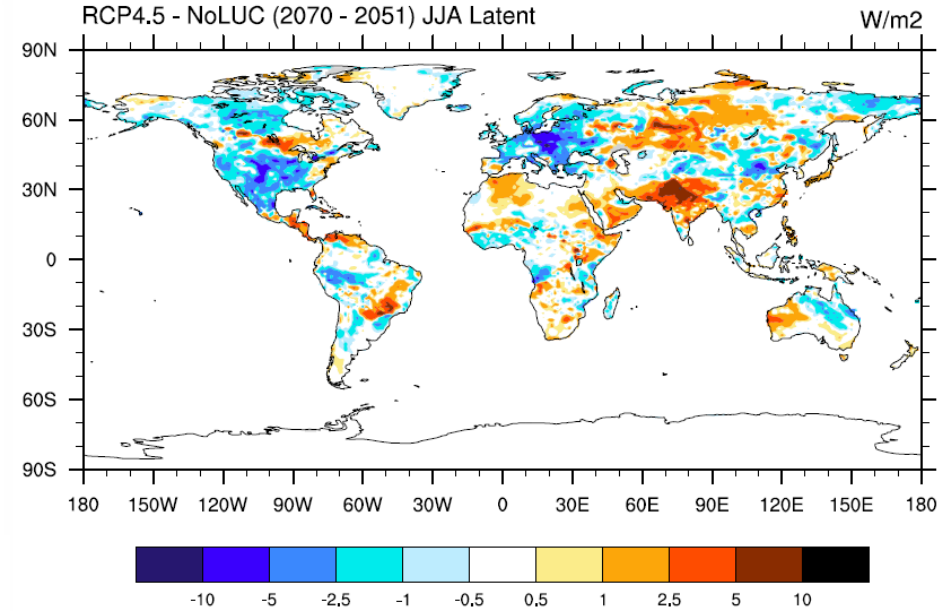


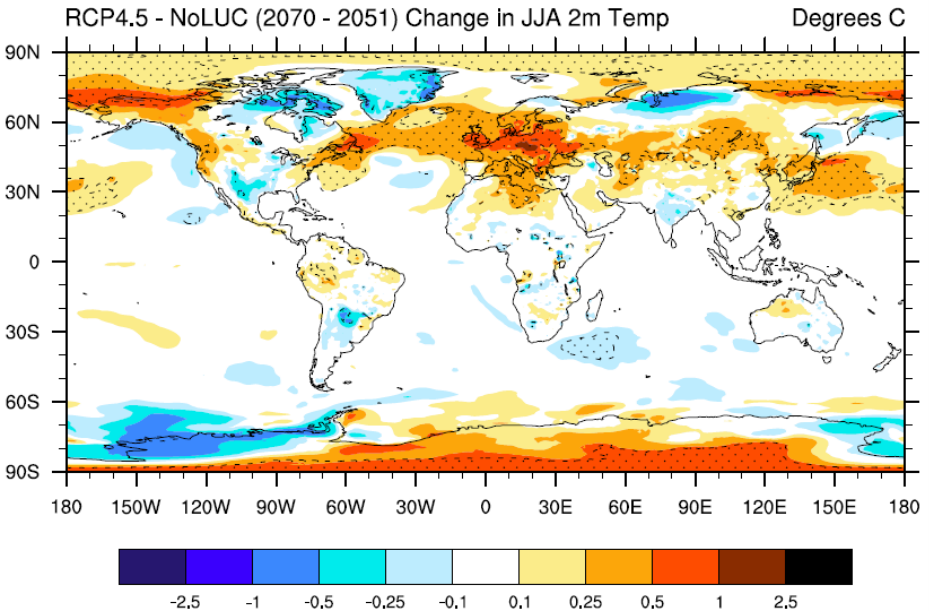


RCP 4.5 Land Cover Change – Latent Flux Air Temp.

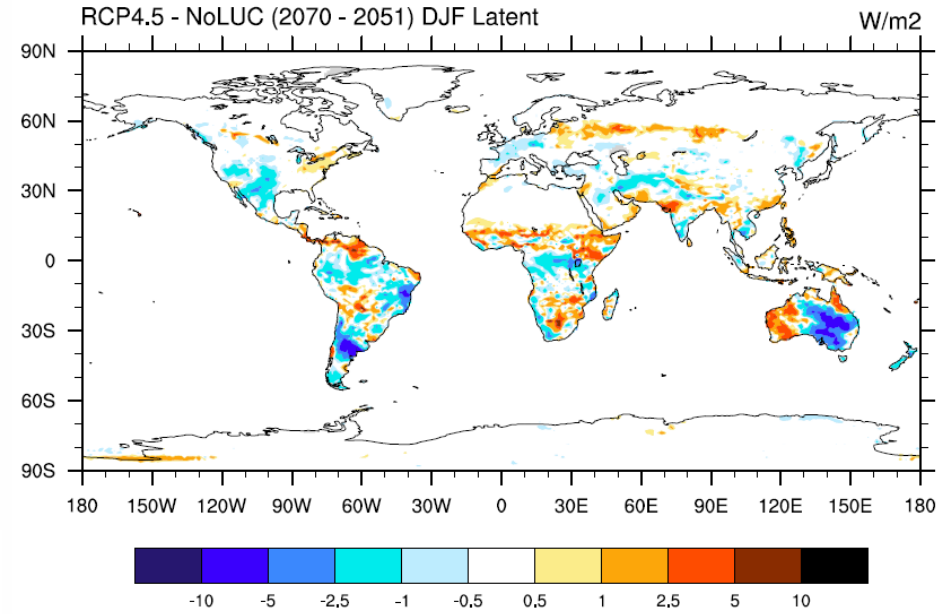


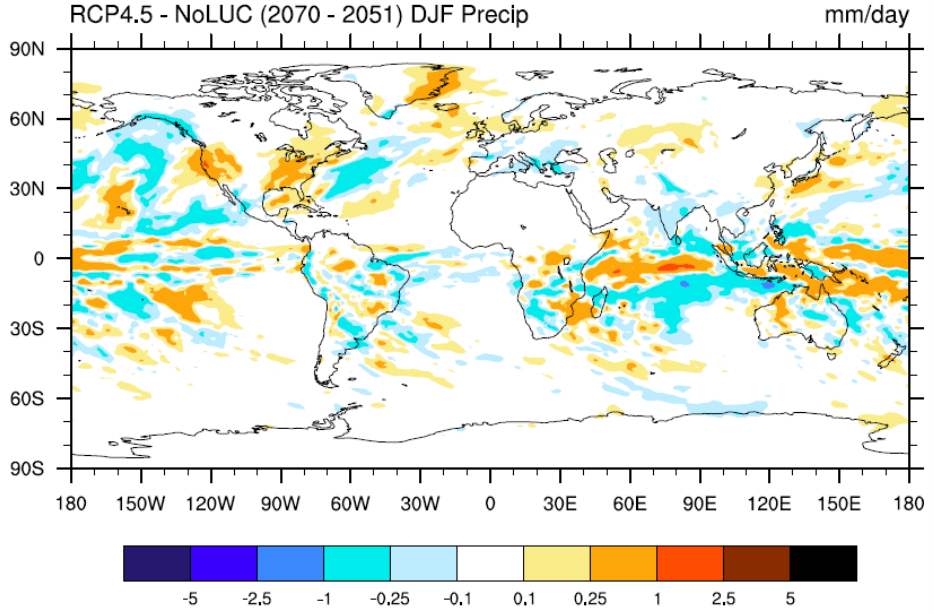


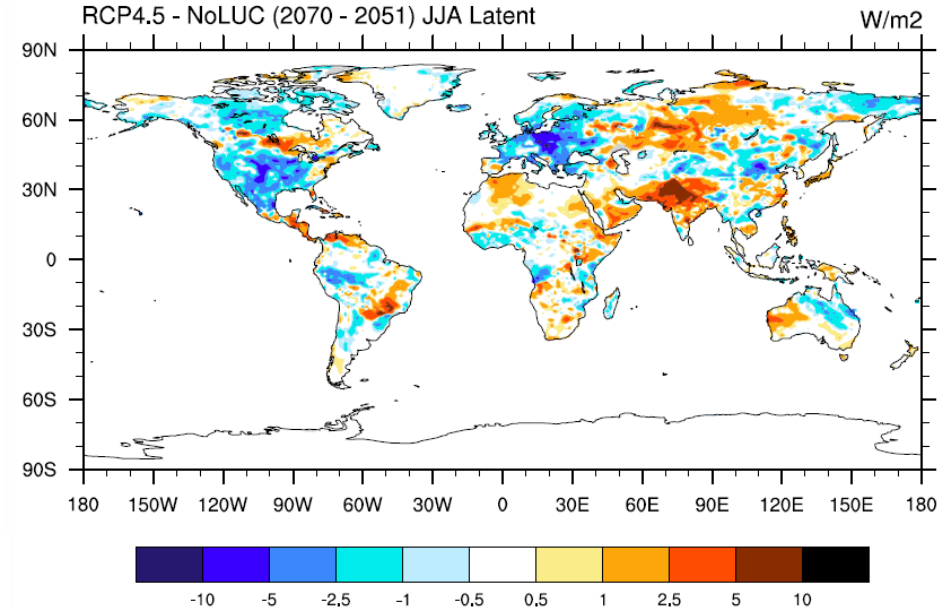


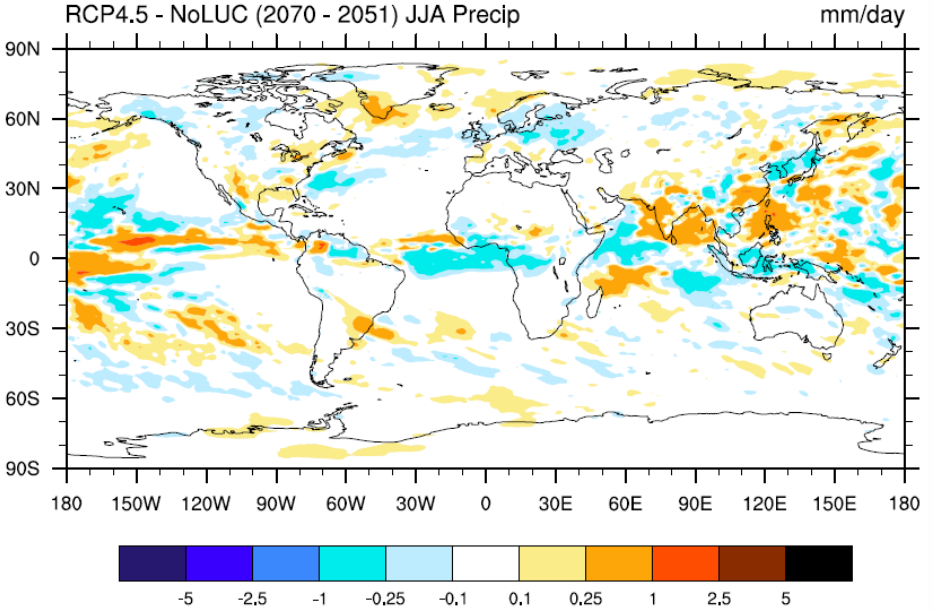


RCP 4.5 Land Cover Change – Latent Flux Precip.

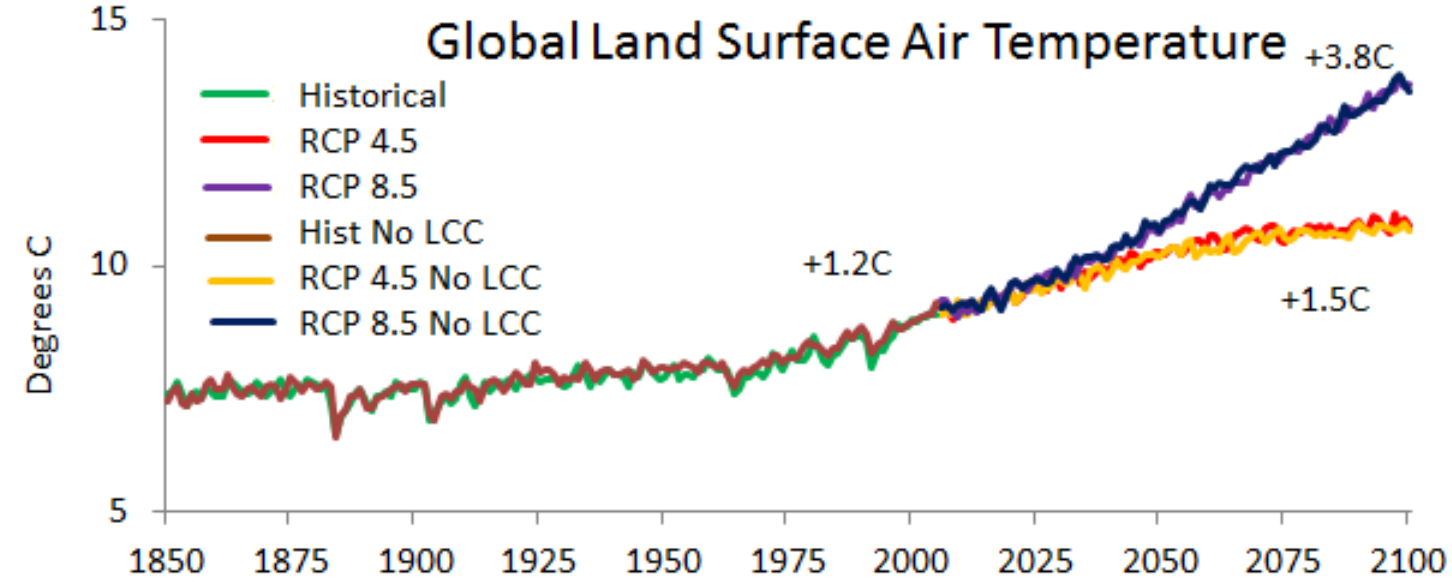


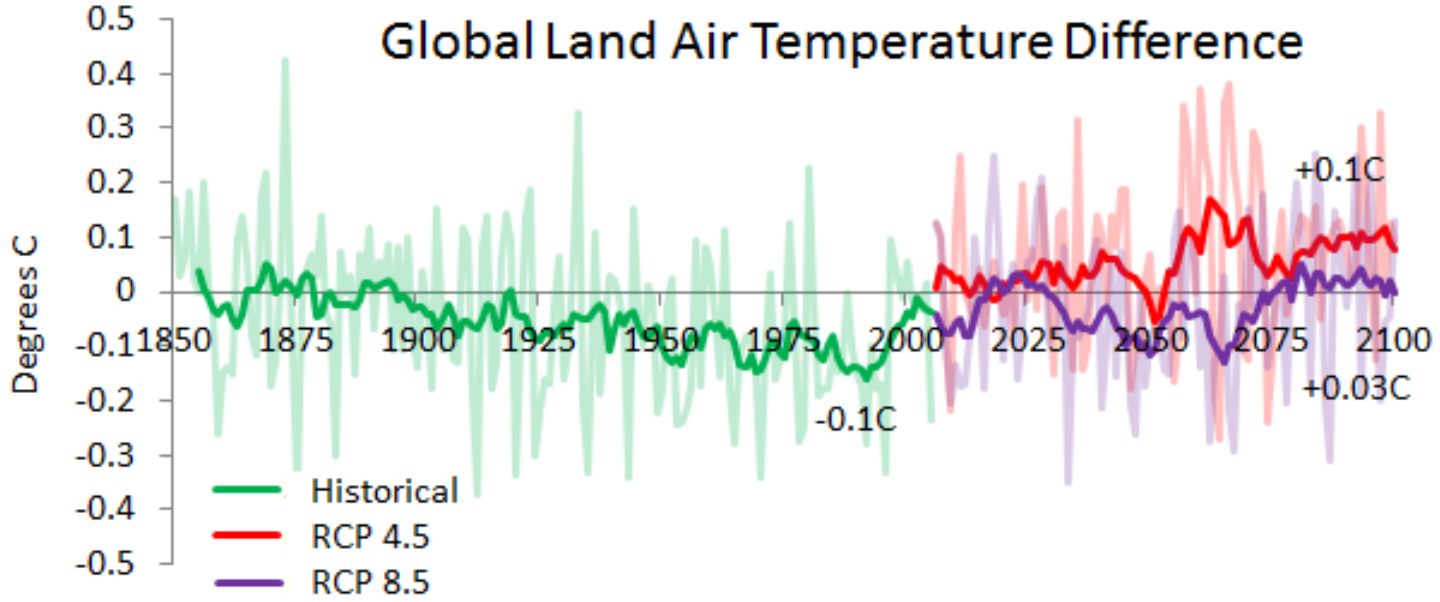






CMIP5 Land Cover Change – Land Air Temperature





CMIP5 Ecosystem Changes: NPP – No Land Use

Changes in Atmospheric CO_2 and climate impacts on Ecosystem Carbon:

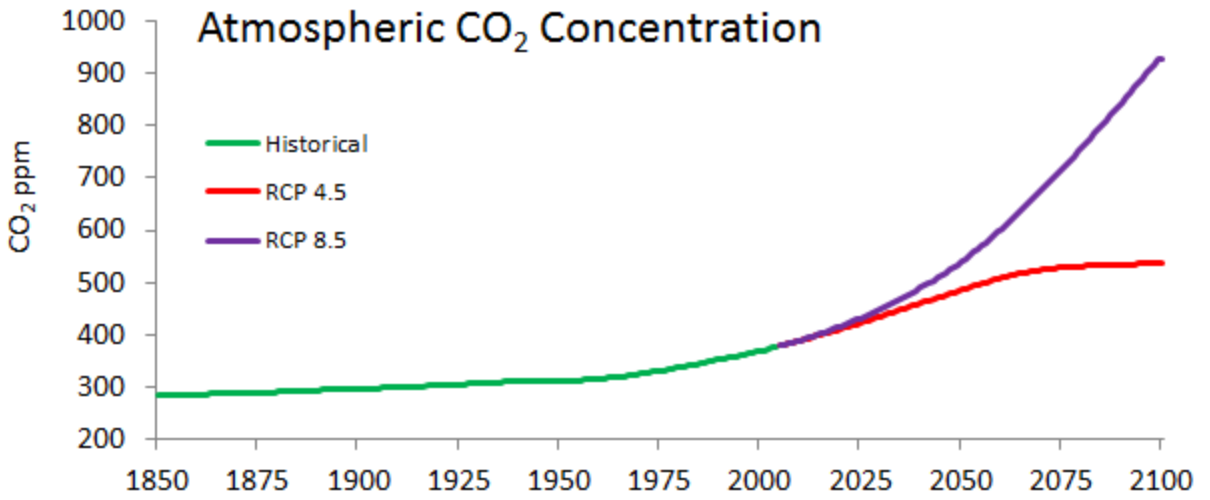
- Net Primary Productivity NPP = Photosynthesis – Growth and Maintenance Respiration

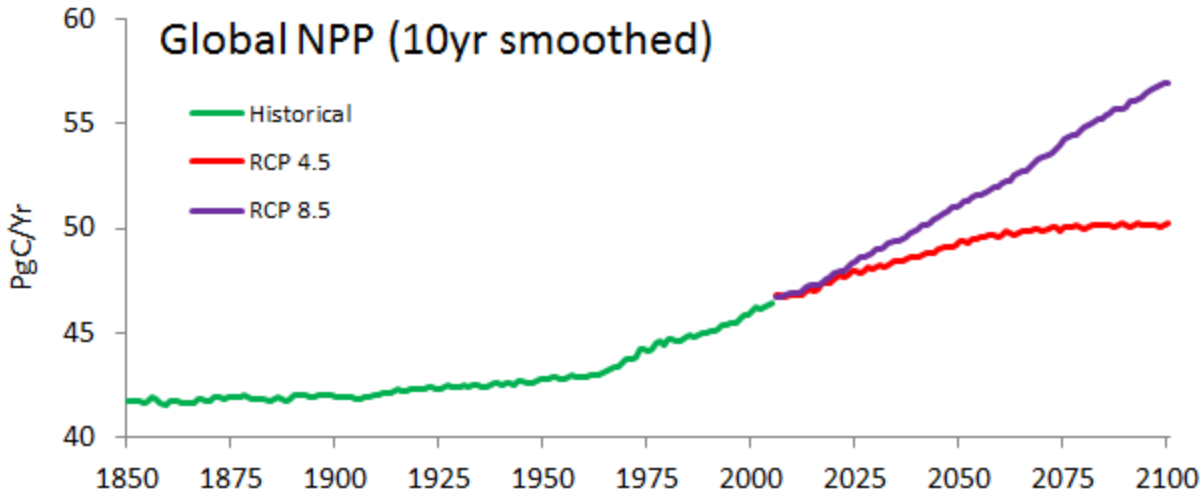
- Photosynthesis rates change through carbon availability

- Transpiration rates change through water use efficiency

- Temperature, rain, snow and evaporative demand change through climate with impacts on soil moisture

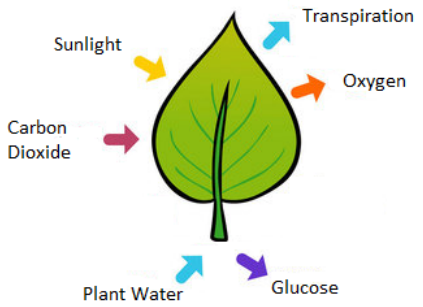
- 1 PgC = 10^{15} gC = 1 GtC





CLM Vegetation Modeling Leaf Level Processes and CO_2

1. Photosynthesis from Farquhar et al. (1980) modified by Harley et al. (1992) and von Caemmerer (2000)



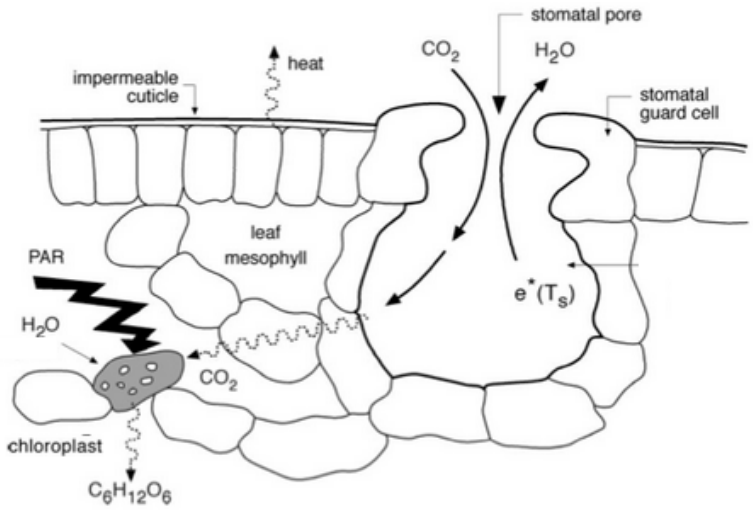
$$A_n = min\begin{Bmatrix} w_c \\ w_j \\ w_e \end{Bmatrix} - R_d$$

w_c *is the Rubisco limited assimilation from* V_{cmax}, *internal leaf* CO_2, *and temp*
w_j *is light limited assimilation from photon flux,* J_{max}, *internal leaf* CO_2, *and temp*
w_e *is export limited assimilation from Triose Phosphate Utilization TPU and temp*
and R_d *is respiration from* V_{cmax}, *and temp*

2. Transpiration from Ball and Berry (1991)

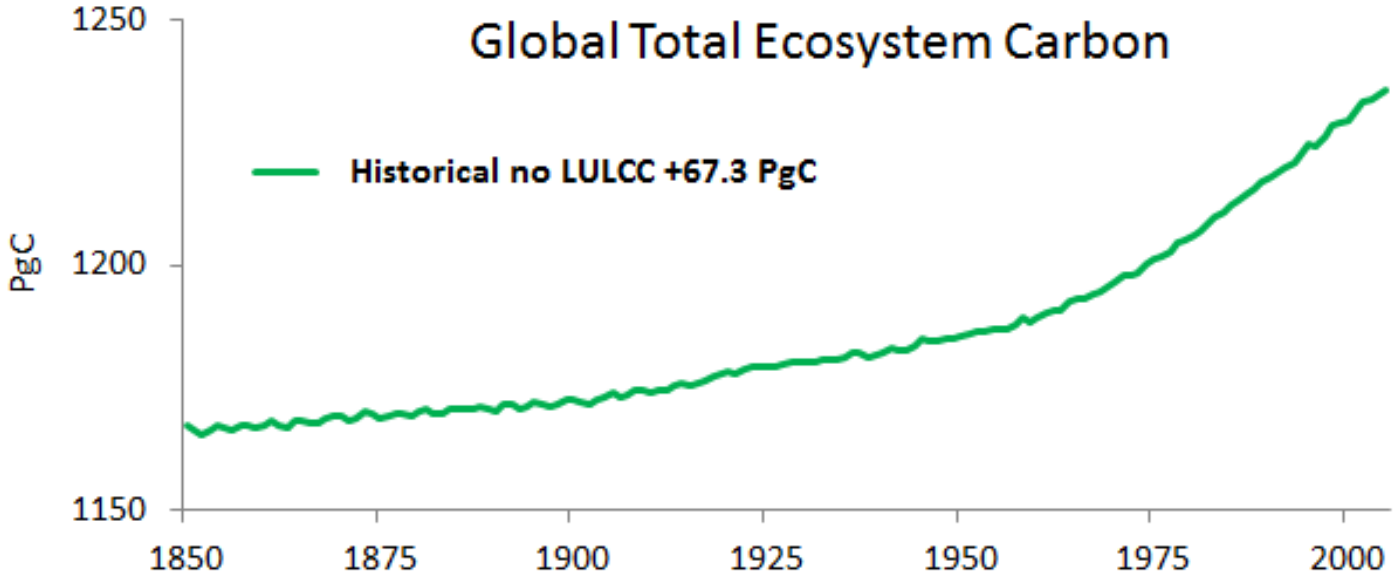
$$g_s = m\frac{A_n h_s}{c_s} + b$$

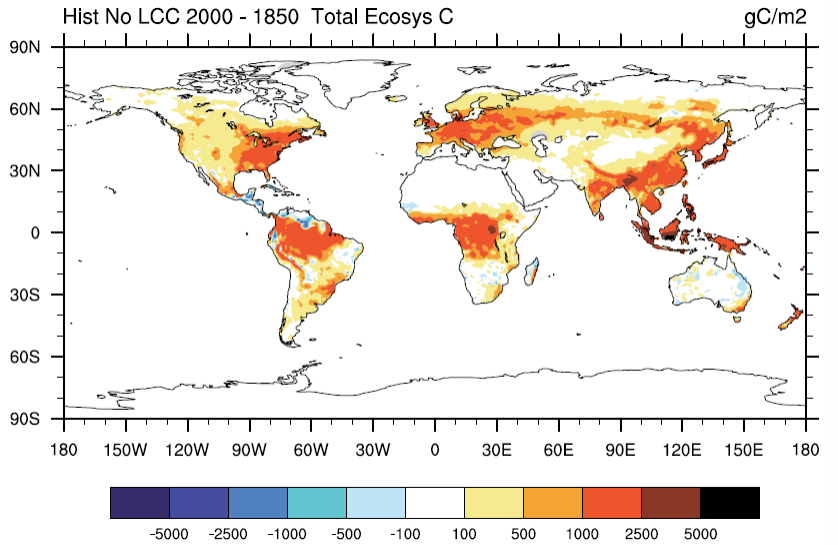
m is the Slope of Conductance to Assimilation,
h_s *is leaf surface relative humidity,*
c_s *is leaf surface* CO_2,
and b is the minimum conductance when $A_n = 0$



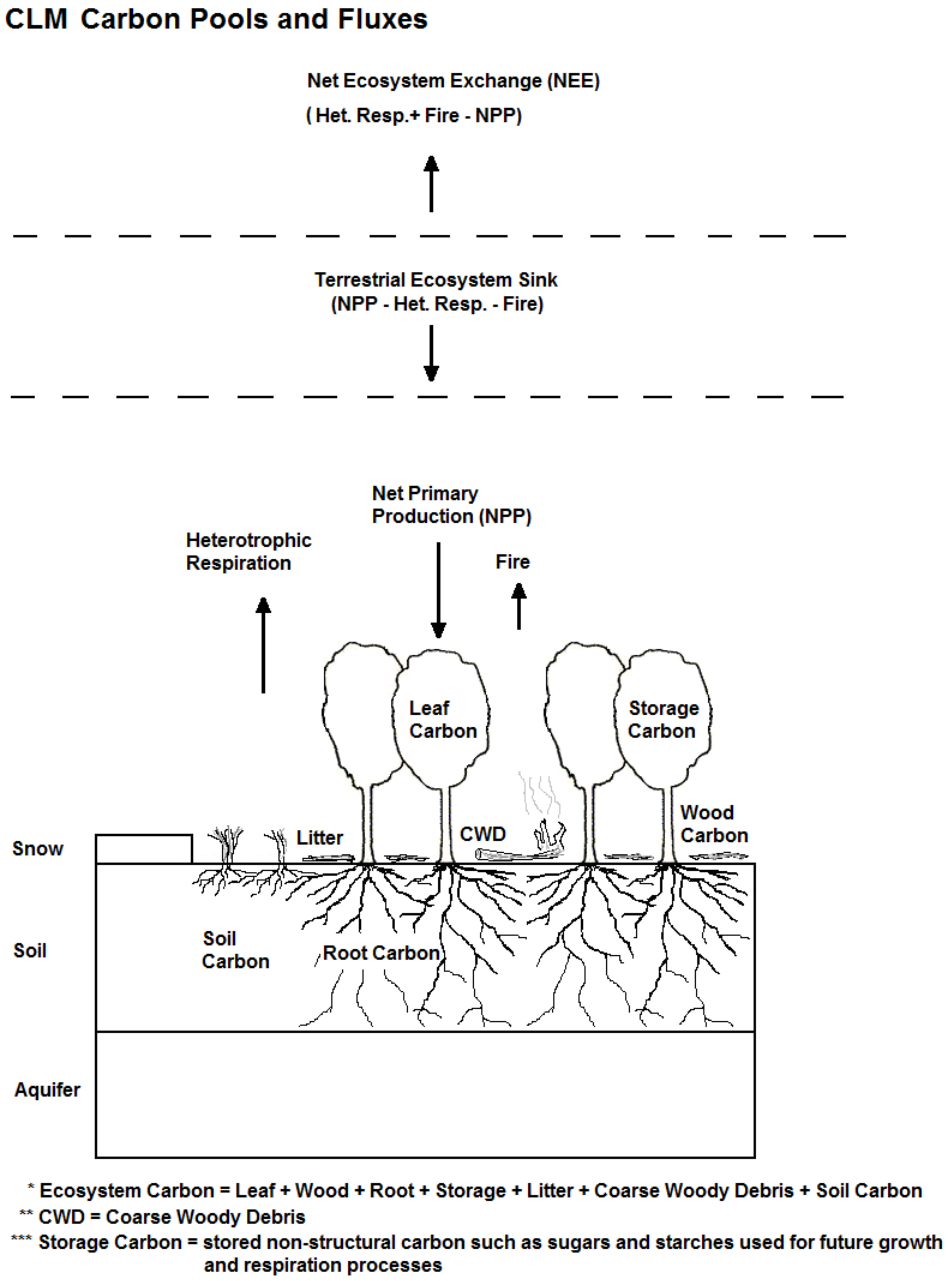
$$c_s = c_a - \frac{1.4}{g_b}A_n P_{atm} \qquad c_i = c_s - \frac{1.6}{g_s}A_n P_{atm} \qquad h_s = \frac{e_s}{e_*[T_v]} = \frac{g_b e_a + g_s e_*[T_v]}{(g_b + g_s)e_*[T_v]}$$

Historical Ecosystem Changes: Ecosys C – No Land Use





Ecosystem Modeling in (CLM BGC) – No Land Use

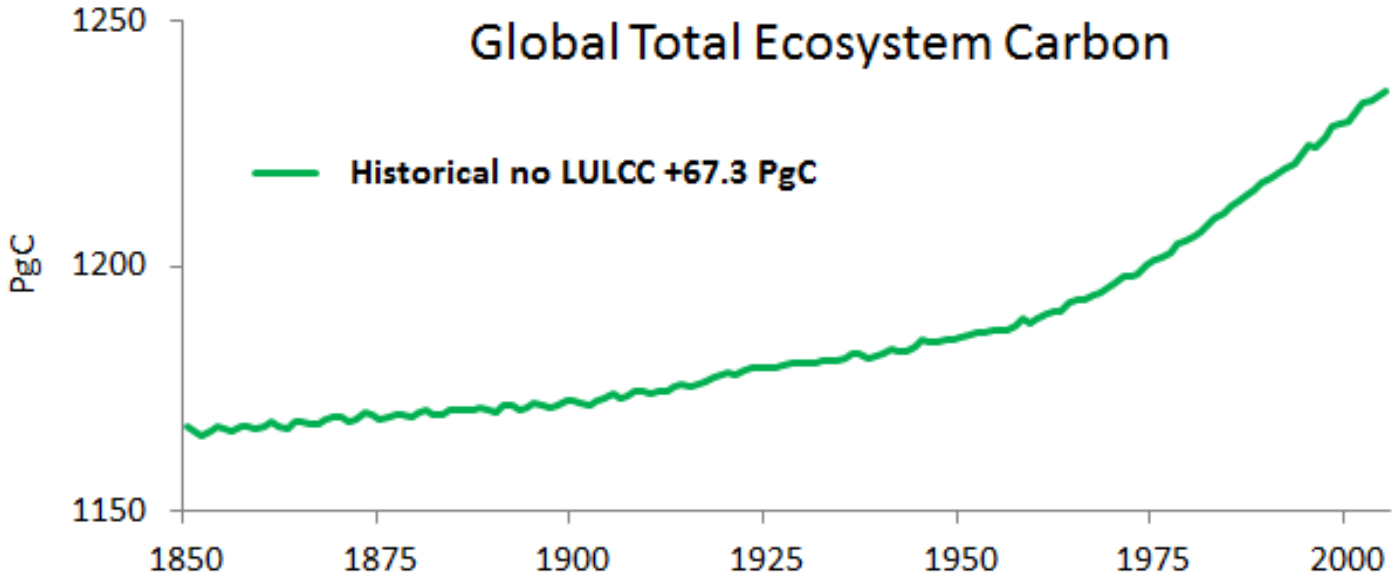


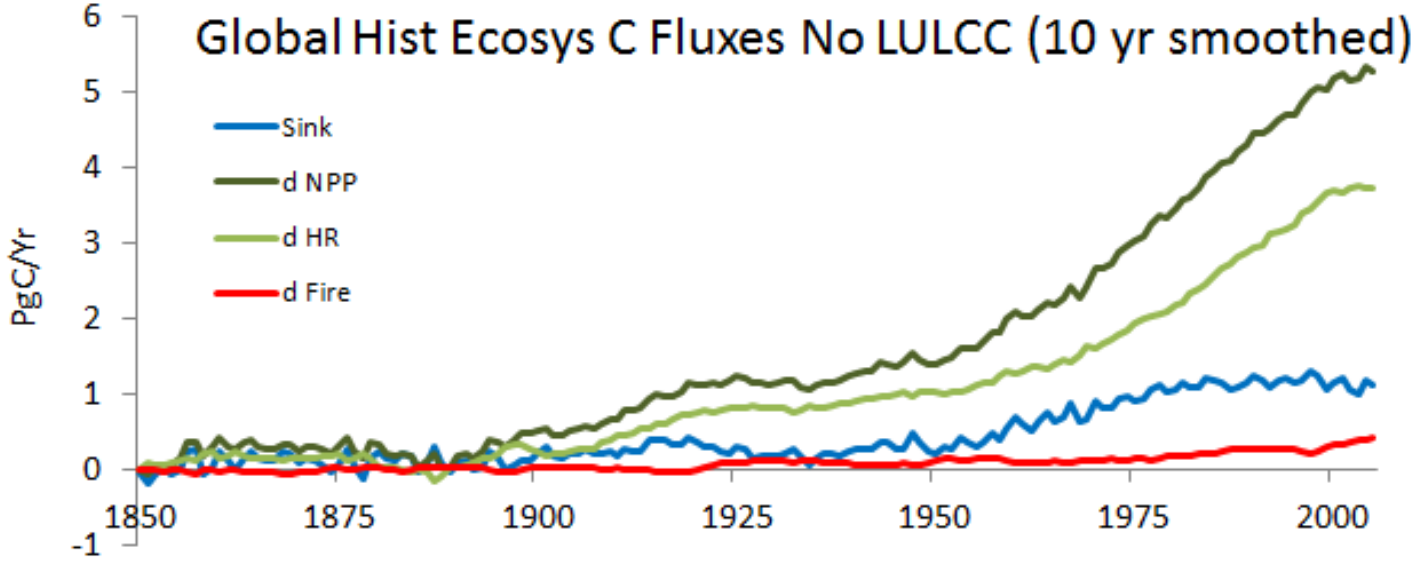
* Ecosystem Carbon = Leaf + Wood + Root + Storage + Litter + Coarse Woody Debris + Soil Carbon

** CWD = Coarse Woody Debris

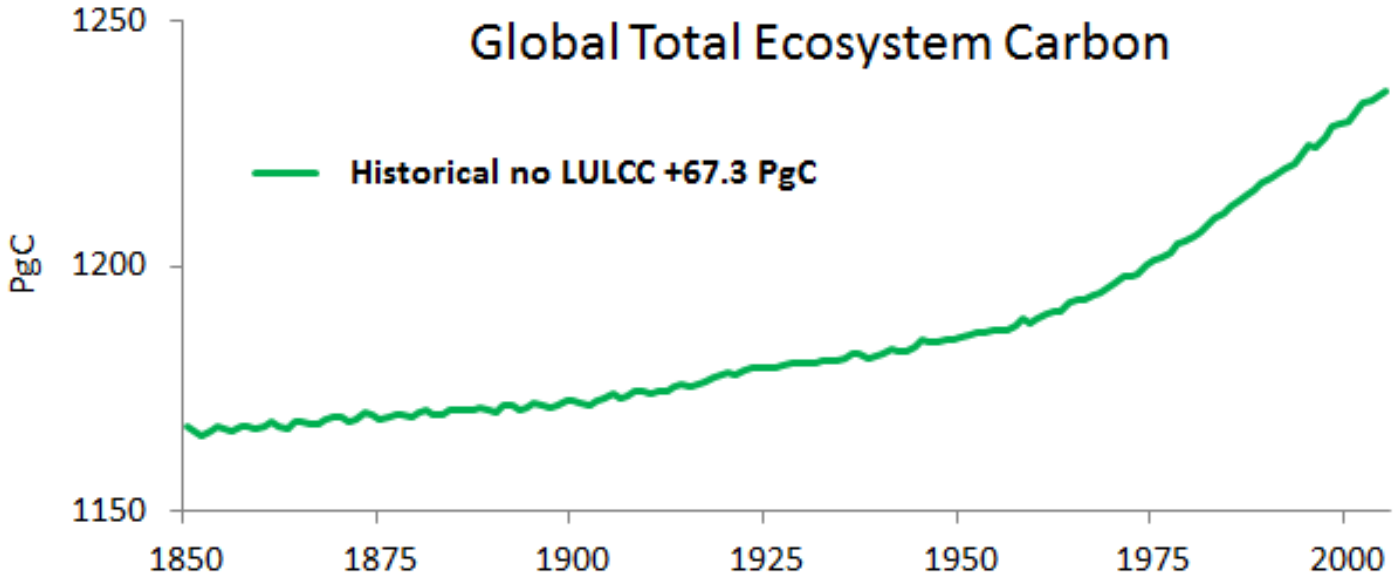
*** Storage Carbon = stored non-structural carbon such as sugars and starches used for future growth and respiration processes

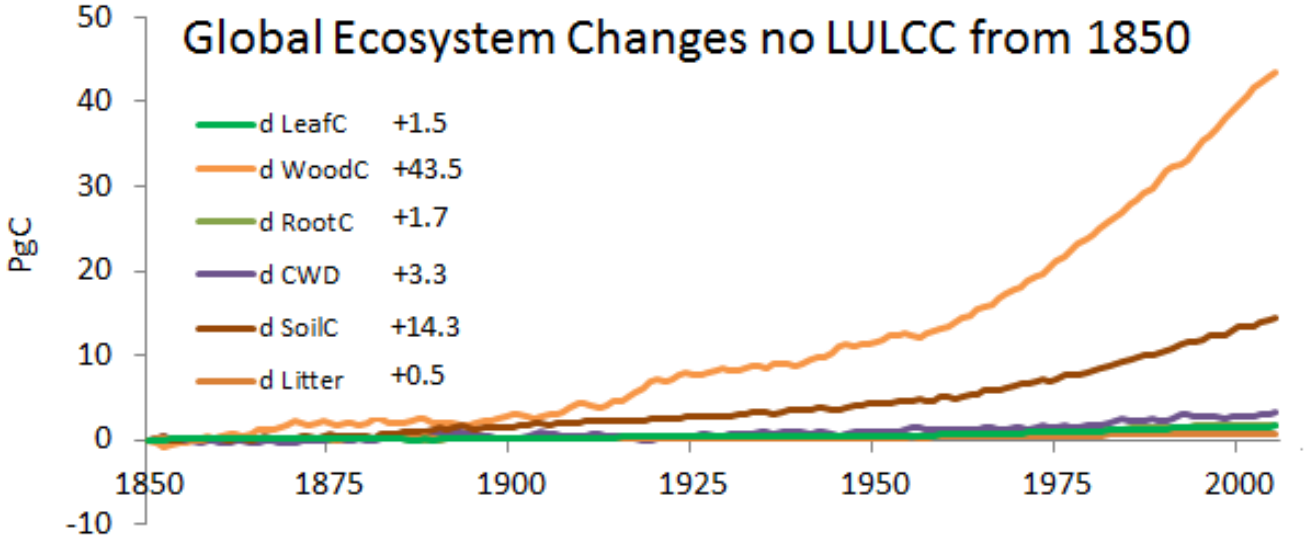
Historical Ecosystem Changes: Ecosys C – No Land Use



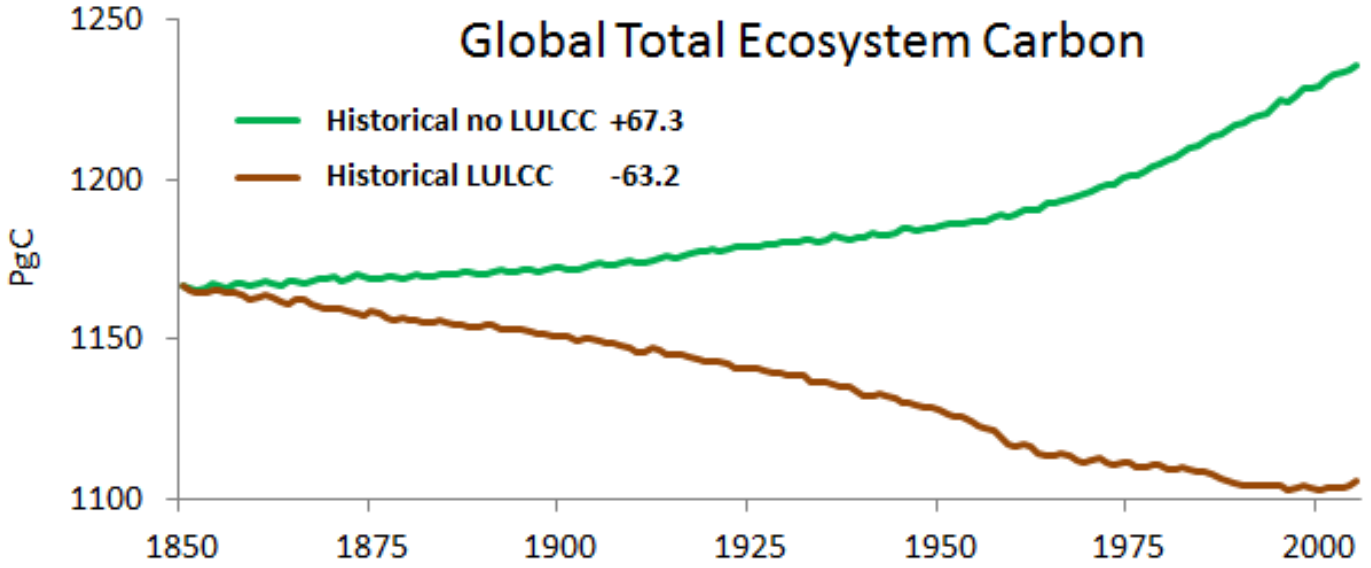


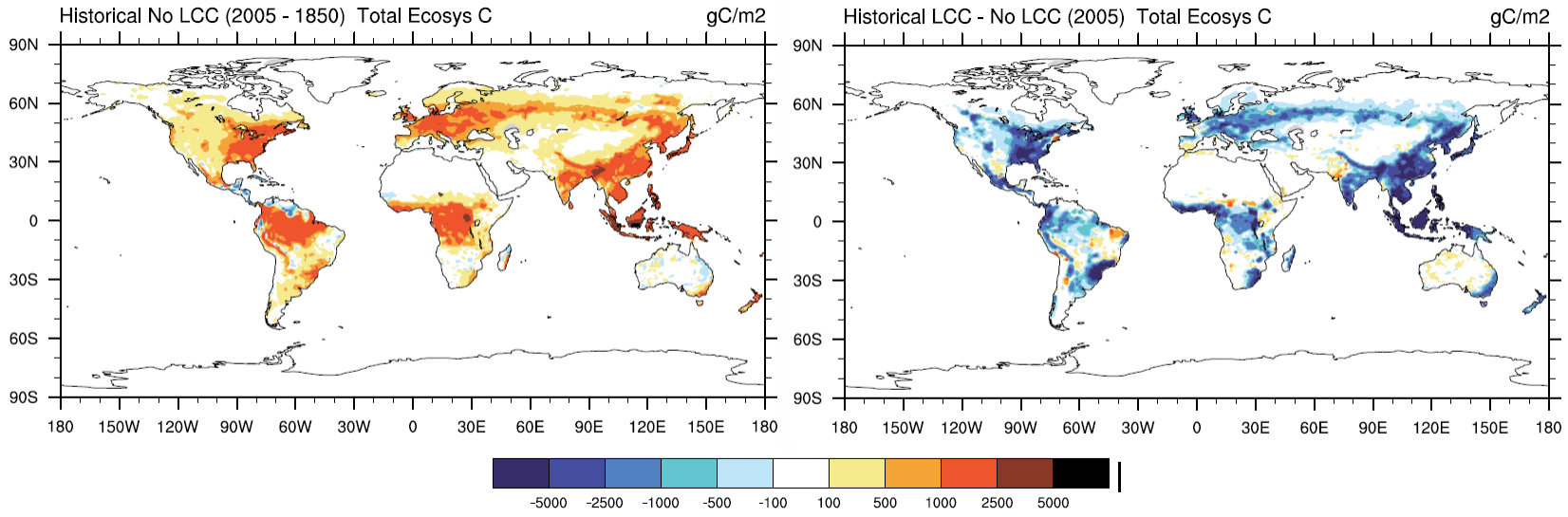
Historical Ecosystem Changes: Ecosys C – No Land Use





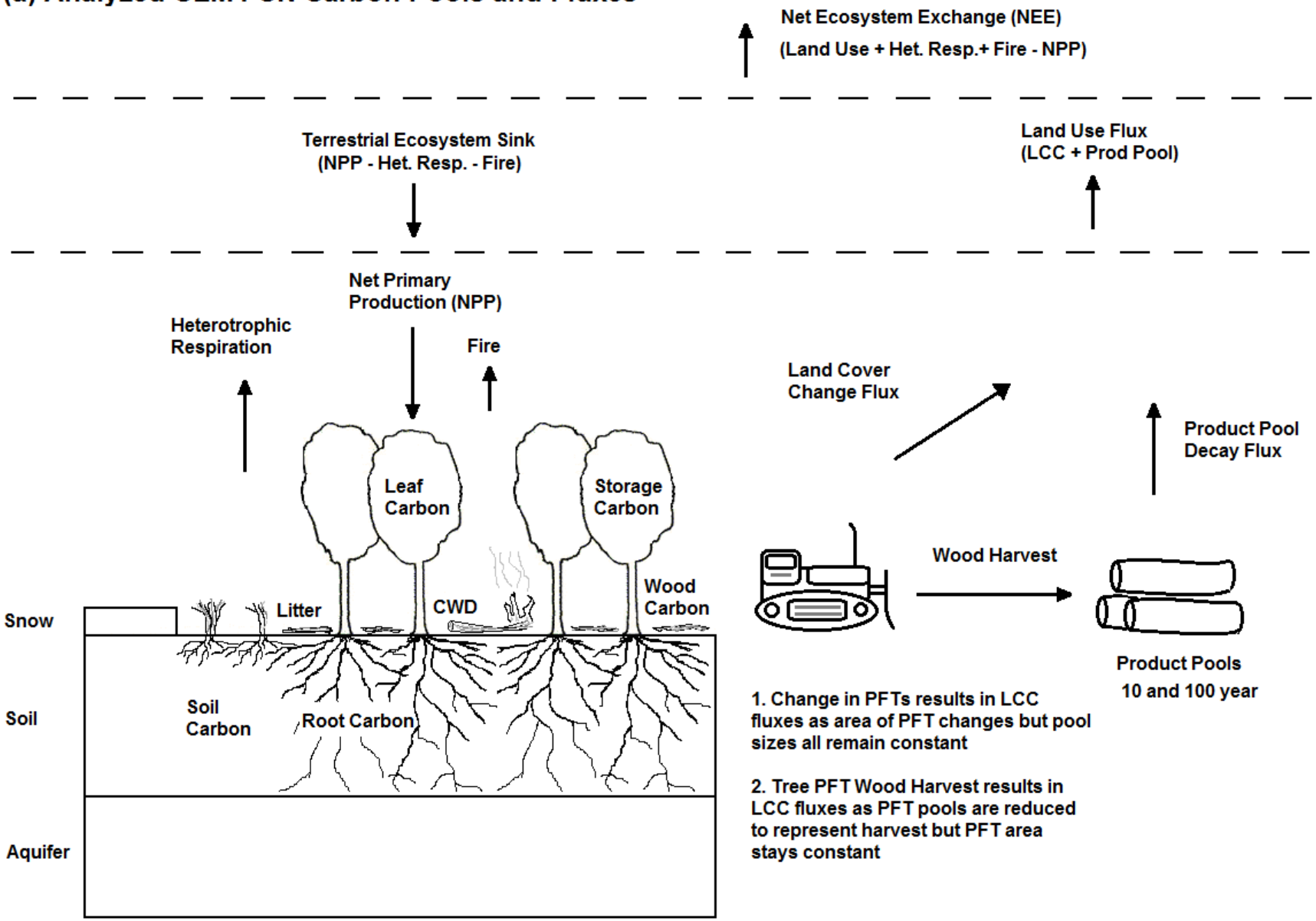
Historical Ecosystem Changes: Land Cover Change





Ecosystem Modeling in (CLM BGC) – Land Cover Change

(a) Analyzed CLM4 CN Carbon Pools and Fluxes



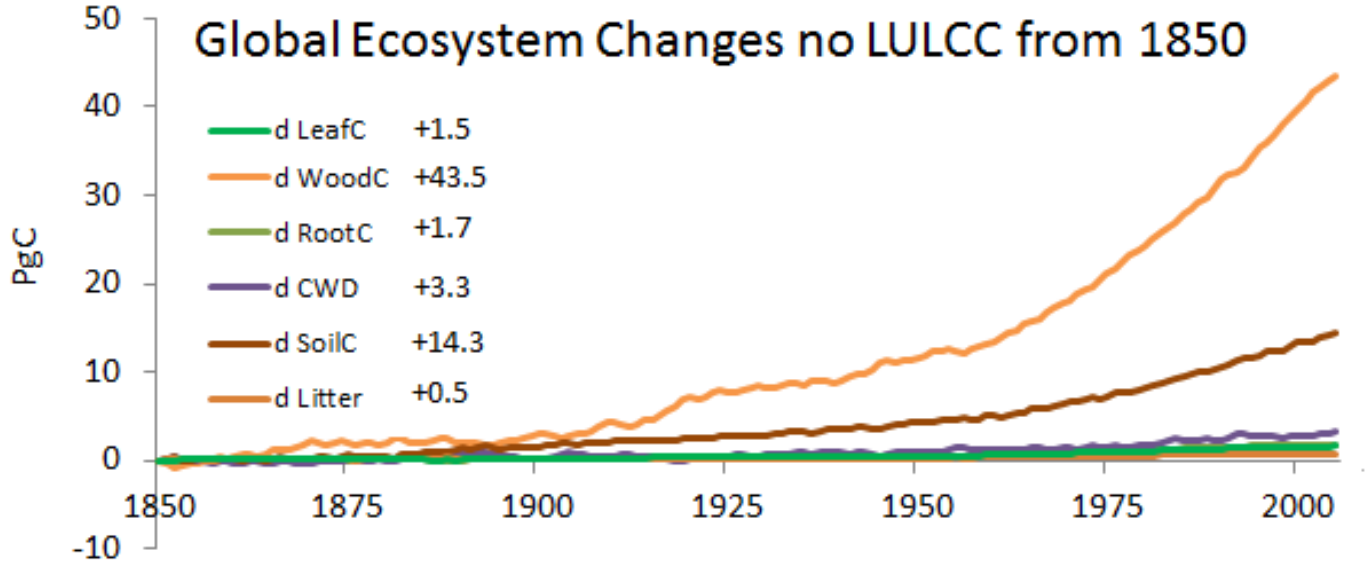
1. Change in PFTs results in LCC fluxes as area of PFT changes but pool sizes all remain constant

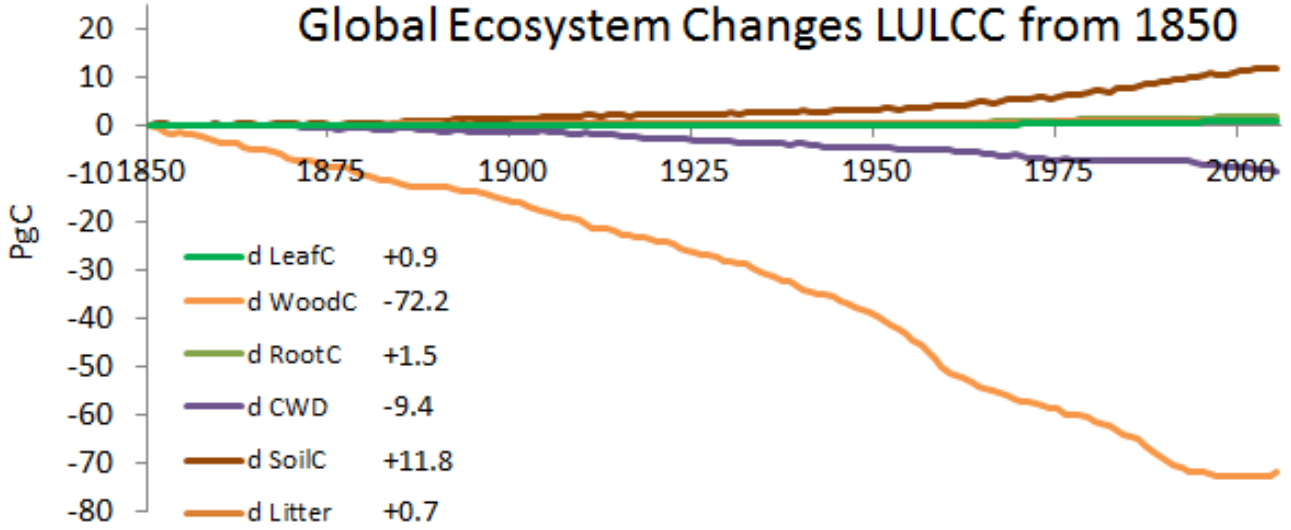
2. Tree PFT Wood Harvest results in LCC fluxes as PFT pools are reduced to represent harvest but PFT area stays constant

* Ecosystem Carbon = Leaf + Wood + Root + Storage + Litter + Coarse Woody Debris + Soil Carbon

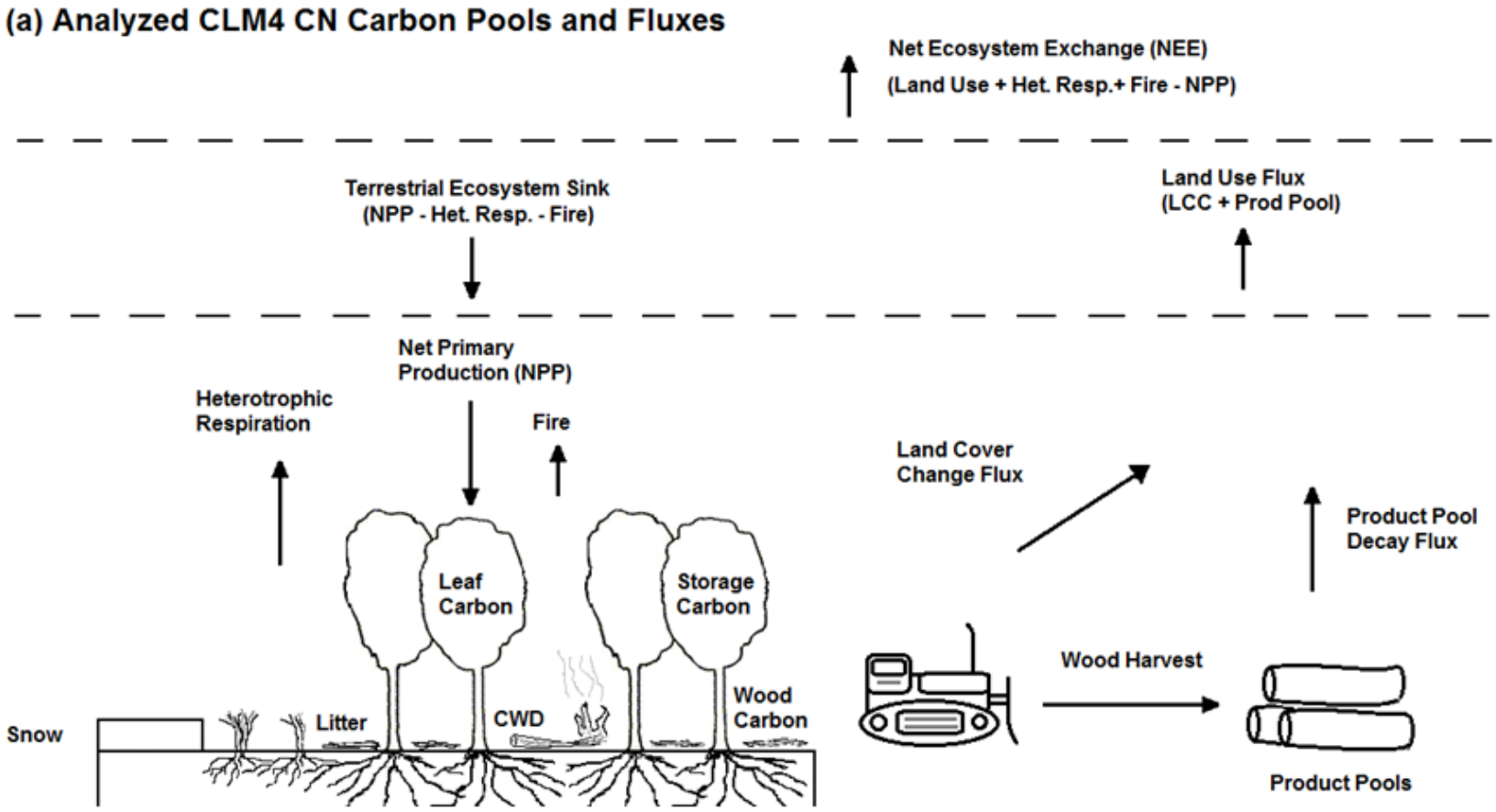
** CWD = Coarse Woody Debris

Historical Ecosystem Changes: Ecosys C – Land Use





Ecosystem Changes in CMIP5 – Land Cover Change



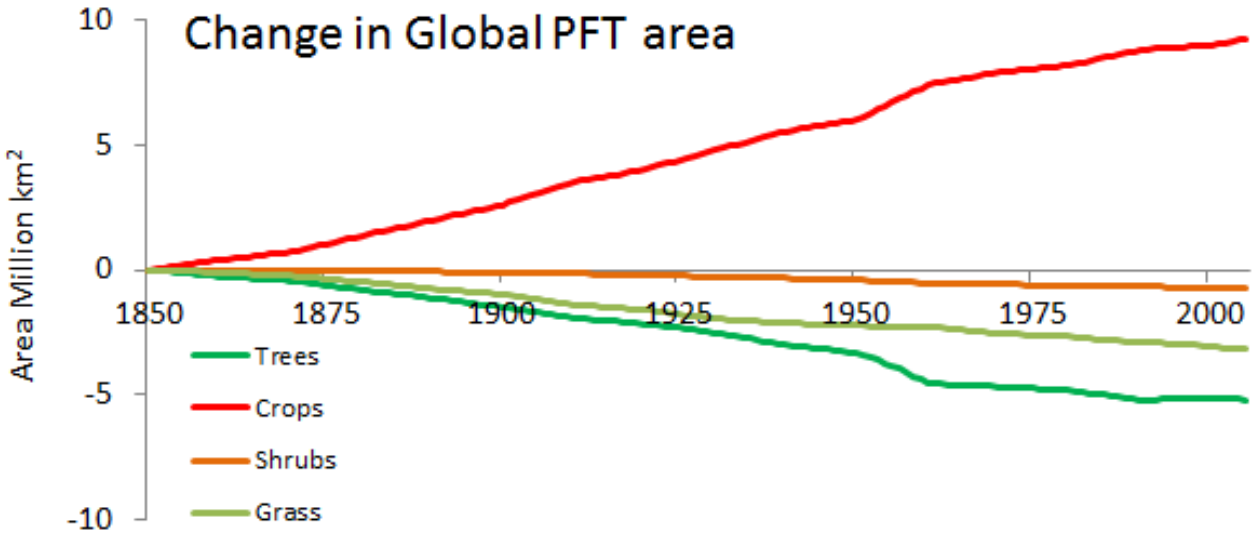
Direct LULCC Fluxes:

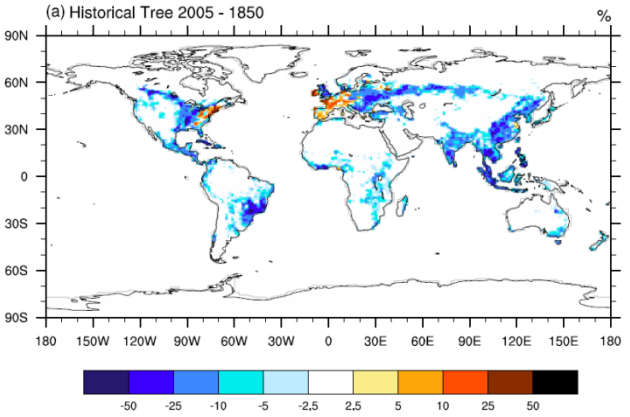
- Conversion Fluxes to the Atmosphere
- Conversion Fluxes to Wood Products
- Wood Harvest Fluxes to Wood Products
- Product Pool Decay to the Atmosphere

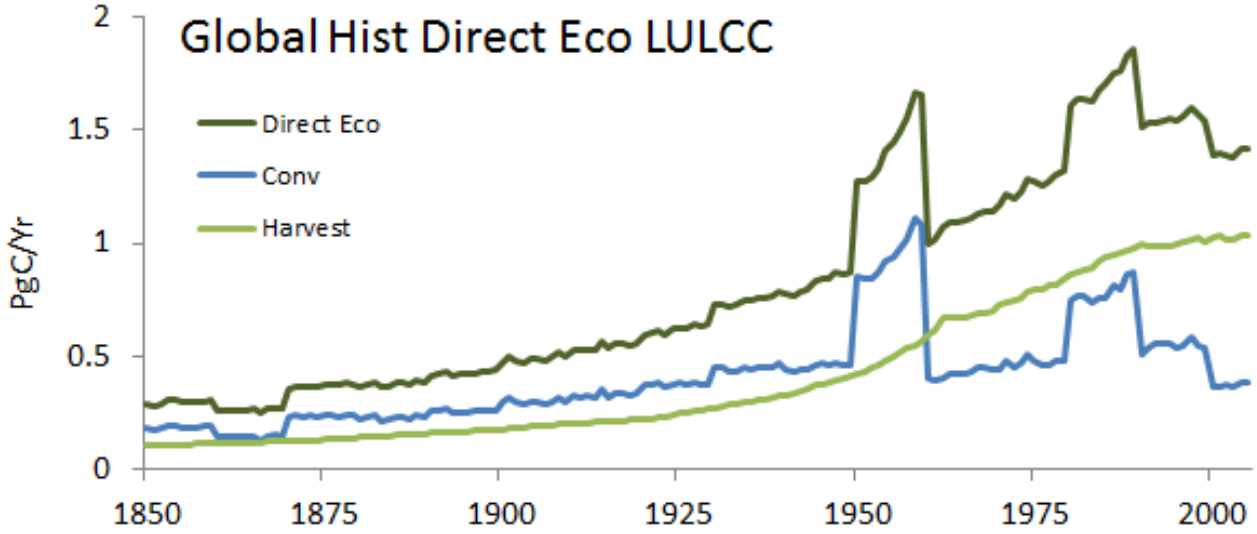
Indirect LULCC Fluxes:

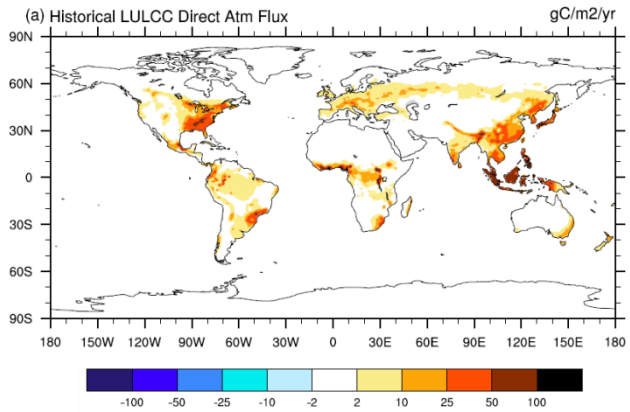
- Loss of potential Ecosystem Sink from Deforestation
- Increase in Ecosystem Sink from Afforestation
- Changes in Fire with new Land Use
- Changes in Soil and Litter Carbon Decay
- Changes in nutrient cycling with new Land Use
- This is the change in the Ecosystem Sink from LULCC

Historical Ecosystem Changes: Direct LULCC Fluxes





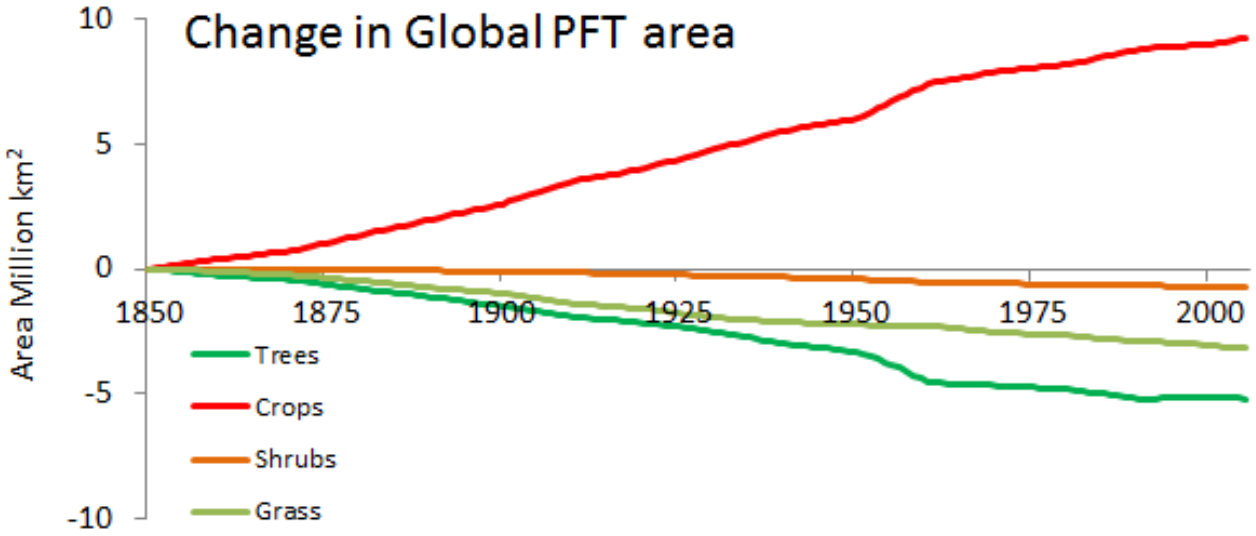


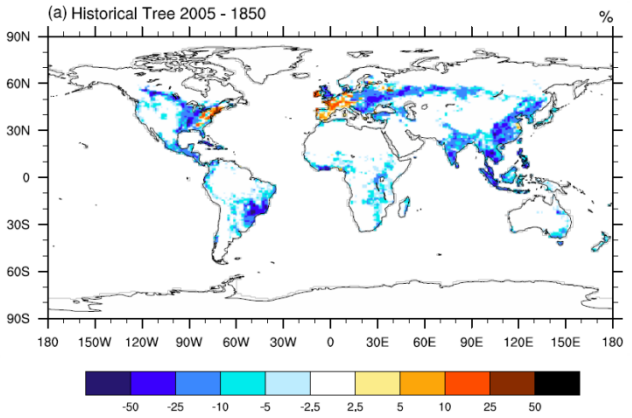


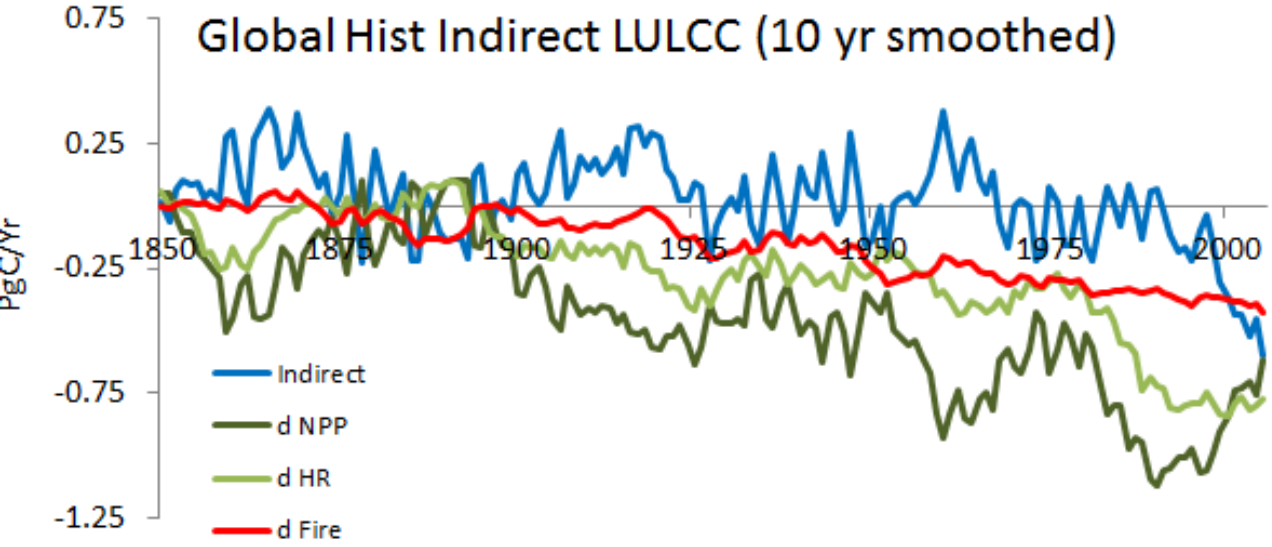
$LULCC_{DIRECT\ ECO}$ = Conversion + Wood Harvest = 126.8 PgC (PgC = 10^{15})

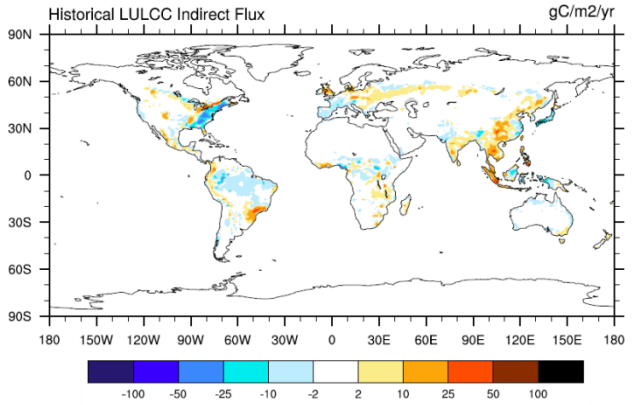
Conversion = 63.2 PgC Wood Harvest = 63.6 PgC

Historical Ecosystem Changes: Indirect LULCC Fluxes





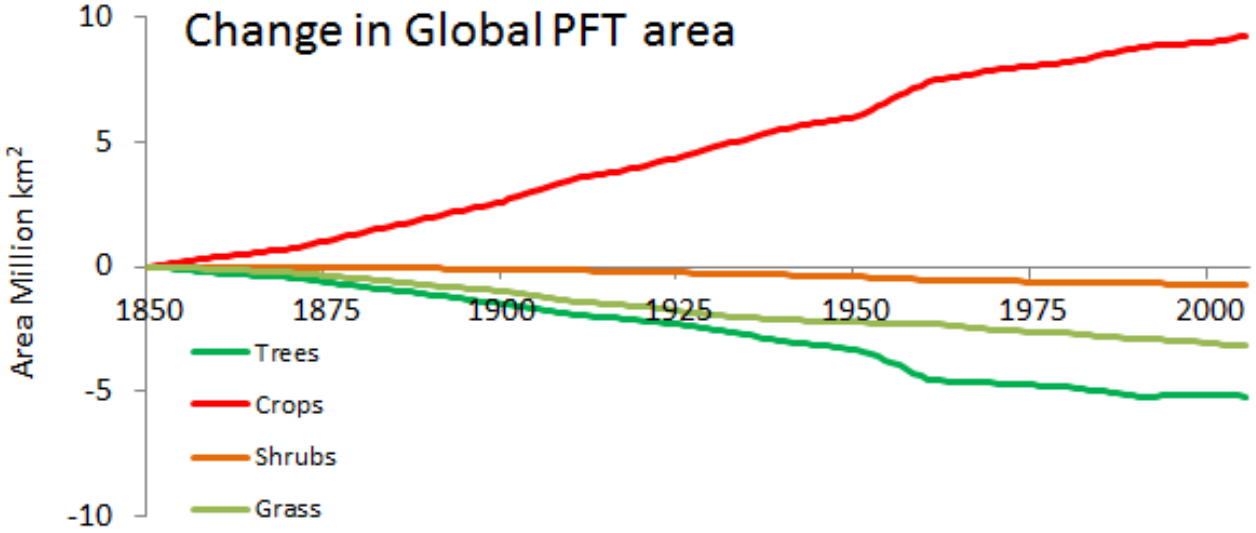


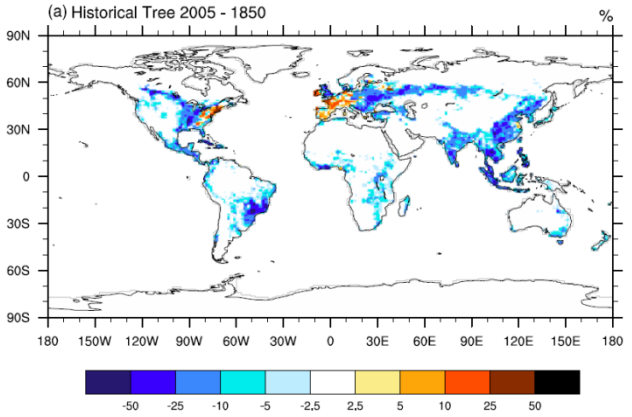


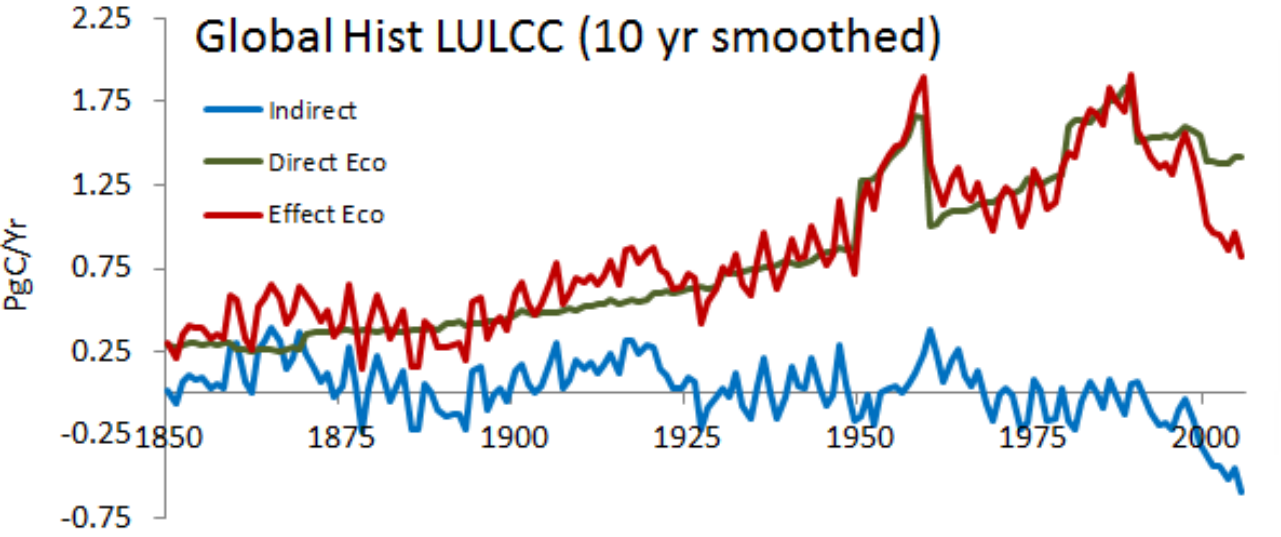
$LULCC_{INDIRECT} = \Delta NPP_{NOLUC-LU} - \Delta HR_{NOLUC-LU} - \Delta FIRE_{NOLUC-LU} = 3.6$ PgC (PgC = 10^{15})

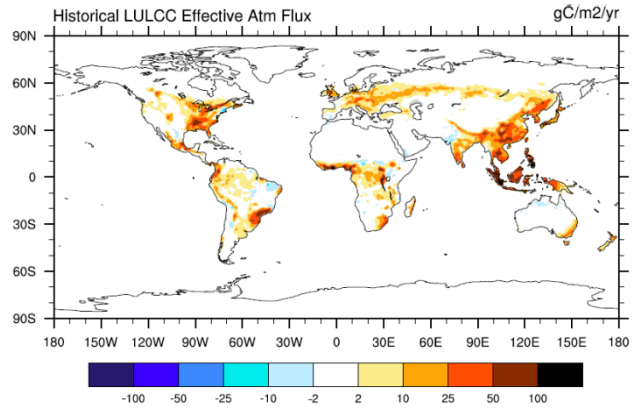
$\Delta NPP_{NOLUC-LU} = 71.6$ PgC $\Delta HR_{NOLUC-LU} = 43.1$ PgC $\Delta FIRE_{NOLUC-LU} = 24.9$ PgC

Historical Ecosystem Changes: Effective LULCC Flux





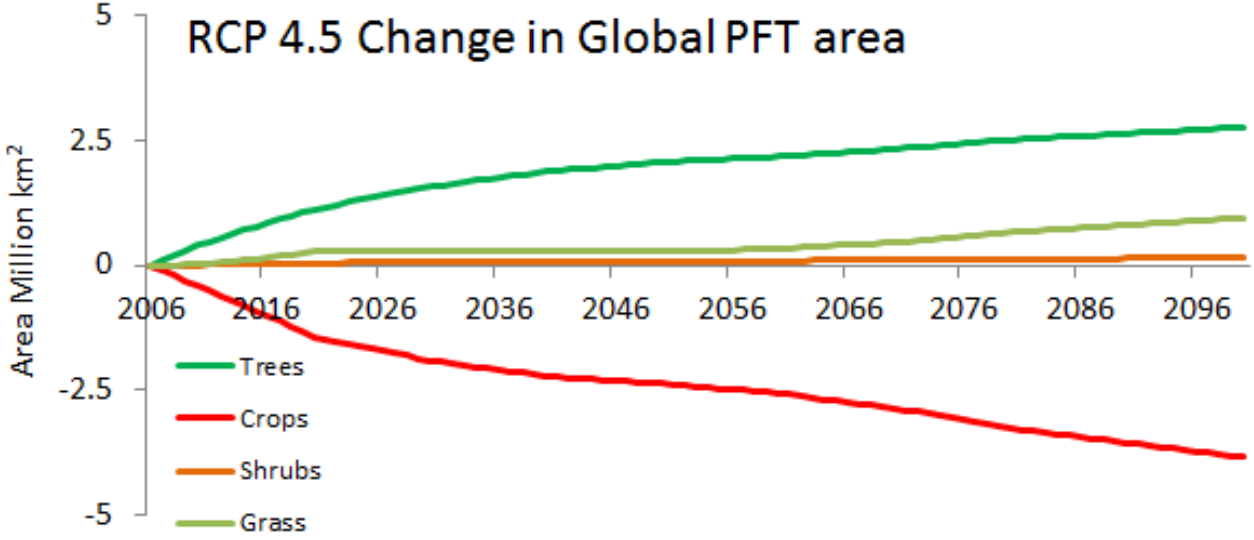


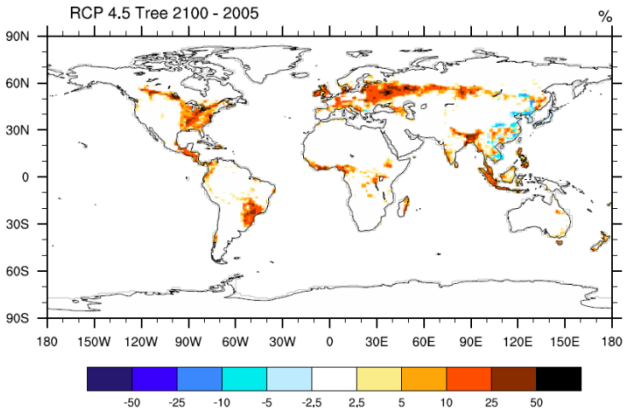


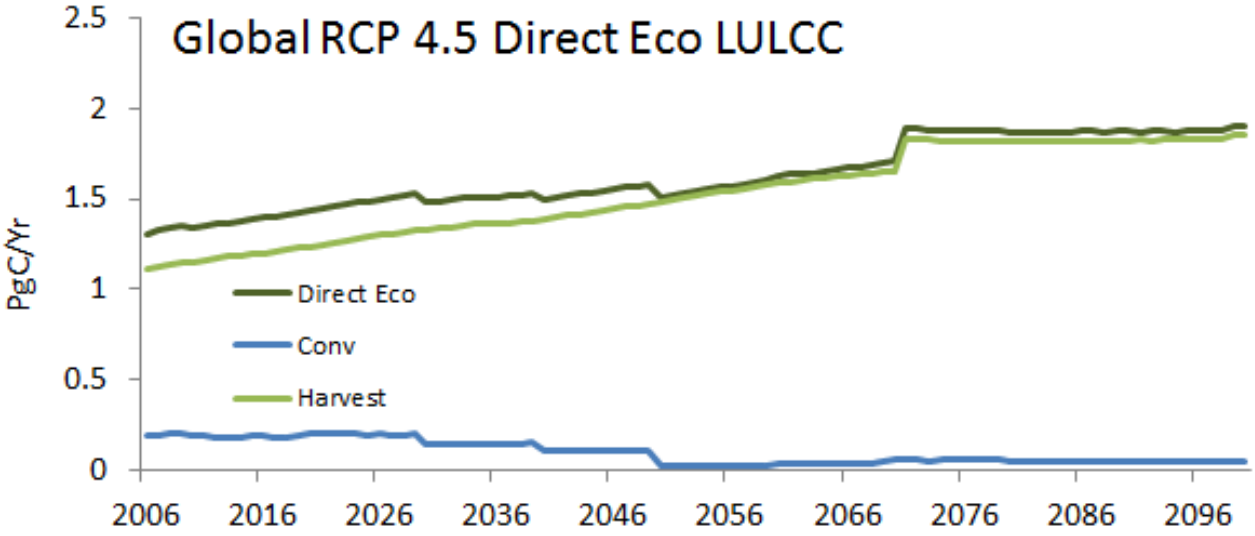
$LULCC_{EFFECTIVE\ ECO} = LULCC_{DIRECT\ ECO} + LULCC_{INDIRECT} = 130.4\ PgC$ $(PgC = 10^{15})$

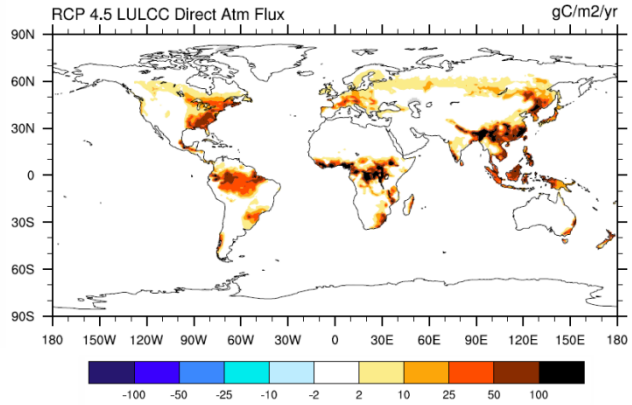
$LULCC_{DIRECT\ ECO} = 126.8\ PgC$ $LULCC_{INDIRECT} = 3.6\ PgC$

RCP 4.5 Ecosystem Changes: Direct LULCC Fluxes





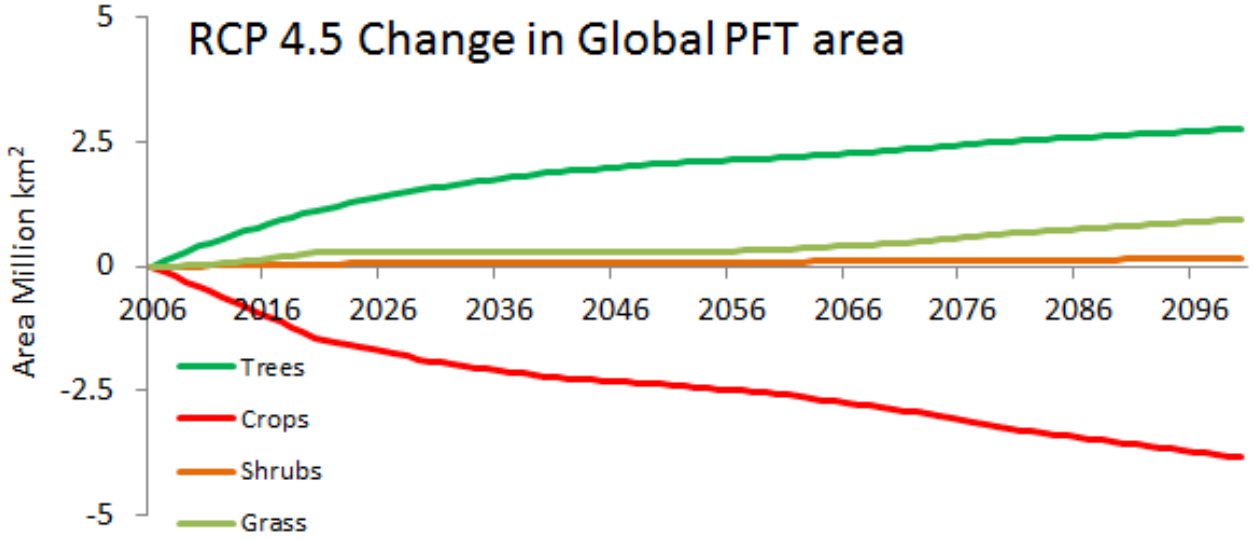


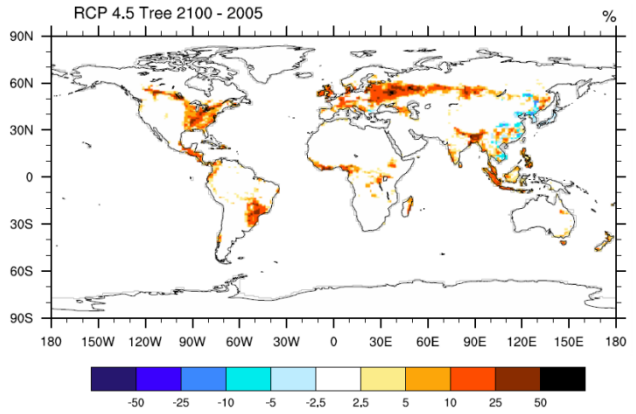


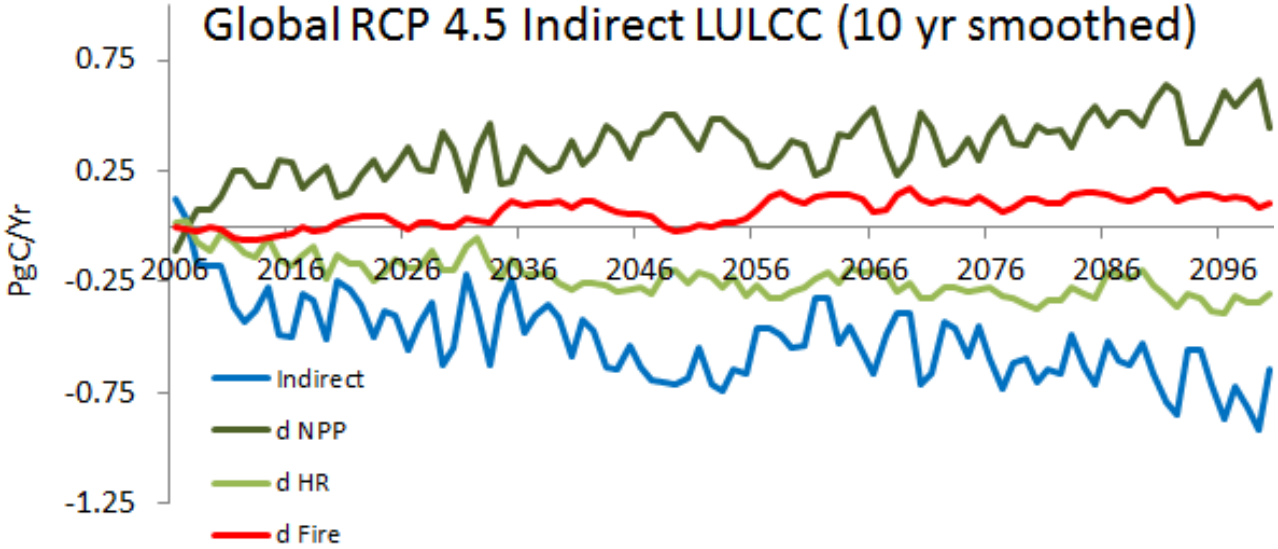
$LULCC_{DIRECT\ ECO}$ = Conversion + Wood Harvest = 152.6 PgC (PgC = 10^{15})

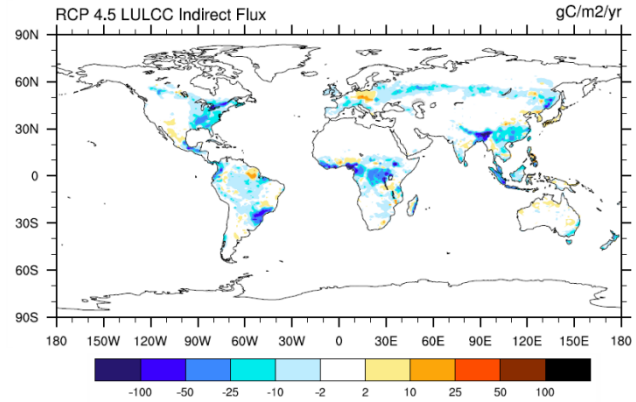
Conversion = 9.5 PgC Wood Harvest = 143.2 PgC

RCP 4.5 Ecosystem Changes: Indirect LULCC Fluxes





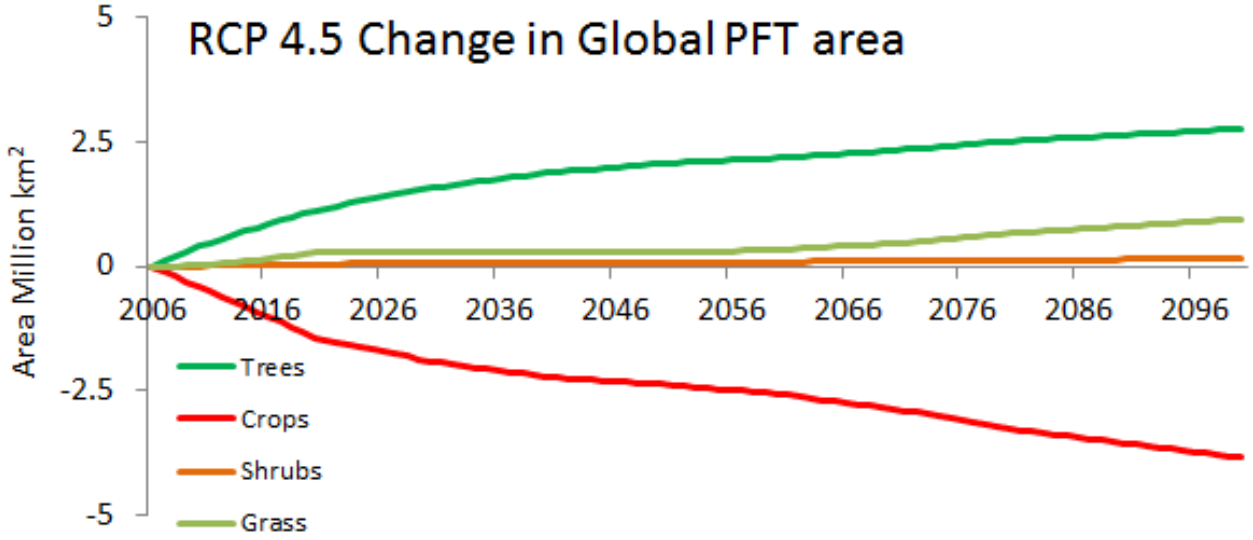


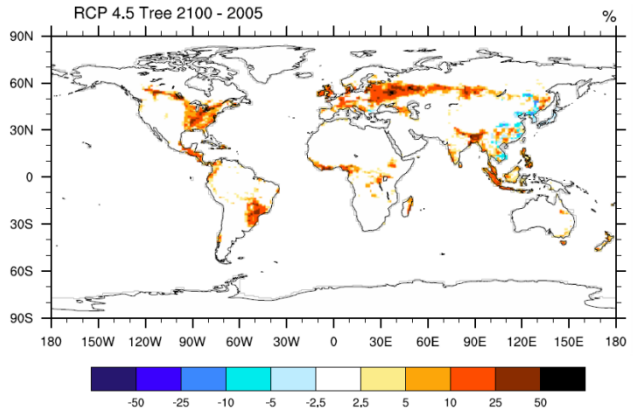


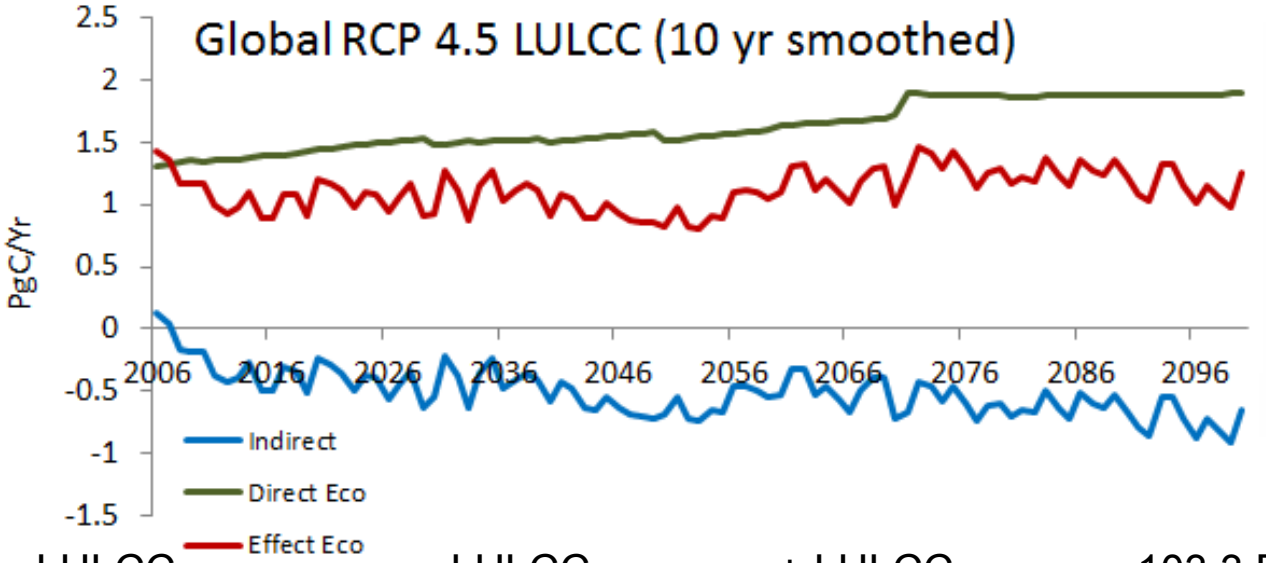
$LULCC_{INDIRECT} = \Delta NPP_{NOLUC-LU} - \Delta HR_{NOLUC-LU} - \Delta FIRE_{NOLUC-LU} = -49.3$ PgC (PgC = 10^{15})

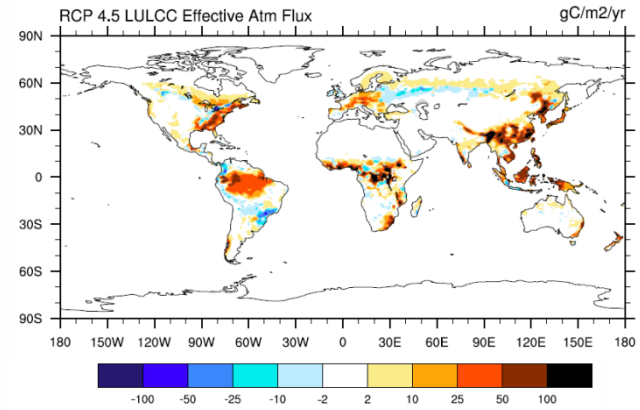
$\Delta NPP_{NOLUC-LU} = -33.9$ PgC $\Delta HR_{NOLUC-LU} = 22.2$ PgC $\Delta FIRE_{NOLUC-LU} = -6.7$ PgC

RCP 4.5 Ecosystem Changes: Effective LULCC Fluxes





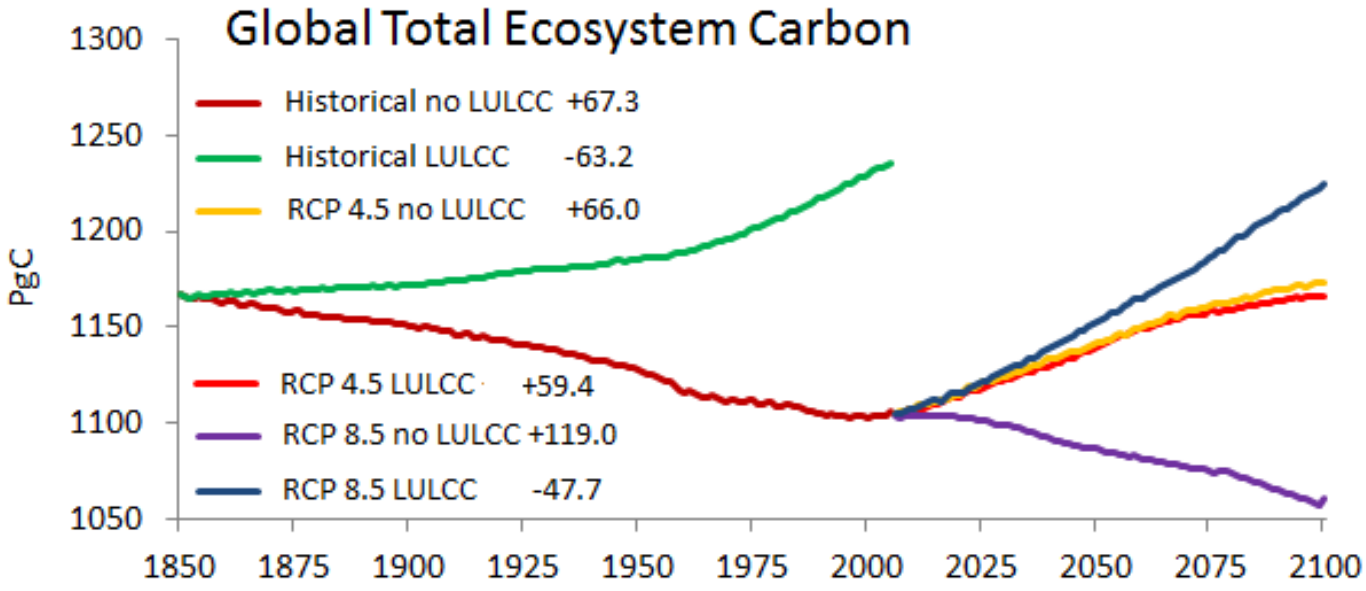




$LULCC_{EFFECTIVE\ ECO} = LULCC_{DIRECT\ ECO} + LULCC_{INDIRECT} = 103.3\ PgC$ (PgC = 10^{15})

$LULCC_{DIRECT\ ECO} = 152.6\ PgC$ $LULCC_{INDIRECT} = -49.3\ PgC$

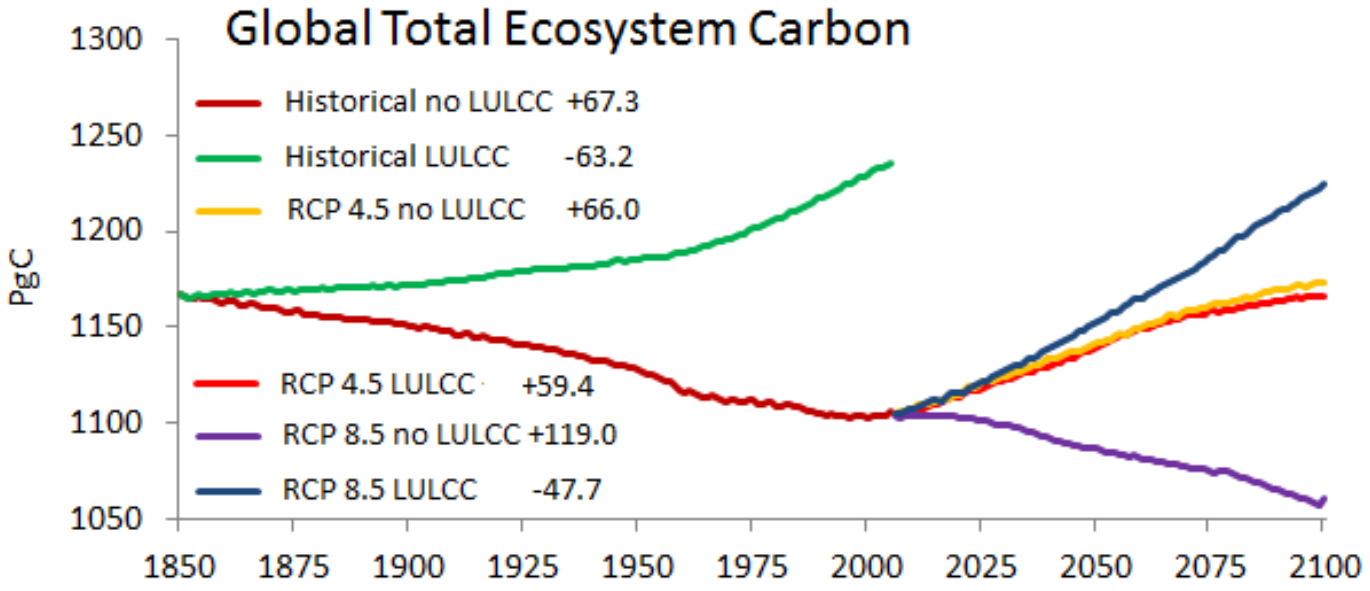
CMIP5 Cumulative LULCC Fluxes – Total Ecosystem Carbon

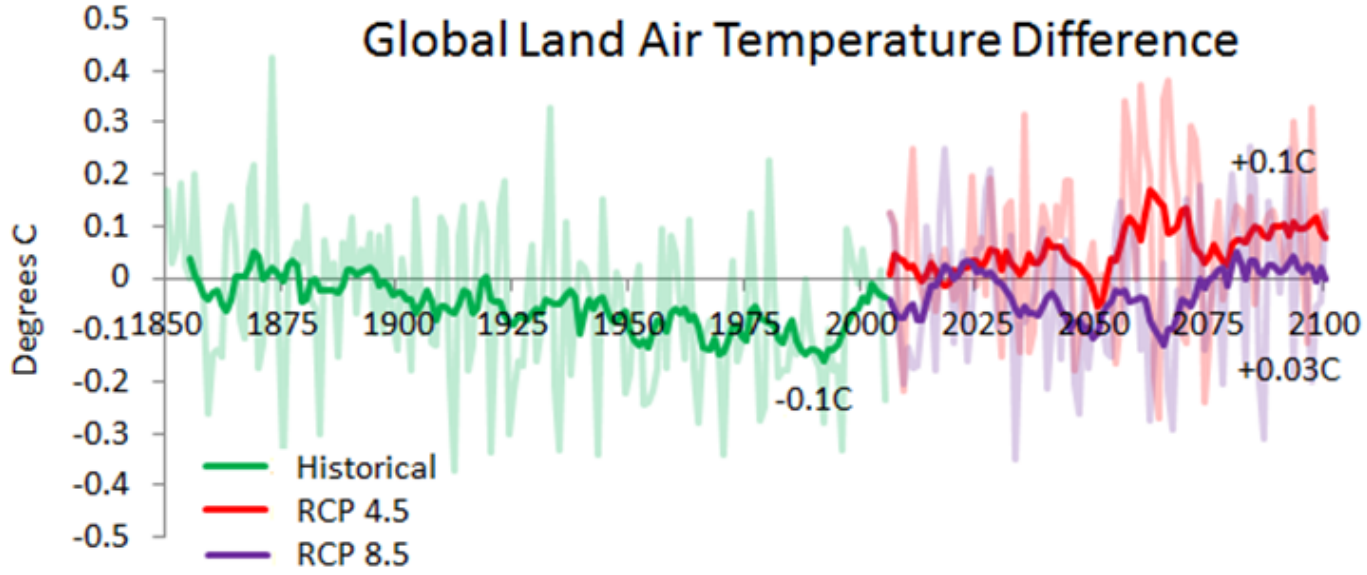


Ecosys Carbon	Eco Direct LULCC	Indirect LULCC	Eco Effective LULCC	CMIP5 Fossil Fuel Emissions
Historical	126.8 PgC	3.6 PgC	130.4 PgC	313.8 PgC
RCP 4.5	152.6 PgC	-49.3 PgC	103.3 PgC	791.5 PgC
RCP 8.5	271.6 PgC	-4.5 PgC	267.2 PgC	1925.0 PgC

*RCP no LULCC simulation have current day wood harvest rates

CMIP5 Cumulative LULCC Fluxes – Total Ecosystem Carbon





CLM5 CMIP6 – New Land Surface Data Sets

1. For CLM5 and the CMIP6 climate simulations there will be new Historical and SSP - RCP land use and land cover change data sets which are currently being compiled for through the Land Use and Scenario Model Intercomparison Projects (LUMIP and ScenarioMIP).

2. The new time series include new functionality following lessons learned through CMIP5 and to include new developments in CLM5.

3. 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
- Secondary Forest
- Crop C3 Annual
- Crop C3 Nitrogen Fixing
- Crop C4 Perennial
- Grazing Rangeland
- Primary Non Forest
- Secondary Non Forest
- Crop C3 Perennial
- Crop C4 Annual
- Grazing Pasture
- Urban

4. 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!

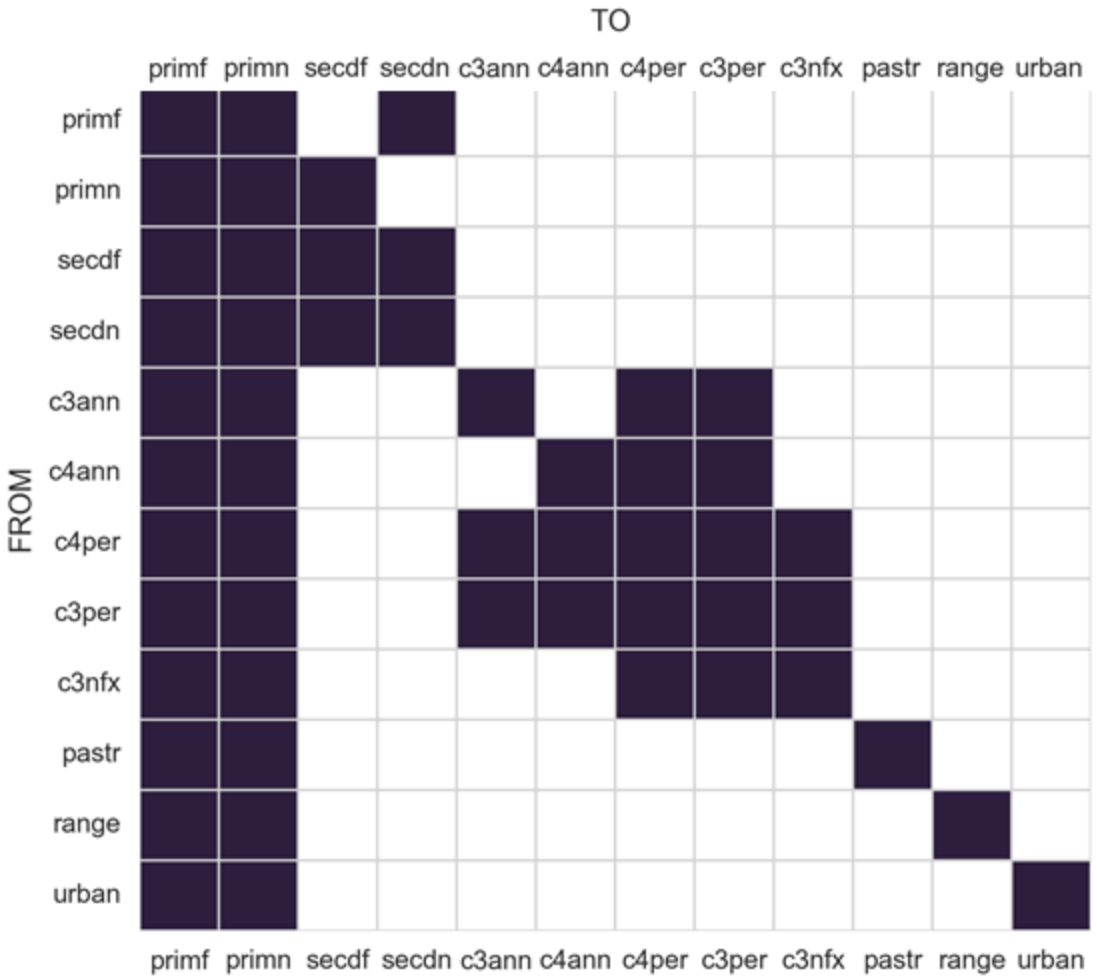
New Resolution
0.25° grid-cell fraction

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)

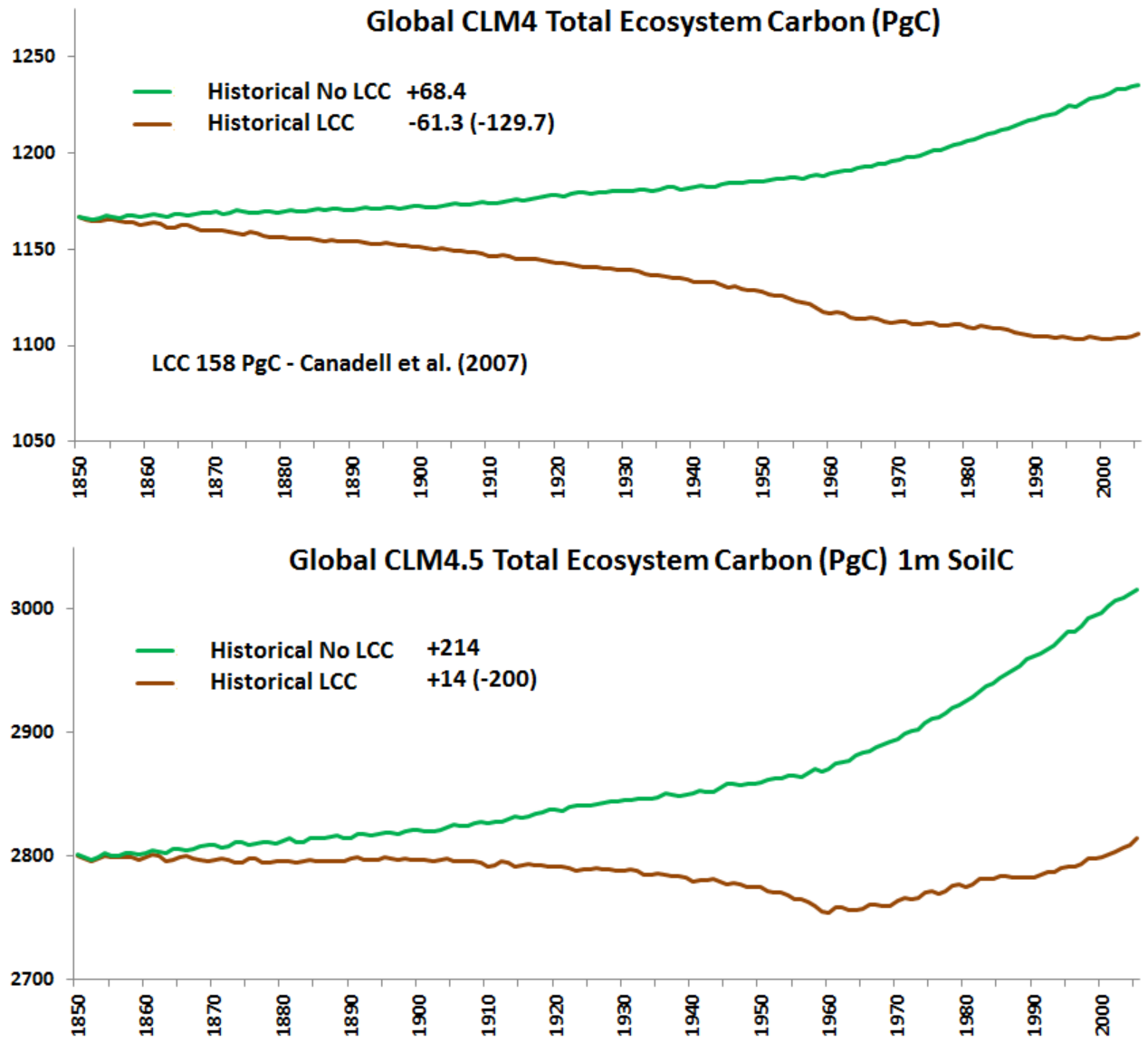
New Management Layers
Agriculture
Fraction of cropland irrigated
Fraction of cropland flooded
Fraction of cropland fertilized (industrial)
Industrial Fertilizer application rates
Fraction of cropland for biofuels
Crop rotations
Wood Harvest
Fraction used for industrial products
Fraction used for commercial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

New Future Scenarios
Six futures, SSP-based

New Transition Matrix



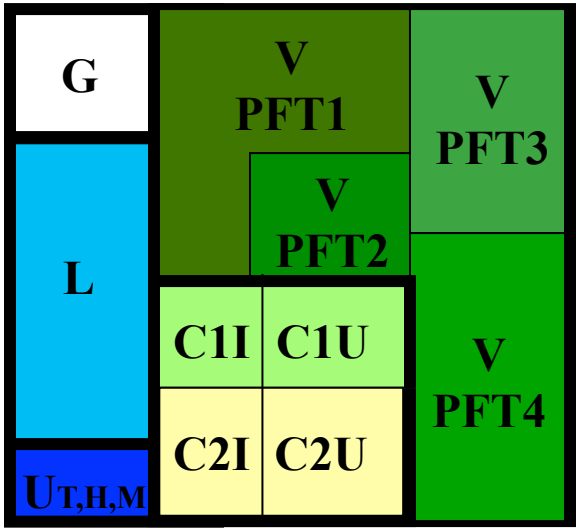
Ecosystem Changes in CLM4.5 – Land Cover Change



*Courtesy Dave Lawrence & Danica Lombardozzi

Gridcell

CLM 4.5 LULCC for Natural PFT and Crop



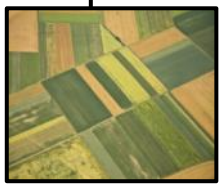
Landunit

Vegetated

Lake

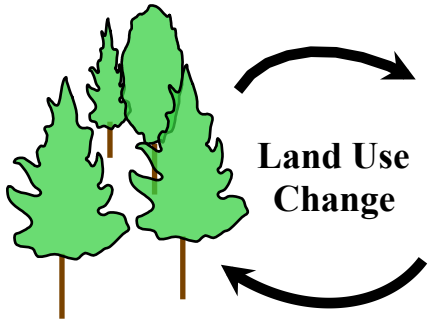
Urban

Glacier



Crop

Crop Model



Land Use Change

Planting

Leaf emergence

Irrig / Fertilize

Grain fill

Harvest

Unirrig

Irrig

Unirrig

Irrig

Crop1

Crop1

Crop2

Crop2 …

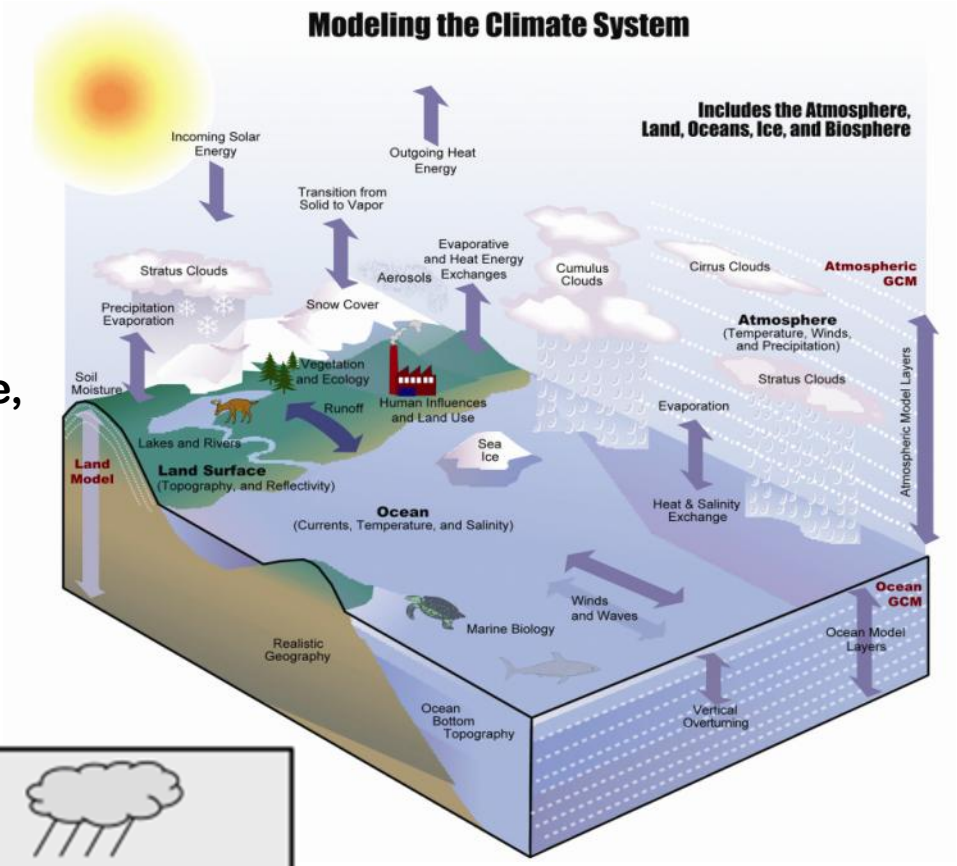
Understanding the Land Surface in the Climate System: Investigations with an Earth System Model (NCAR CESM)

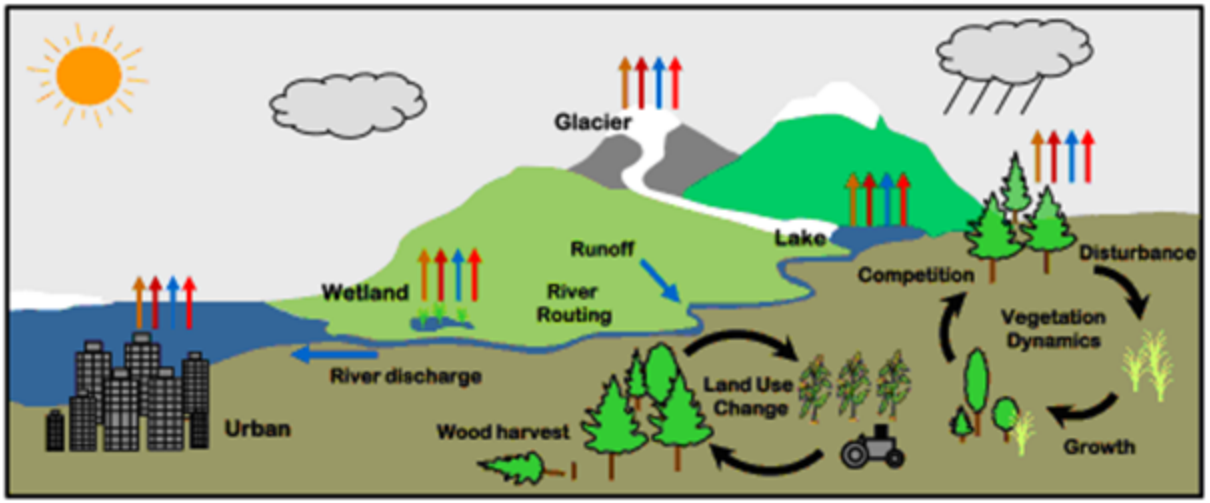
Land Management in CESM:

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

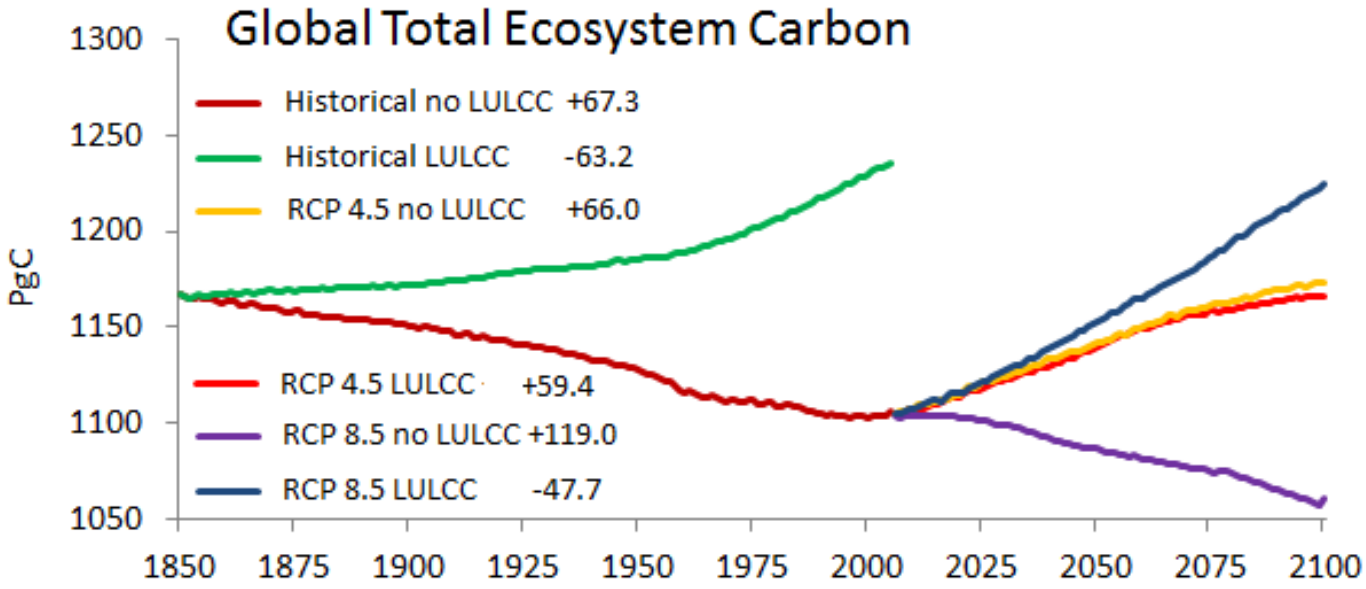
-How are we transforming Natural Ecosystems through Deforestation, Pasture, Wood Harvesting, or Afforestation?

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





CMIP5 Cumulative LULCC Fluxes – Total Ecosystem Carbon



Ecosys Carbon	Eco Direct LULCC	Indirect LULCC	Terrestrial Sink	NEE	Δ Eco C	Δ Prod
Historic NoLC	-	-	67.3 PgC	-67.3 PgC	67.3 PgC	-
LULCC	126.8 PgC	3.6 PgC	63.6 PgC	54.8 PgC	-63.2 PgC	8.4 PgC
RCP4.5 NoLC*	96.7 PgC	-	162.7 PgC	-66.5 PgC	66.0 PgC	0.5 PgC
LULCC	152.6 PgC	-49.3 PgC	212.0 PgC	-65.7 PgC	59.4 PgC	6.3 PgC
RCP8.5 NoLC*	100.4 PgC	-	219.4 PgC	-120.2 PgC	119.0 PgC	1.2 PgC
LULCC	271.6 PgC	-4.5 PgC	223.9 PgC	29.1 PgC	-47.7 PgC	18.6 PgC

*RCP no LULCC simulation have current day wood harvest rates