NCAR Earth System Laboratory NESL

Simulating Land Cover Change and the Terrestrial Carbon Cycle in CCSM 4.0 for CMIP5

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Terrestrial Science Section

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1. IPCC Assessment Report 5 – Land Cover Change

1. The next IPCC assessment report (AR5) modeling experiments are defined in the Coupled Model Inter-comparison Project phase 5 (CMIP5) protocol described in [*Taylor, et al.*, 2009]

2. Land cover change is included in the CMIP5 protocol for the 1850 – 2005 Historical period and for the 2006 – 2100 Representative Concentration Pathway (RCP) periods

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
   - Secondary Vegetation
   - Cropping
   - Pasture

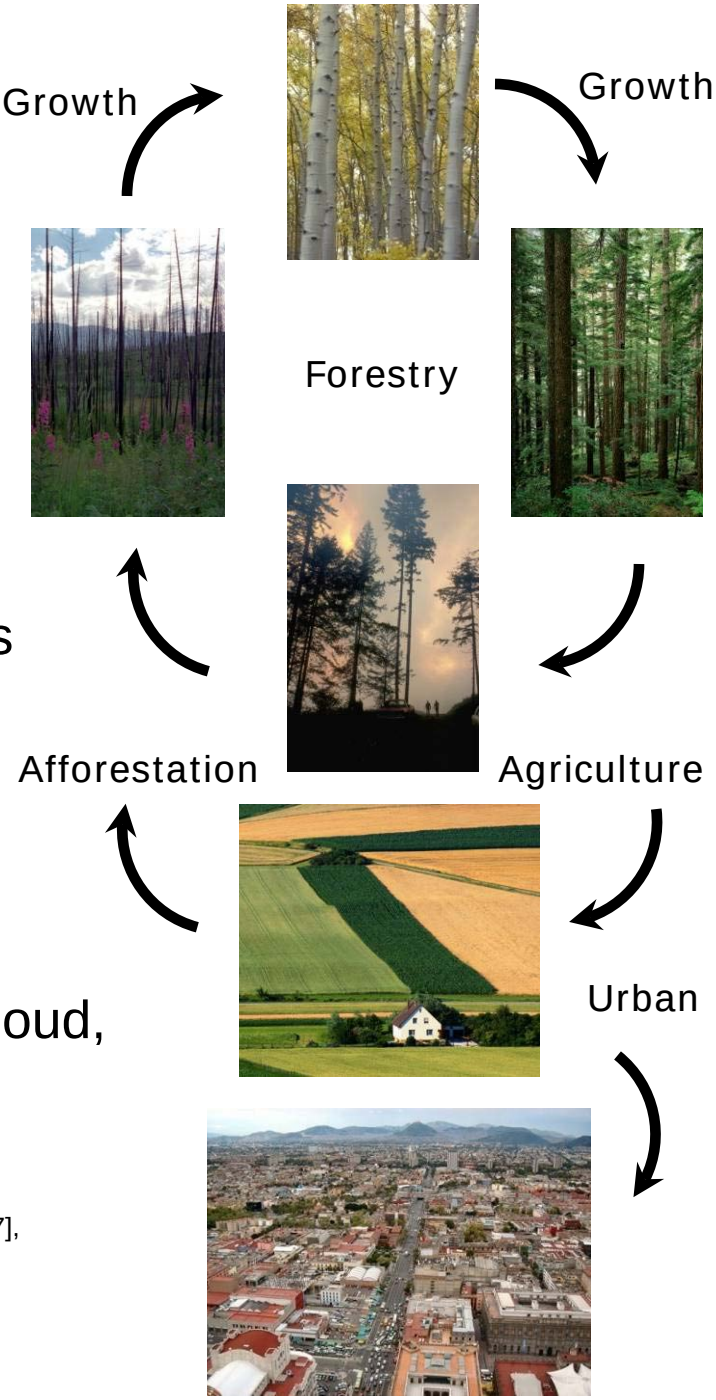
4. Harvesting of biomass is also prescribed for both primary and secondary vegetation land units

1. Human Land Cover Change

1. Direct Biogeophysical Impacts:
- Albedo – Radiation (Snow Interactions)
- Surface Hydrology (Irrigation)
- Surface Roughness

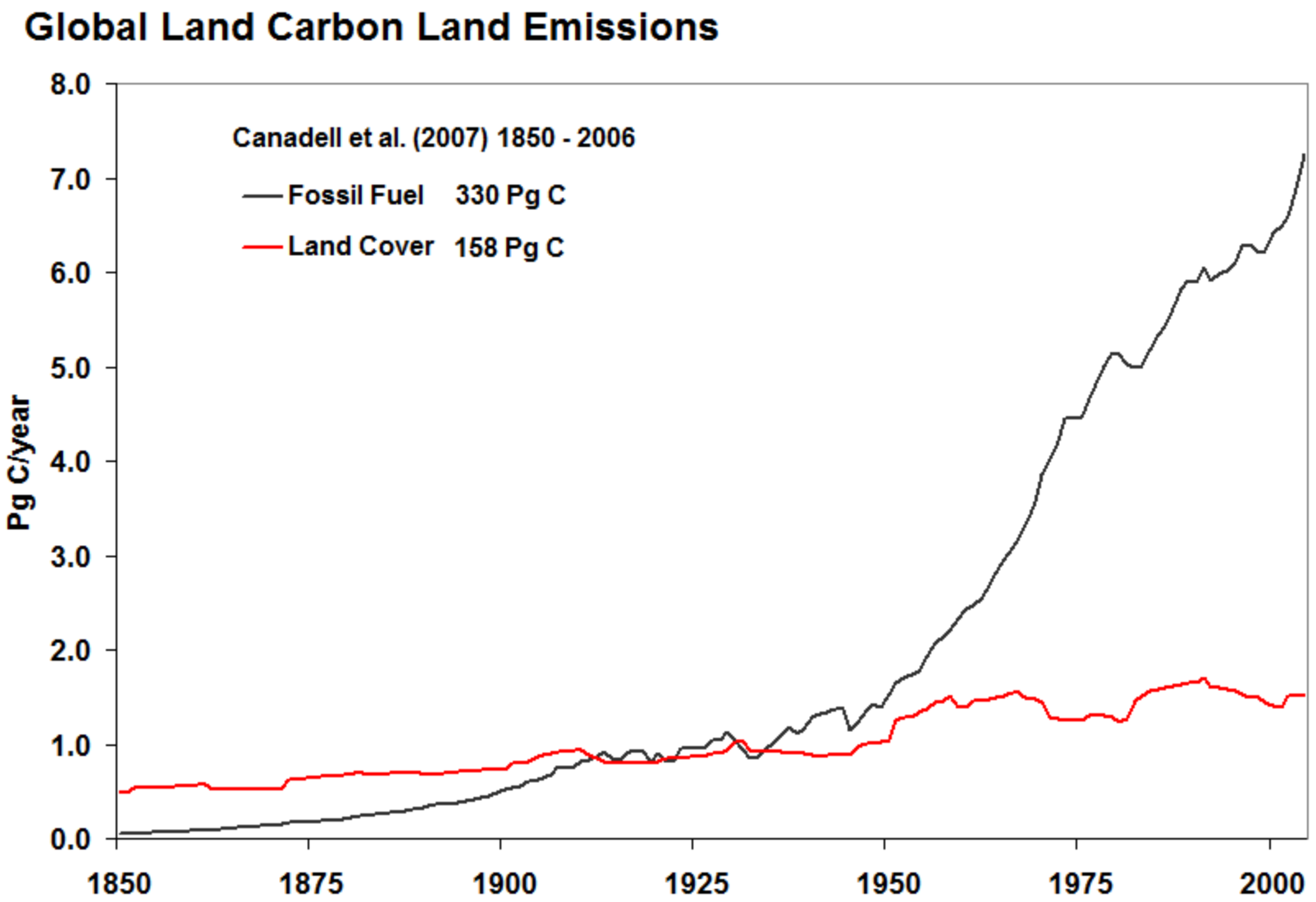
2. Direct Biogeochemical Impacts:
- Vegetation and Soil Carbon Fluxes from Conversion Natural -> Human systems
- Harvesting from Forestry and Agriculture

3. Indirect Impacts:
- Increased Photosynthesis through higher CO_2, Nitrogen, Phosphorus and Potassium
- Atmospheric Responses in Temperature, Cloud, Precipitation and Larger Scale Circulation
- Methane, Dust, Volatile Organics, Aerosols



Lawrence and Chase, [2010], *Feddema, et al.*, [2005], *Findell, et al.*, [2007], *IPCC*, [2007], *Bonan*, [2008], and *Canadell, et al.*, [2007]

1. Land Cover Change Contribution:

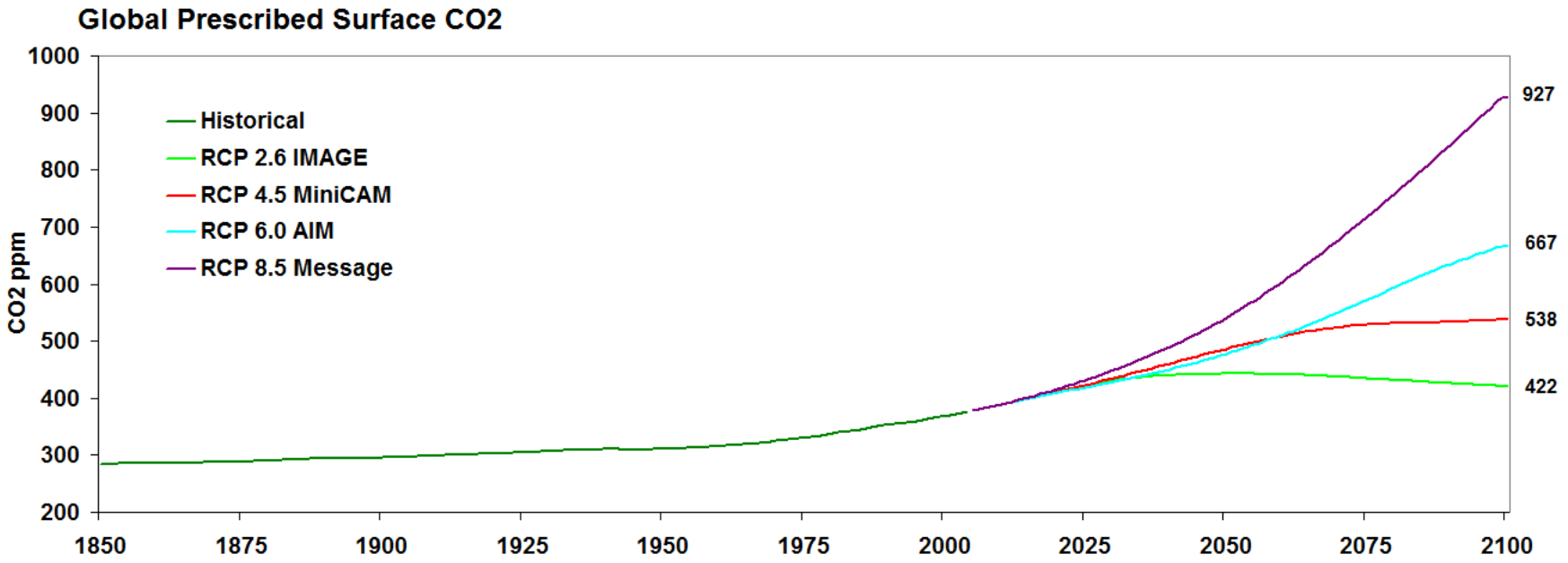


2. CMIP5 Historical and RCP Details

Development and management scenarios for the 21st Century Representative Concentration Pathways are:

Time Series	Source	Description and Reference
Historical	Global Land Model ,UNH	Historical reconstruction from the HYDE 3.0 database combined with historical national estimates [*Hurtt, et al.*, 2006]
RCP 2.6	IMAGE, Netherlands	Low greenhouse scenario reaching 3.1 W/m2 mid-century, returning to 2.6 W/m2 by 2100. [*van Vuuren, et al.*, 2007]
RCP 4.5	MiniCAM, PNNL	Stabilization scenario reaching 4.5 W/m2 before 2100 with land cover change a major part of stabilization [*Wise, et al.*, 2009]
RCP 6.0	AIM, NIES, Japan	Stabilization scenario reaching 6.0 W/m2 before 2100 with land cover change a major part of stabilization [*Fujino, et al.*, 2006]
RCP 8.5	MESSAGE, IIASA, Austria	Increasing greenhouse scenario leading to 8.5 W/m2 at 2100. Underlying scenario drivers are based on the IPCC A2 scenario. [*Riahi, et al.*, 2007]

2. CMIP5 Historical and RCP Prescribed CO2



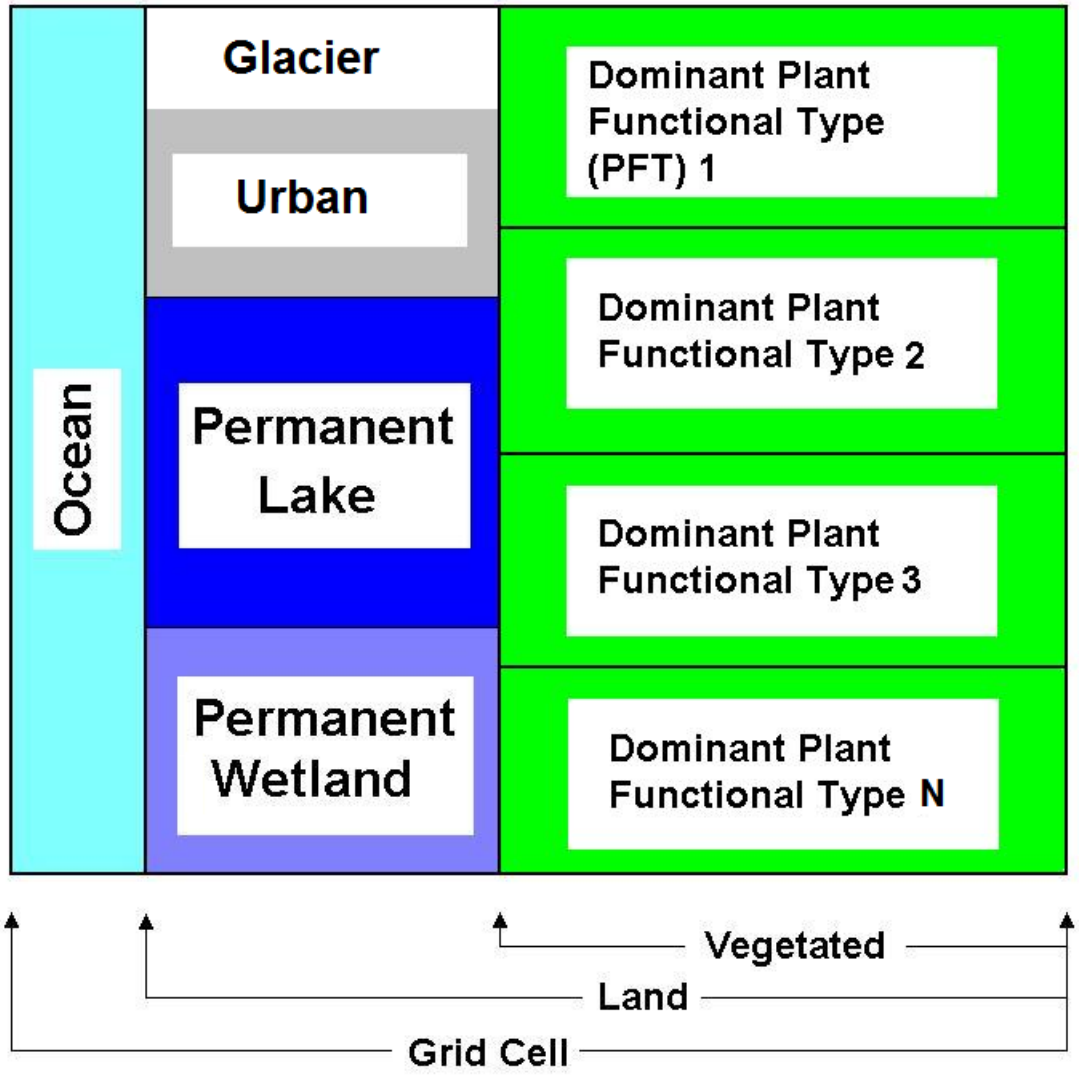
2. CMIP5 Historical and RCP Land Cover Change

CMIP5 Total Area of Land Cover Change for Historical and RCP Time Series (10^6 km^2).

RCP Land Unit Vegetation Impact Scale: Best – 2nd Best – 2nd Worst – Worst

Time Series	Primary	Secondary	Crop	Pasture
Historical 1850-2005	-48.98	13.71	9.81	25.47
RCP 2.6 Image	-15.27	10.66	5.29	-0.67
RCP 4.5 MiniCAM	-12.05	20.71	-4.15	-4.52
RCP 6.0 AIM	-11.88	23.61	3.70	-15.42
RCP 8.5 Message	-19.01	12.79	2.77	3.44

3. Representing Land Cover in CLM: Plant Functional Types



Tree:

Needleleaf Evergreen Temperate
Needleleaf Evergreen Boreal
Needleleaf Deciduous Boreal
Broadleaf Evergreen Tropical
Broadleaf Evergreen Temperate
Broadleaf Deciduous Tropical
Broadleaf Deciduous Temperate
Broadleaf Deciduous Boreal

Herbaceous / Understorey:

Evergreen Shrub
Deciduous Temperate Shrub
Deciduous Boreal Shrub
C3 Arctic Grass
C3 non-Arctic Grass
C4 Grass
Crop

Bare

3. CMIP5 Transient Land Cover in CLM 4 PFTs Method

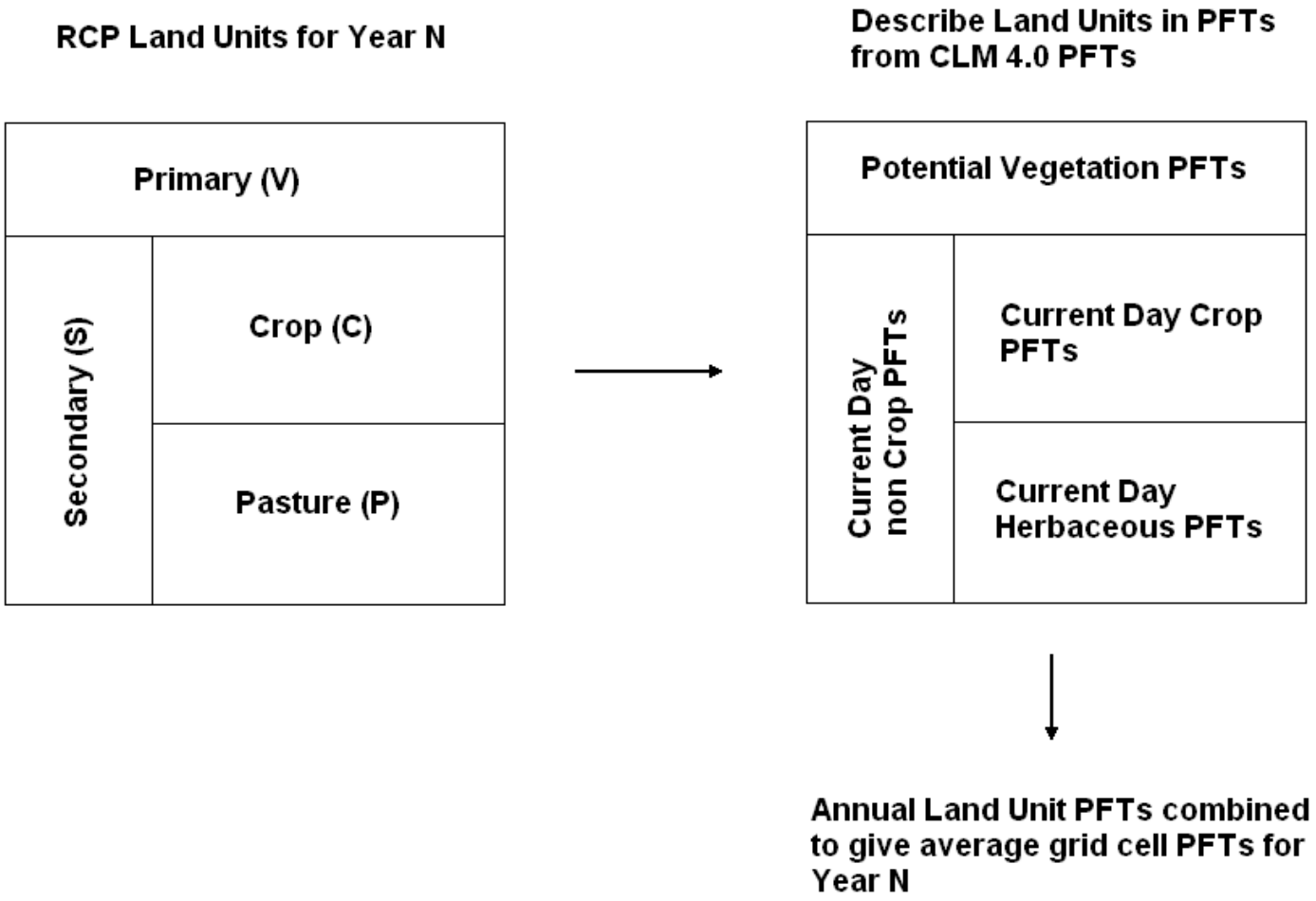
1. Firstly Crop PFT composition is directly specified from the Crop land unit fractional area.

2. Secondly Pasture PFTs are assigned based on grass PFTs found in the potential vegetation and current day CLM4 land surface parameters scaled by the area of the Pasture land unit.

3. Thirdly Primary PFTs are assigned from potential vegetation PFTs scaled by the fractional area of the Primary land unit.

4. Finally Secondary PFTs are assigned from current day non-crop and non-pasture PFTs scaled by the fractional area of the Secondary land unit.

3. CMIP5 Transient Land Cover in CLM 4 PFTs



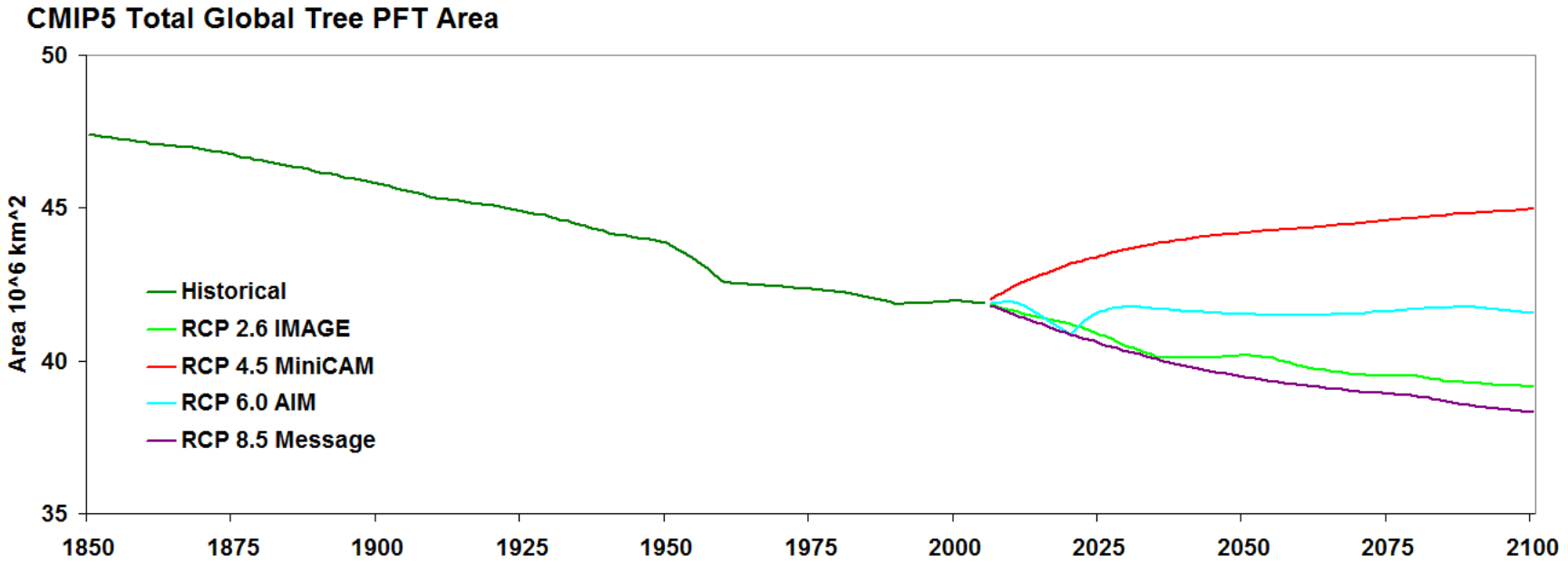
3. CMIP5 Historical and RCP Land Cover Change PFTs

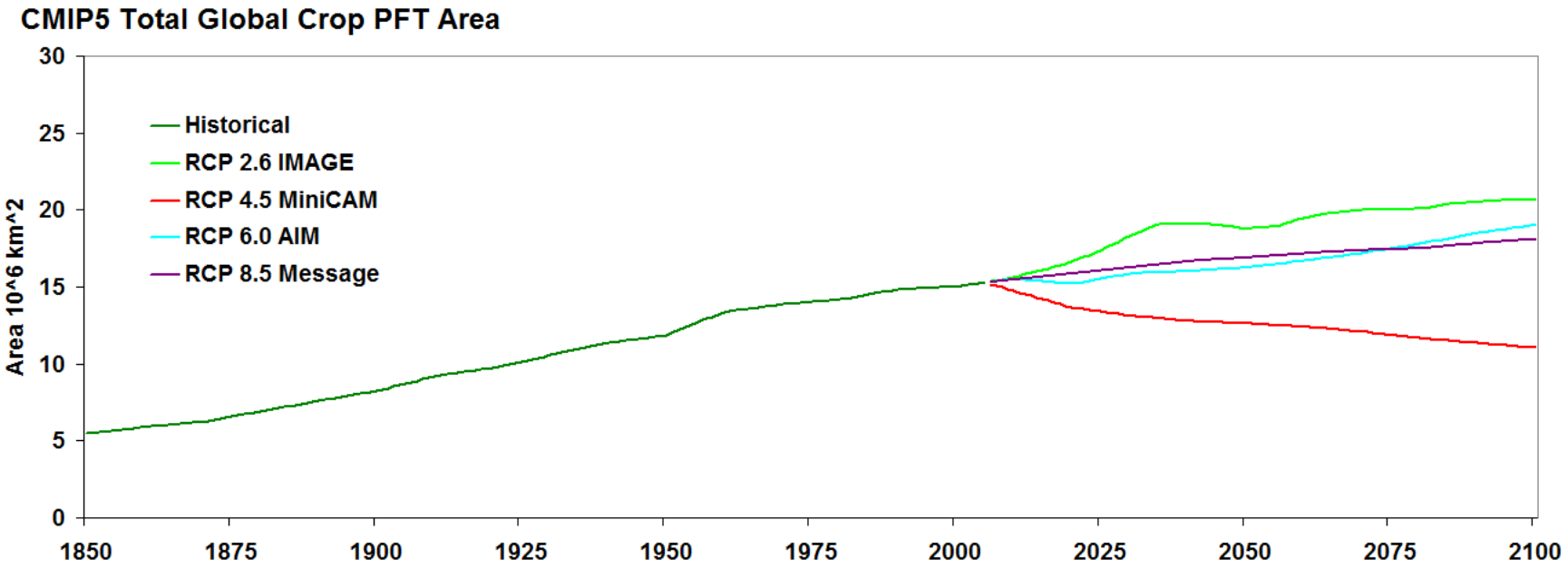
CMIP5 Total Area of Land Cover Change for Historical and RCP Time Series (10^6 km^2).

RCP PFT Vegetation Impact Scale: Best – 2nd Best – 2nd Worst – Worst

Time Series	Tree PFTs	Shrub PFTs	Crop PFTs	Grass PFTs
Historical 1850-2005	**-5.53**	**-0.97**	**9.81**	**-3.25**
RCP 2.6 Image	**-2.68**	**-0.41**	**5.29**	**-2.10**
RCP 4.5 MiniCAM	**2.96**	**0.19**	**-4.15**	**0.99**
RCP 6.0 AIM	**-0.33**	**-0.31**	**3.70**	**-2.95**
RCP 8.5 Message	**-3.51**	**-0.10**	**2.77**	**0.85**

3. CMIP5 Transient Land Cover in CLM 4 PFTs





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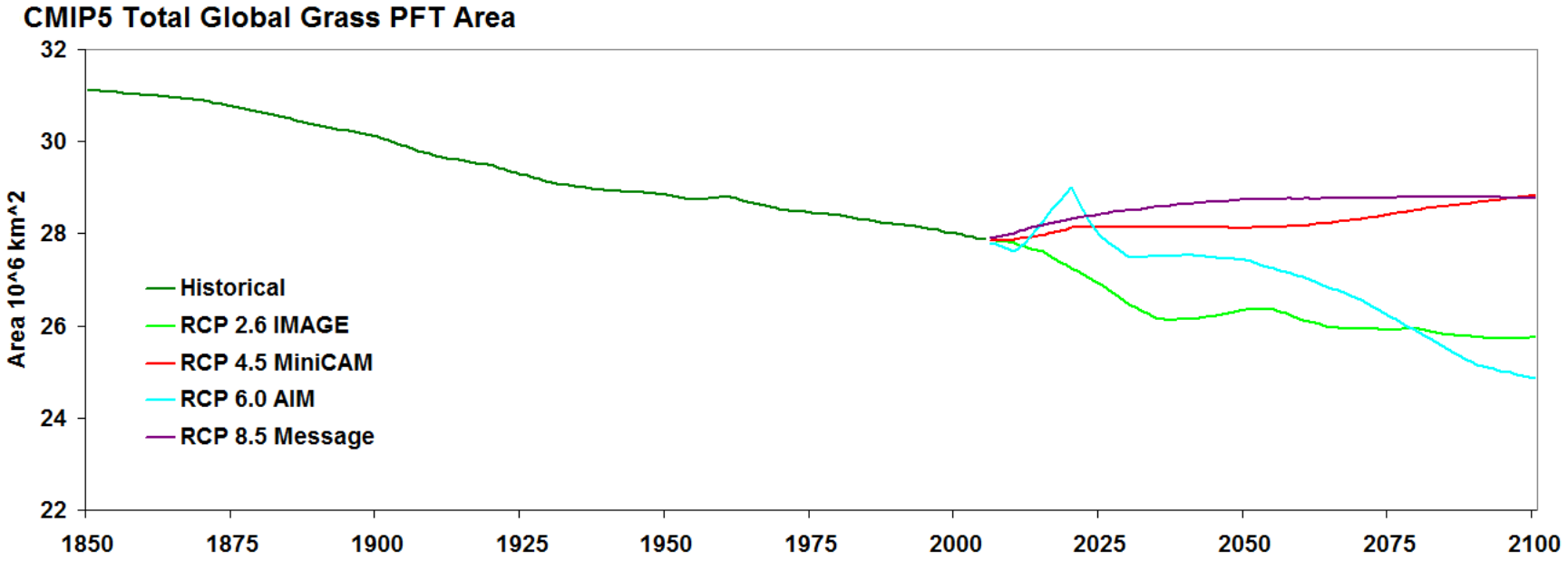
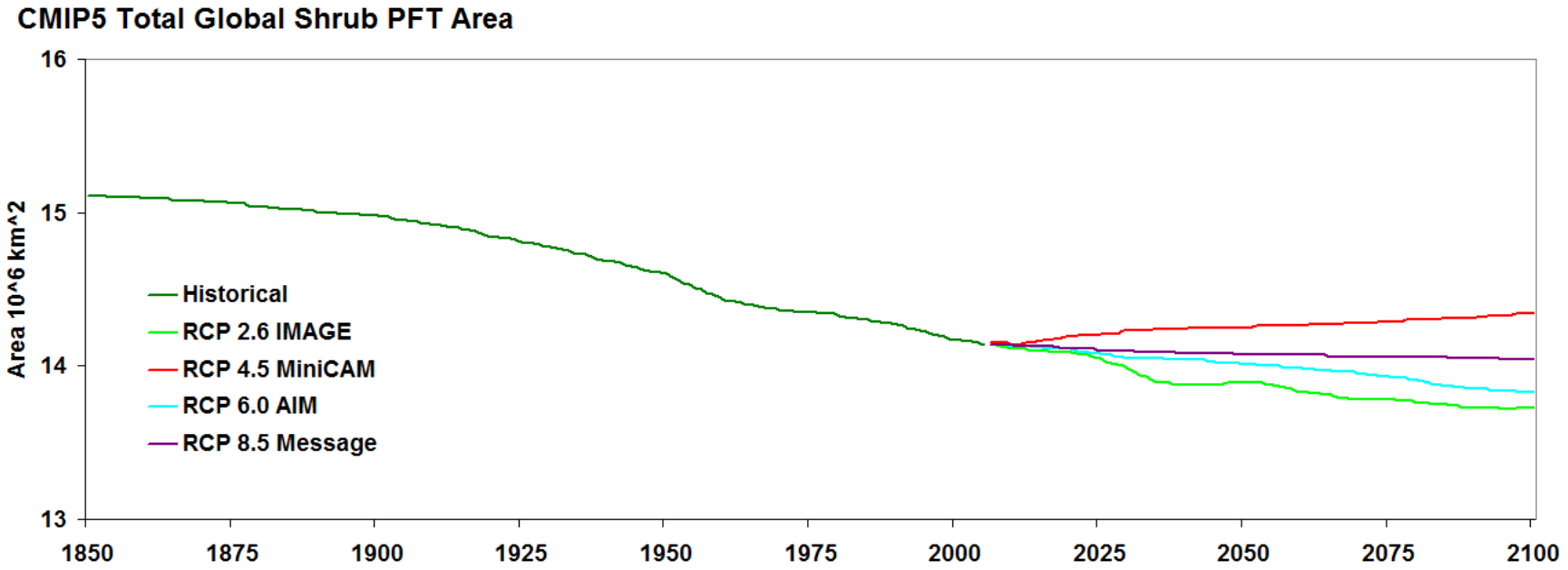
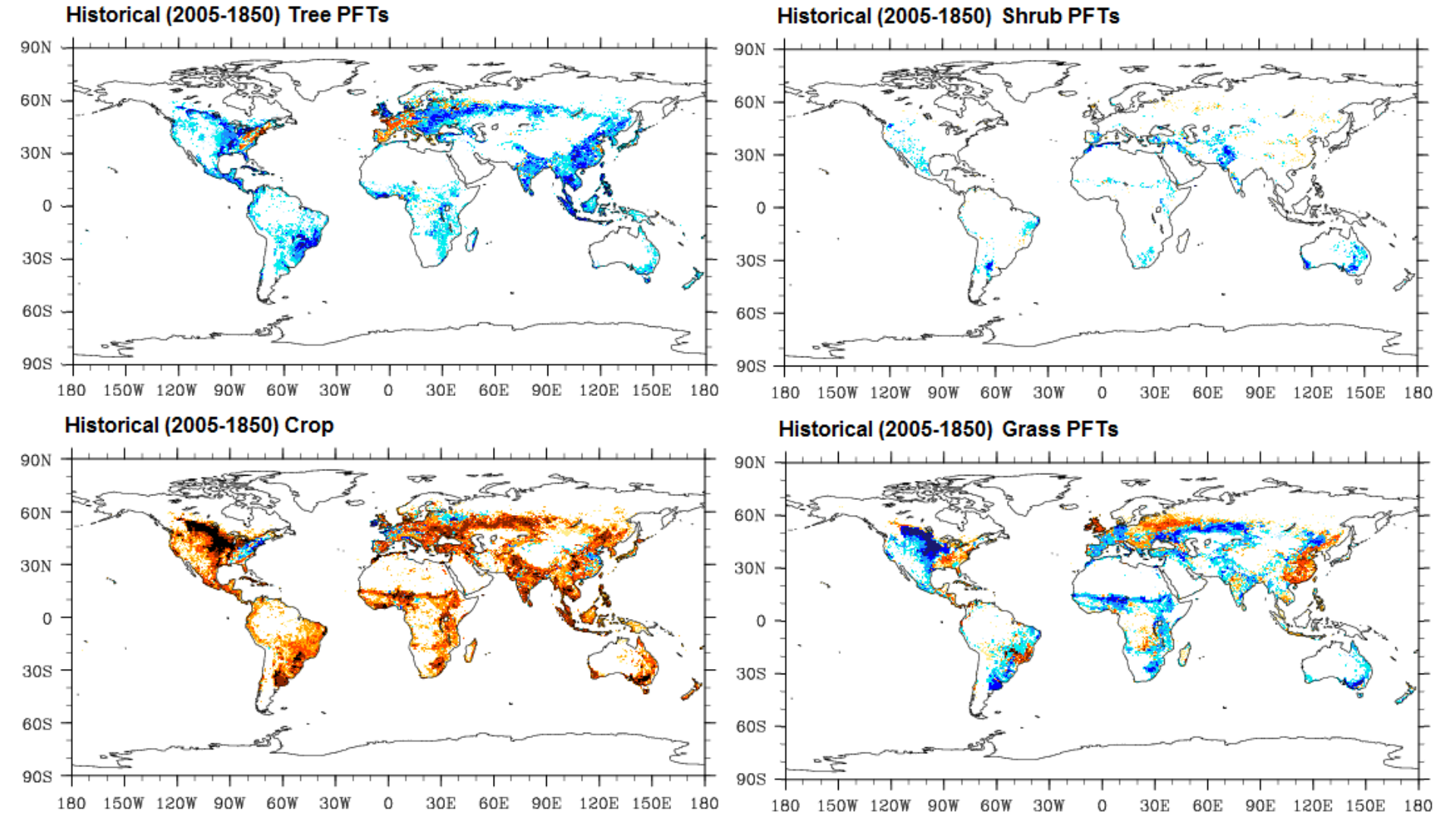
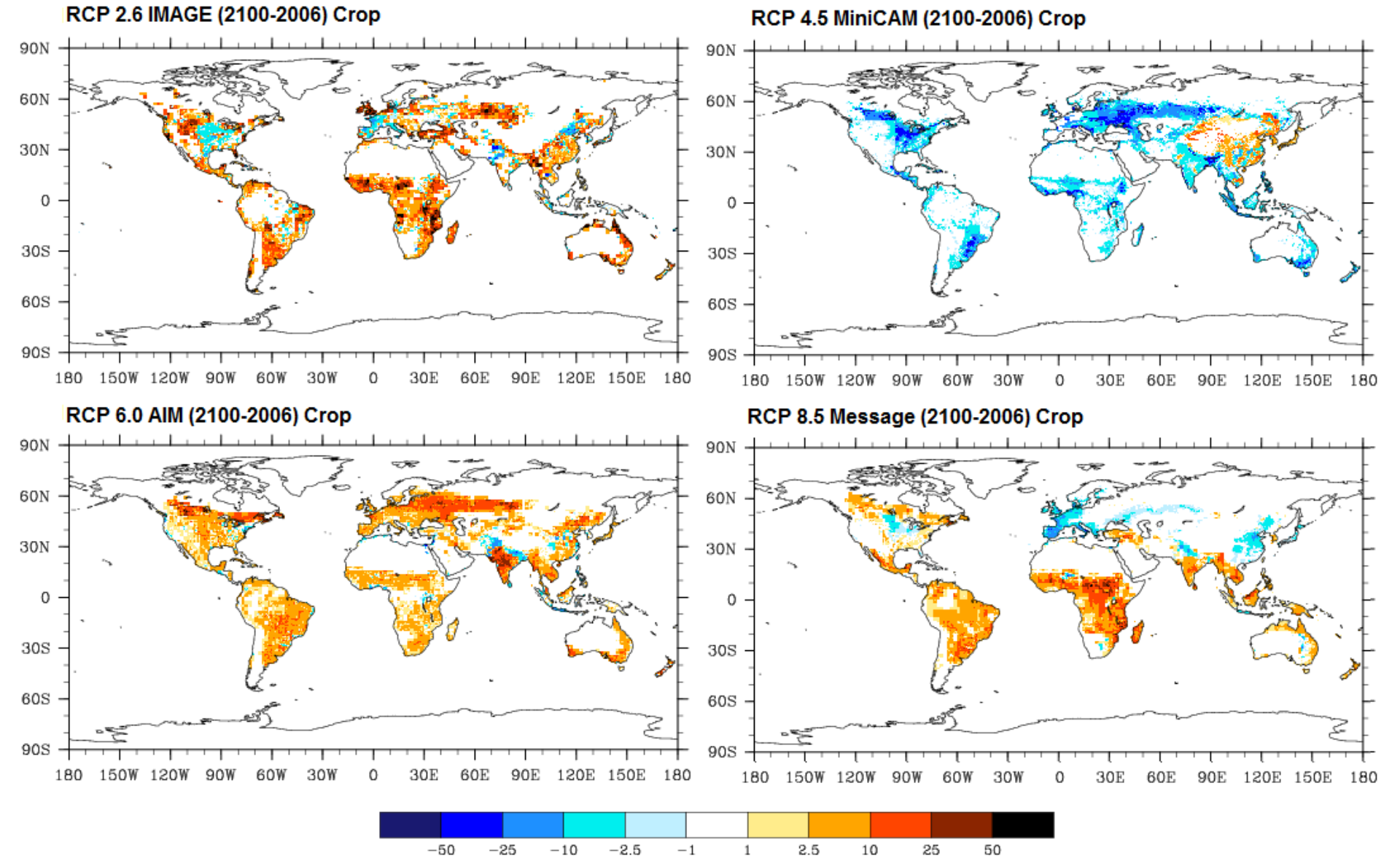




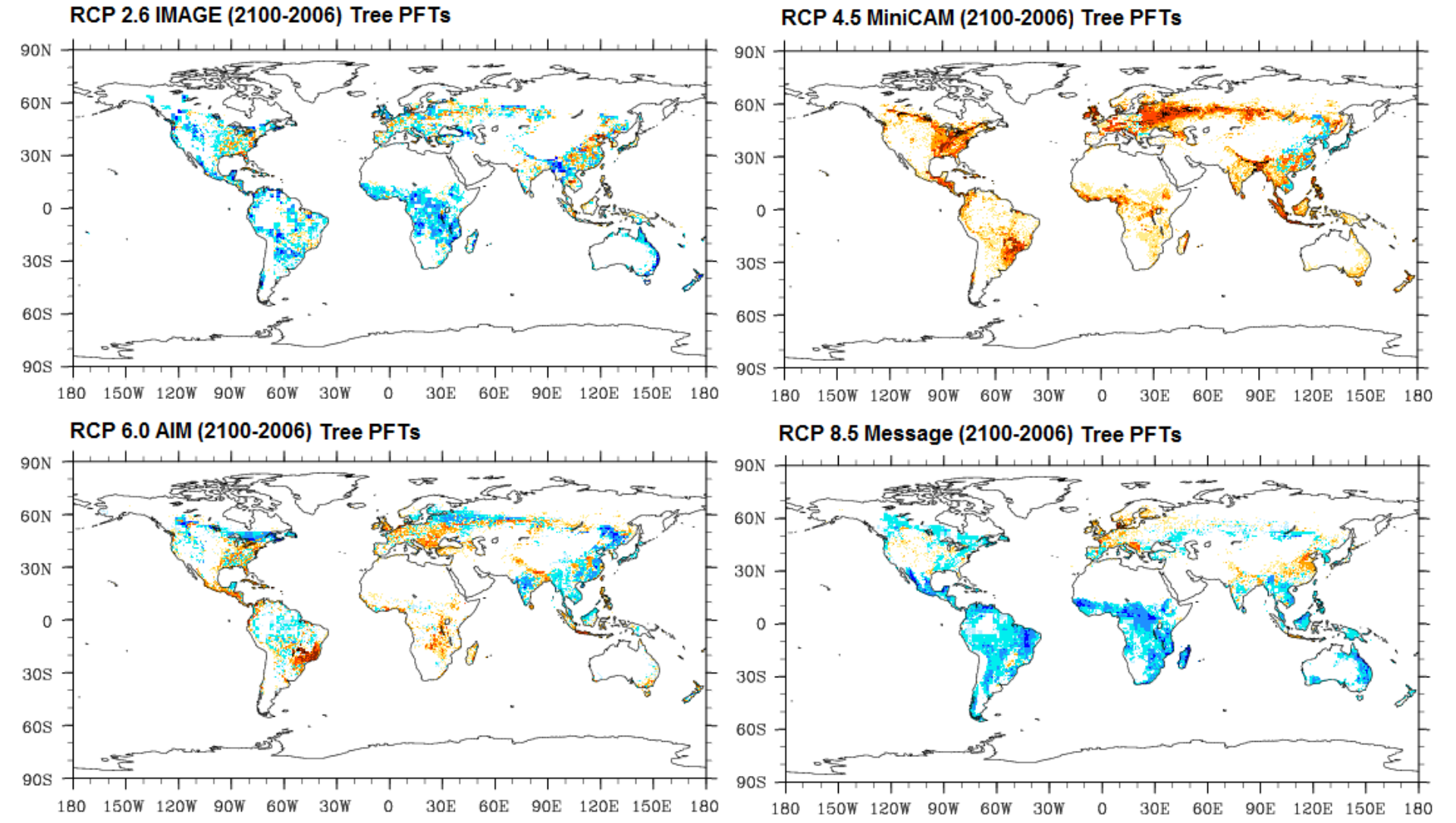
4. CMIP5 - Historical Land Cover Change – PFTs %area



3. CMIP5 - RCP Land Cover Change PFTs – Crop %area



3. CMIP5 - RCP Land Cover Change PFTs – Trees %area



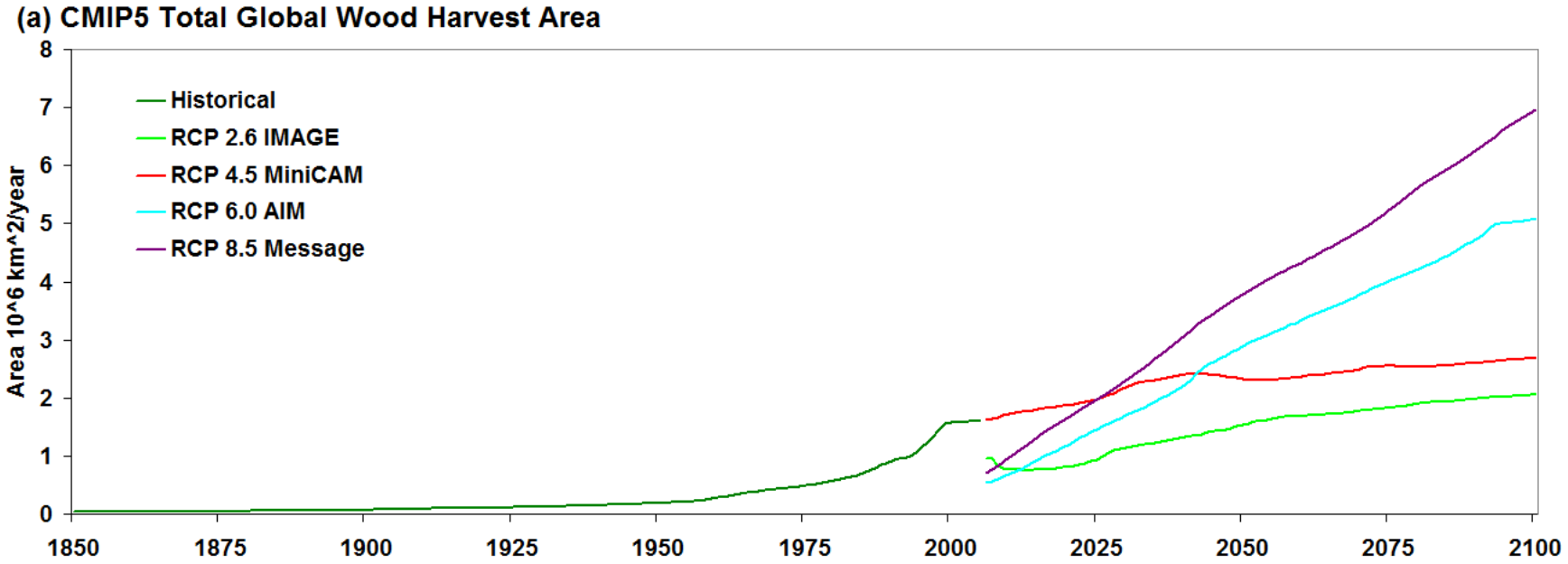
4. CMIP5 Primary and Secondary Wood Harvest

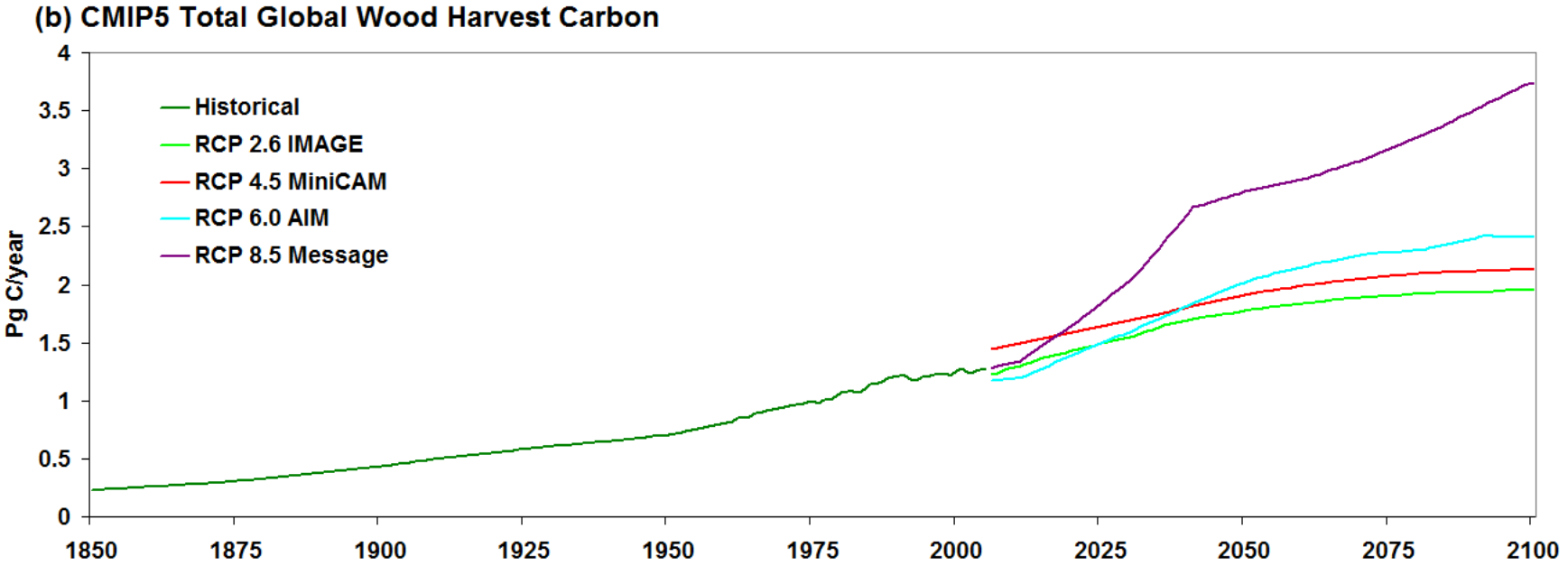
1. Primary and Secondary wood harvest are prescribed on the same 0.5 degree grid as the land use class transitions for each year.

2. For consistency with the land use transitions the area of land harvested is specified for each grid cell for each year

3. To ensure consistency with the wood products specified in the Integrated Assessment Models the amount of carbon harvested is also specified for each grid cell for each year.

4. CMIP5 Historical and RCP Total Wood Harvest





4. CMIP5 Primary and Secondary Wood Harvest

1. As the different land units have different standing amount of wood carbon and different harvest intensities, the harvest area and carbon amounts are both broken down into for the five classes of:

   - Primary Forest

   - Primary Non-Forest

   - Secondary Mature Forest

   - Secondary Young Forest

   - Secondary Non-Forest

4. CMIP5 Primary and Secondary Wood Harvest – Area

CMIP5 Total Area of Wood Harvest for Historical and RCP Time Series (10^6 km^2).

RCP PFT Vegetation Impact Scale: Best – 2nd Best – 2nd Worst – Worst

Time Series	Primary Forest	Primary Non Forest	Secondary Mat Forest	Secondary Yng Forest	Secondary Non Forest	All Harvest
Historical 1850-2005	7.85	7.74	1.05	9.81	20.99	47.44
RCP 2.6 Image	7.64	3.23	2.09	60.90	66.79	140.65
RCP 4.5 MiniCAM	9.14	2.20	2.88	66.99	137.66	218.87
RCP 6.0 AIM	4.00	3.92	162.13	15.48	90.15	275.68
RCP 8.5 Message	6.81	7.24	120.68	4.57	226.97	366.27

4. CMIP5 Primary and Secondary Wood Harvest – Carbon

CMIP5 Total Carbon of Wood Harvest for Historical and RCP Time Series (PgC).

RCP PFT Vegetation Impact Scale: Best – 2nd Best – 2nd Worst – Worst

Time Series	Primary Forest	Primary Non Forest	Secondary Mat Forest	Secondary Yng Forest	Secondary Non Forest	All Harvest
Historical 1850-2005	71.21	1.63	9.71	16.00	2.98	101.53
RCP 2.6 Image	65.99	2.16	18.36	59.08	18.99	164.59
RCP 4.5 MiniCAM	75.20	0.78	25.29	63.63	14.70	179.61
RCP 6.0 AIM	41.13	3.86	100.97	6.32	32.90	185.18
RCP 8.5 Message	60.18	7.10	116.78	5.10	63.80	252.96

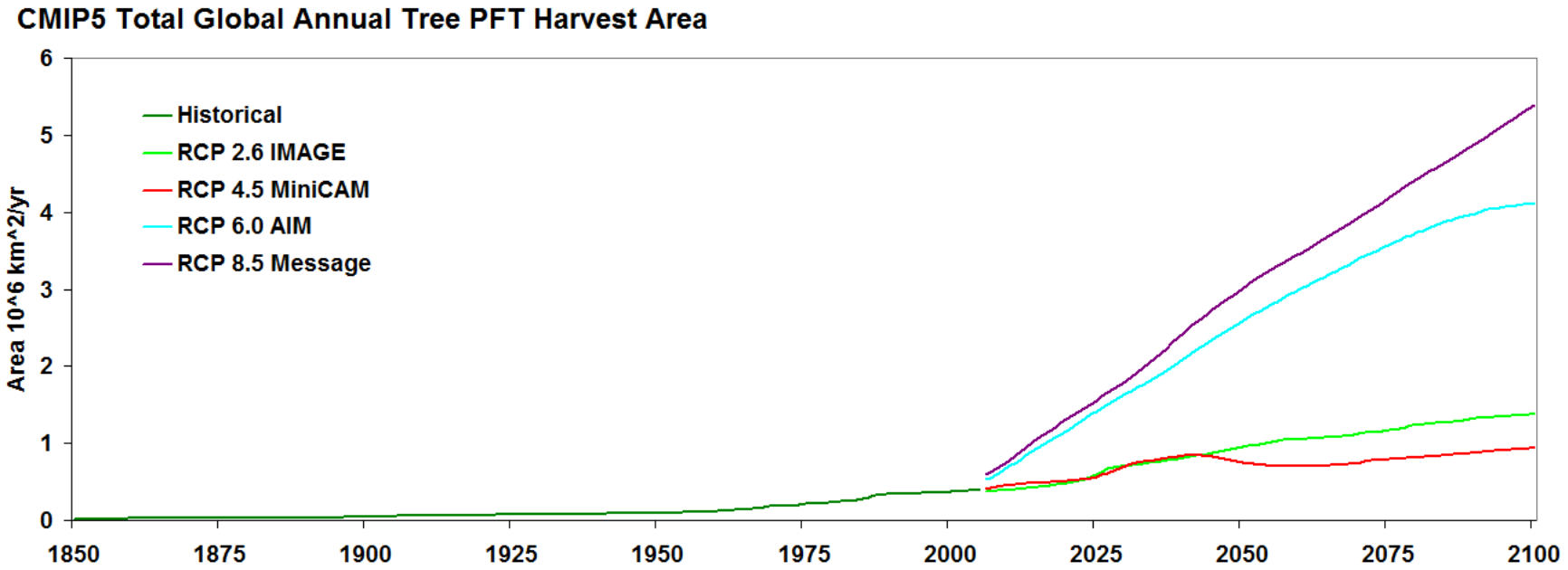
5. CMIP5 Wood Harvest in CLM 4 PFTs

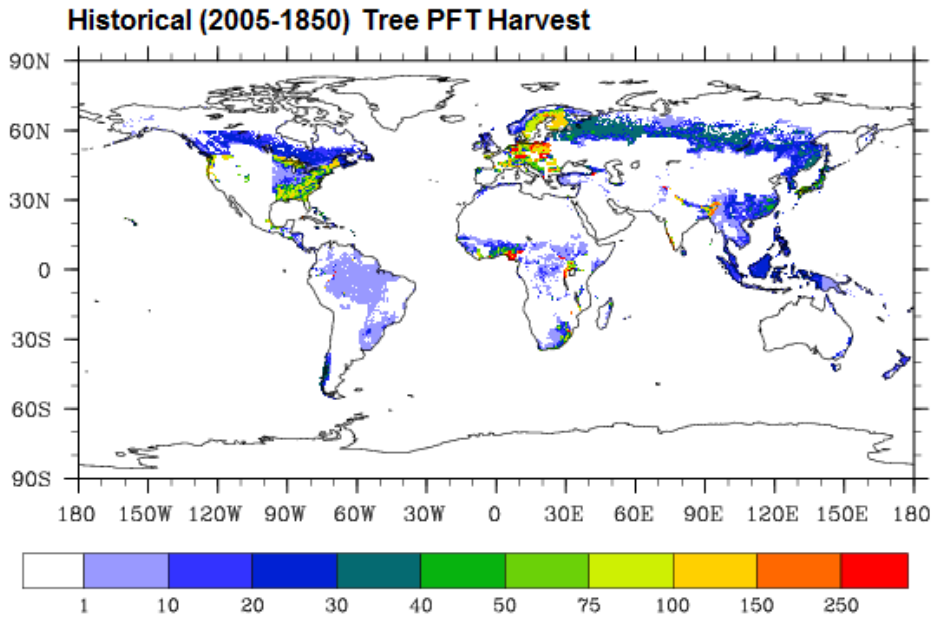
1. Annual tree PFT harvest parameters are calculated for CLM4 based on the harvest area information of the CMIP5 time series

2. The area values are combined with the transient tree PFT values for each grid cell for year giving a tree PFT harvest fraction

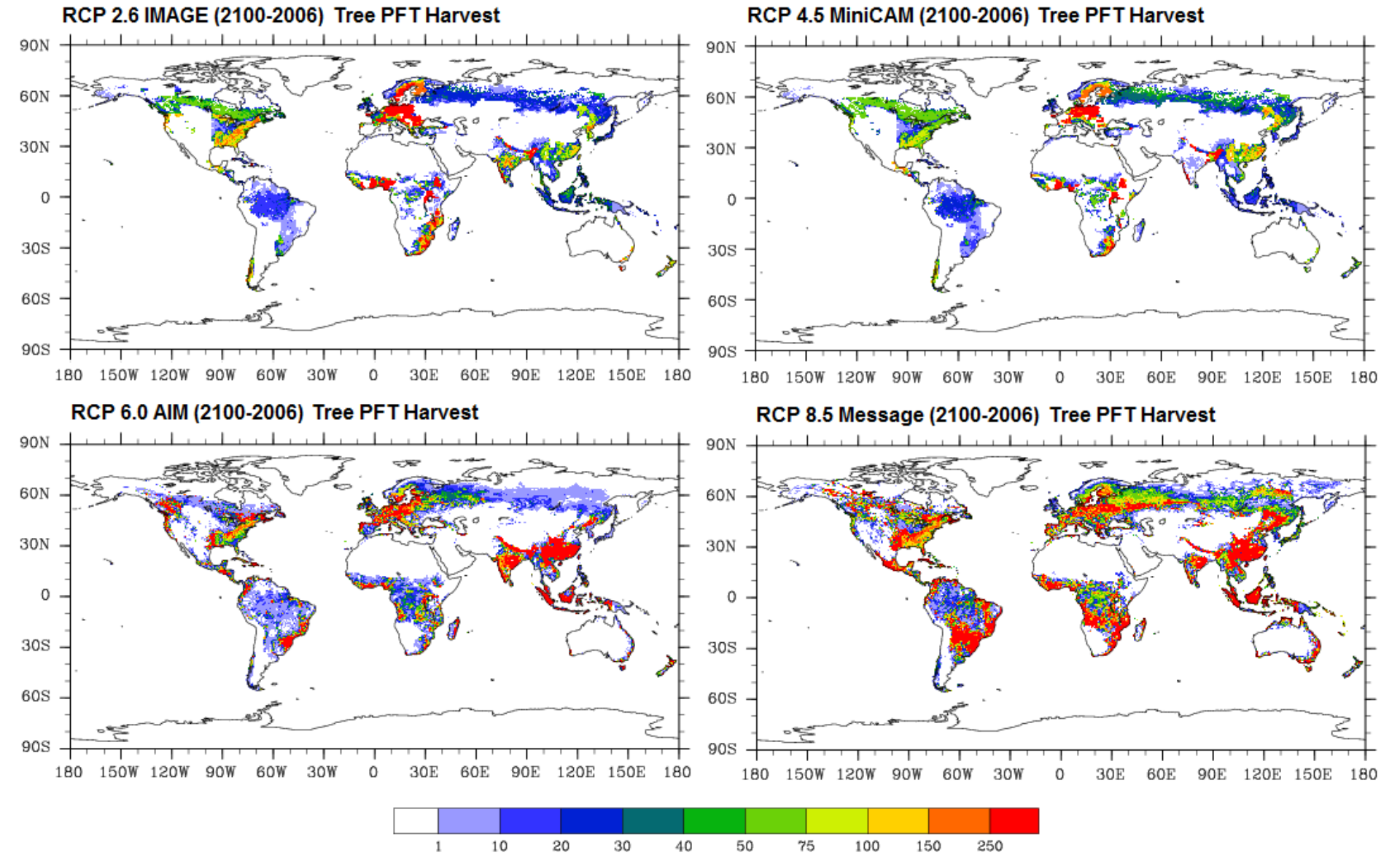
3. The UNH area values are therefore prescribed directly in CLM4 normalized to Tree PFT values.

5. CMIP5 Historical and RCP Tree PFT Harvest



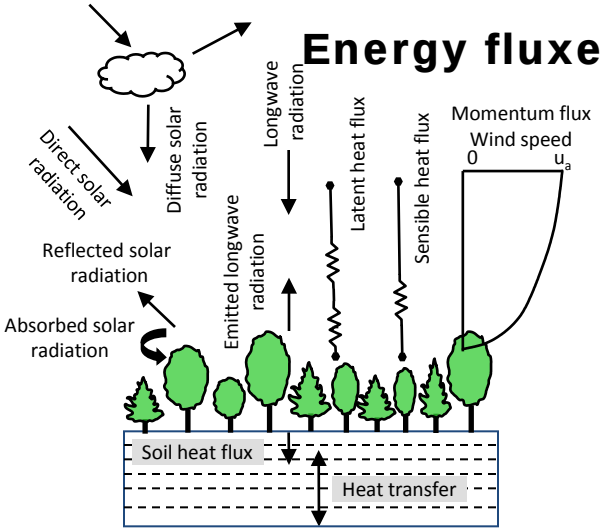


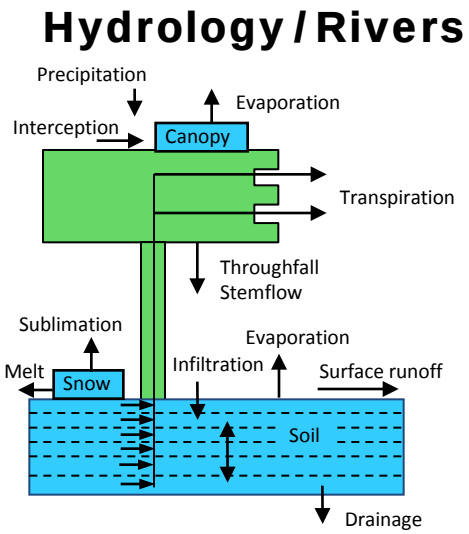
5. CMIP5 - RCP Land Cover Change Tree PFT Harvest %



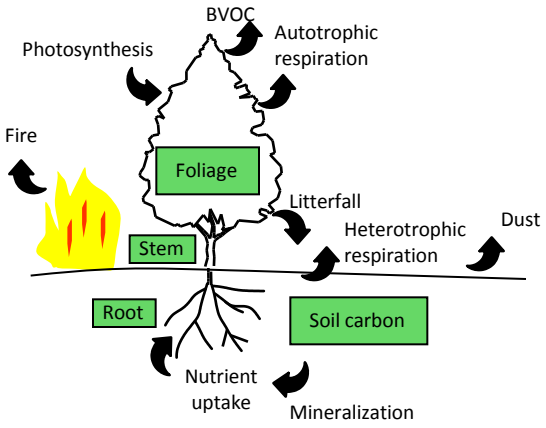
6. Land Cover Change in (CLM4)

Biogeophysical Processes





Biogeochemical Cycles



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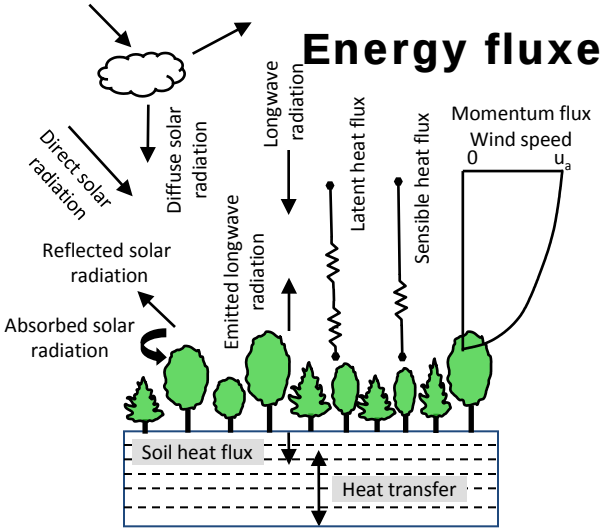

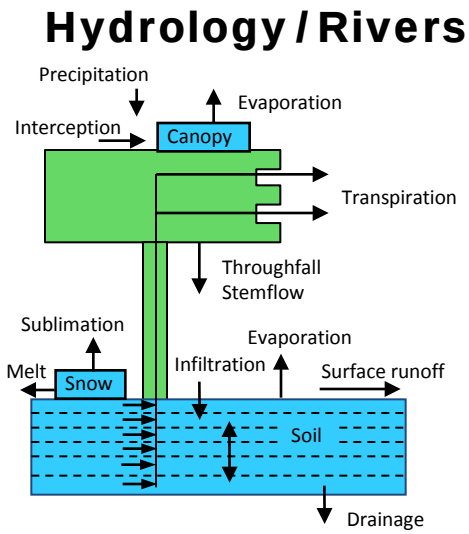

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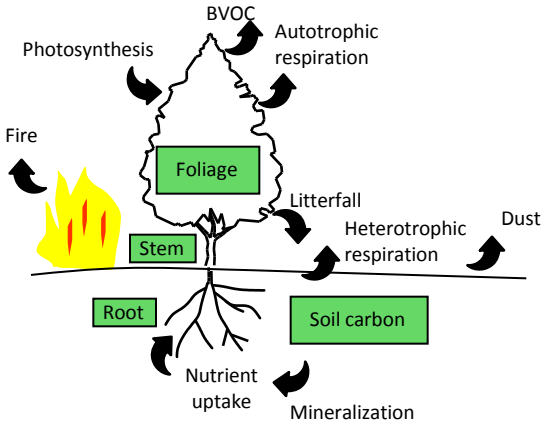
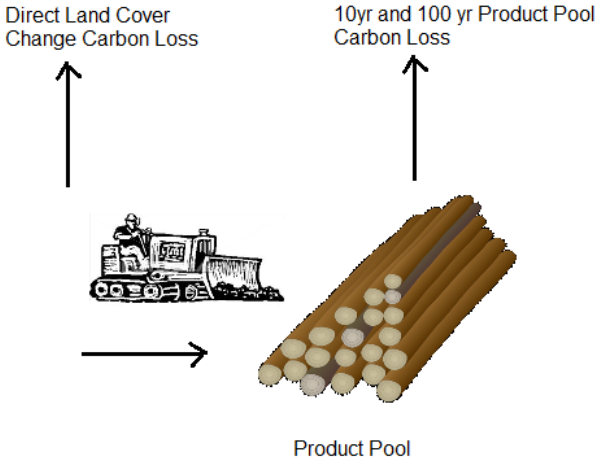
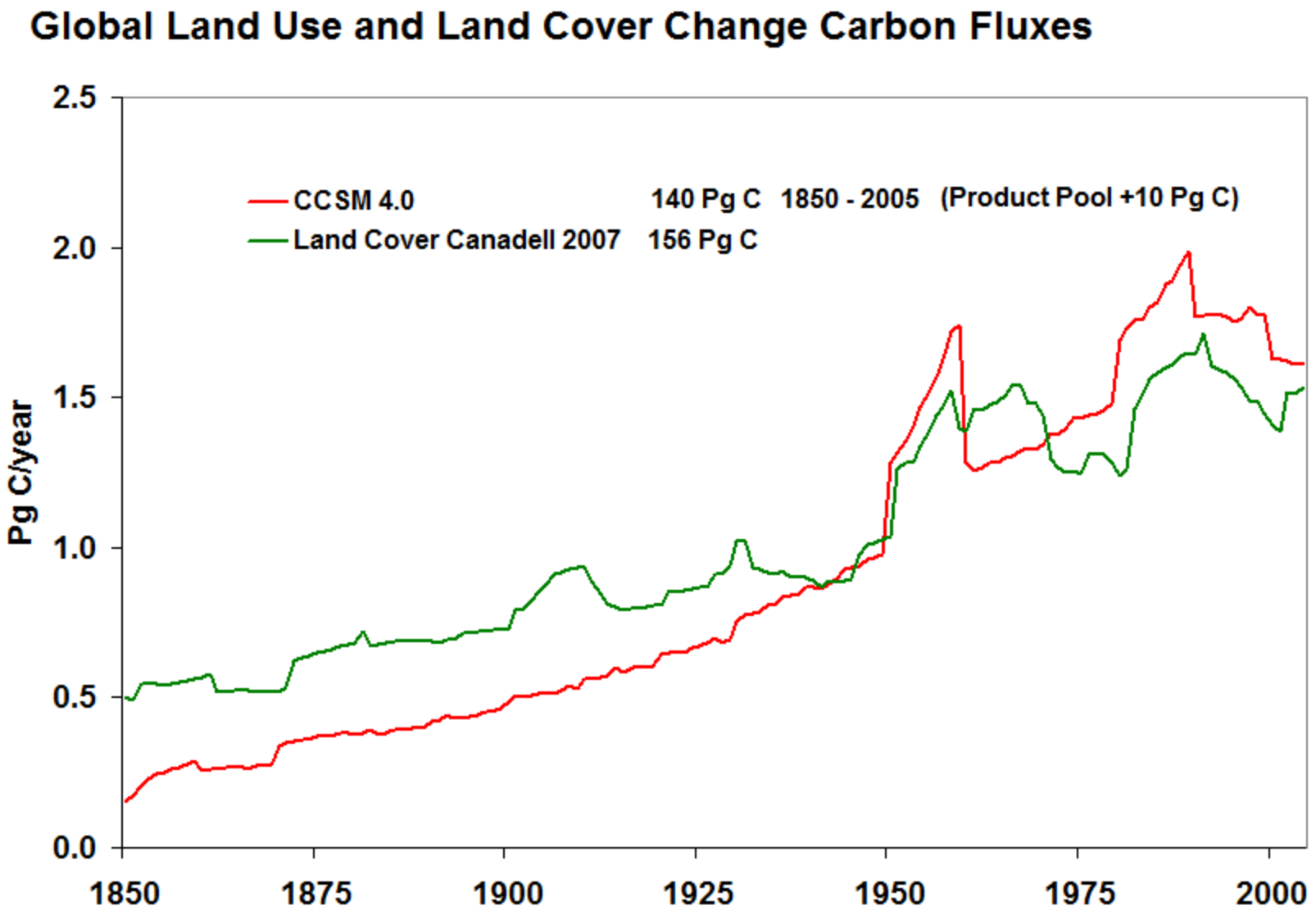




6. LCC in CCSM 4 – Coupled Climate & Prescribed CO_2



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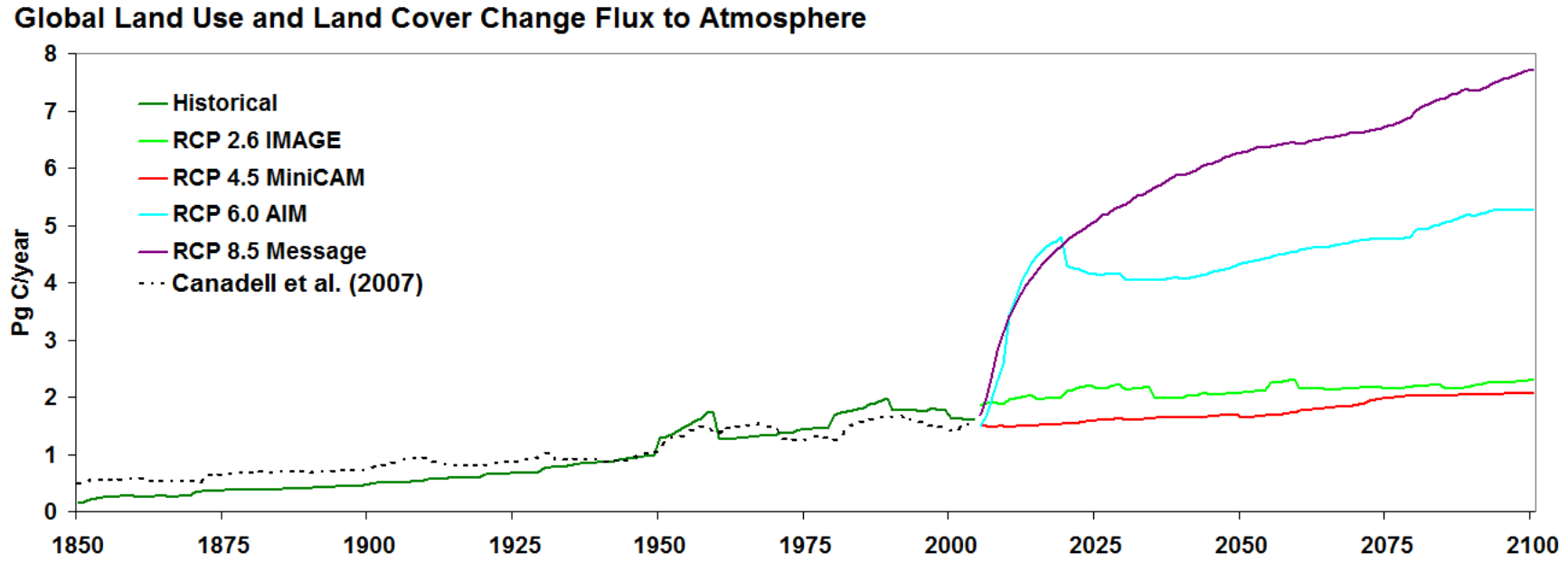
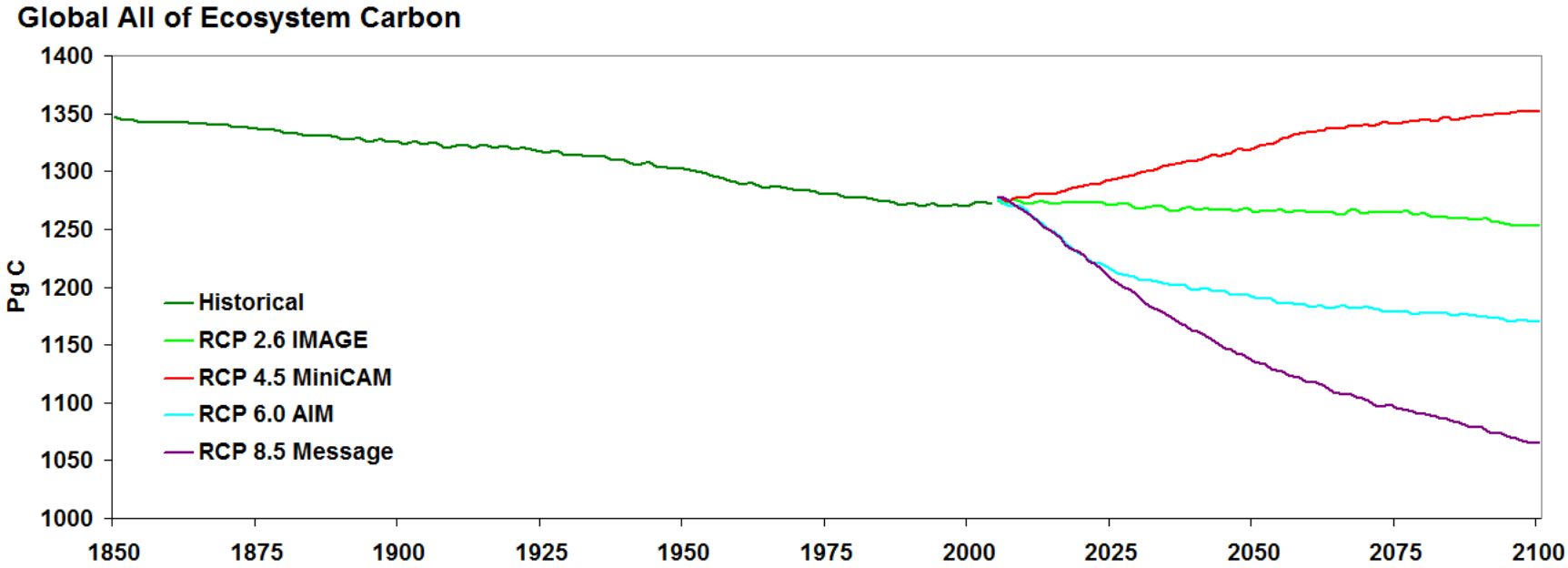


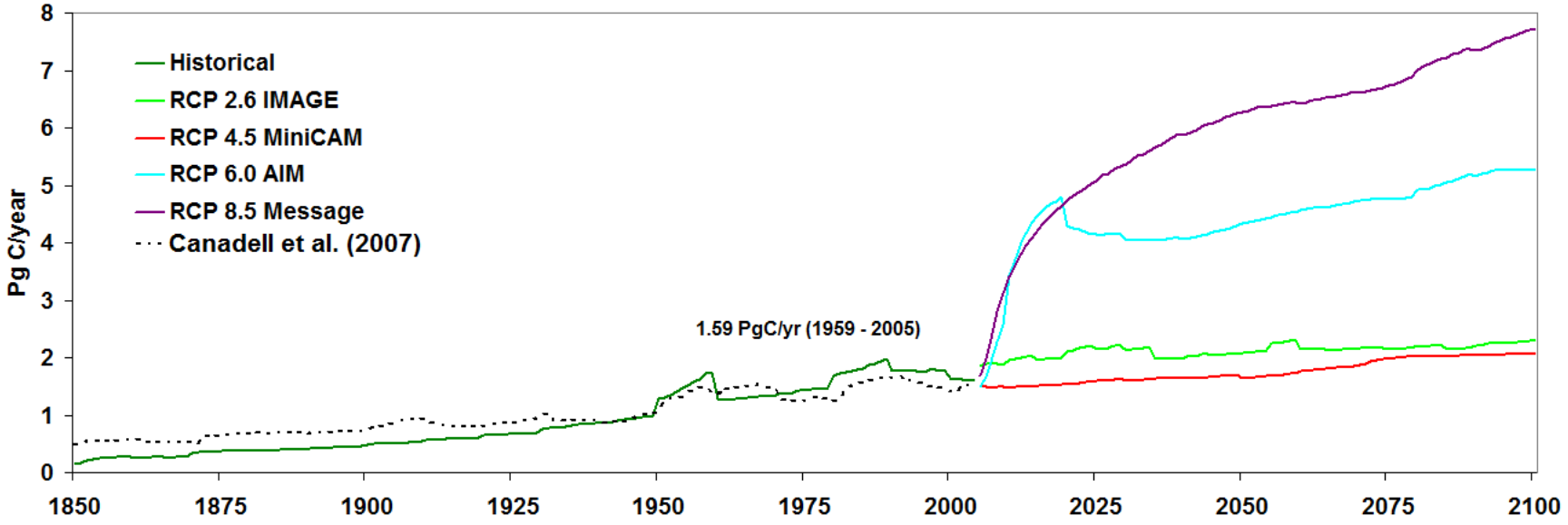


6. LCC in CCSM 4 – Canadell et al (2007)

Table 1. Summary of means and proportional trends of the global carbon budget for various time periods

Global carbon budget	Mean 1959–2006	Mean 1970–1999	Mean 1990–1999	Mean 2000–2006	Proportional trend, % y^{-1} 1959–2006
Economy, kgC/U.S. dollars					
Carbon intensity	0.29*	0.30	0.26	0.24	−1.18†
Sources, PgC y^{-1}					
Fossil Fuel (F_{Foss})	5.3	5.6	6.5	7.6	2.12
Land Use Change (F_{LUC})	1.5	1.5	1.6	1.5	0.21
Total ($F_{Foss} + F_{LUC}$)	6.7	7.0	8.0	9.1	1.71
Sinks, PgC y^{-1}					
Atmosphere	2.9	3.1	3.2	4.1	1.89
Ocean	1.9	2.0	2.2	2.2	1.25
Land	1.9	2.0	2.7	2.8	1.87
Distribution of annual emissions					
Atmosphere‡	0.43	0.44	0.39	0.45	0.25 ± 0.21§
Ocean	0.28	0.28	0.27	0.24	−0.42
Land	0.29	0.28	0.34	0.30	0.06

Global Land Use and Land Cover Change Flux to Atmosphere



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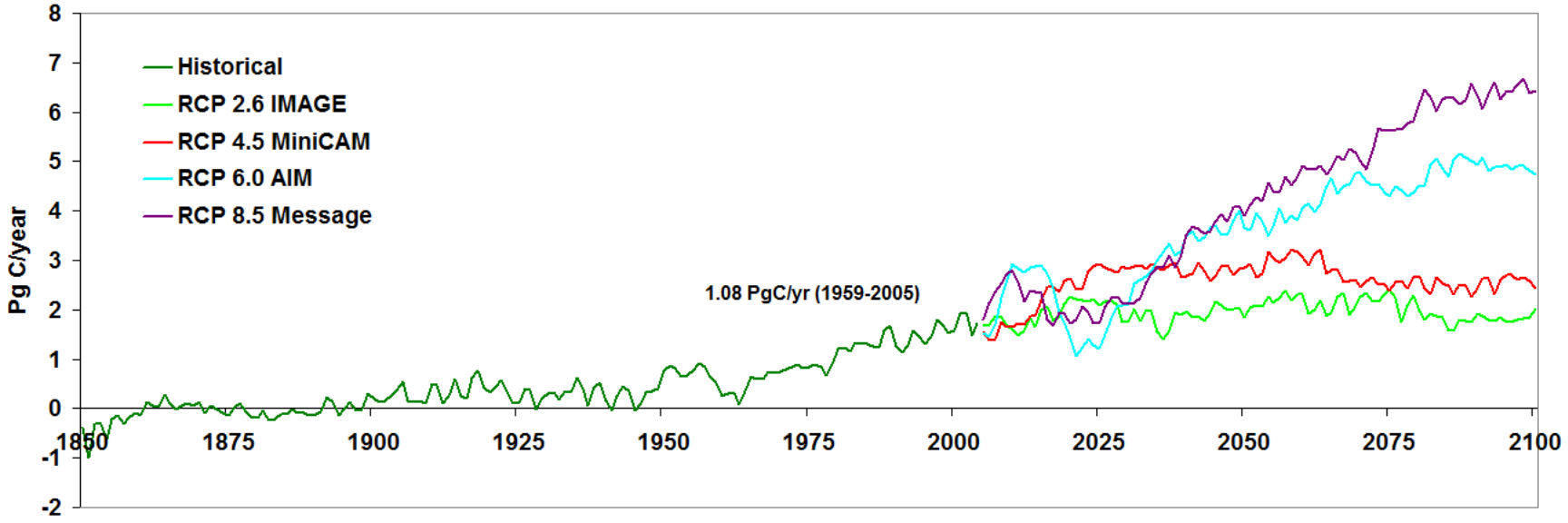
Ecosystem Sink = (NEE-Landuse)*-1.0



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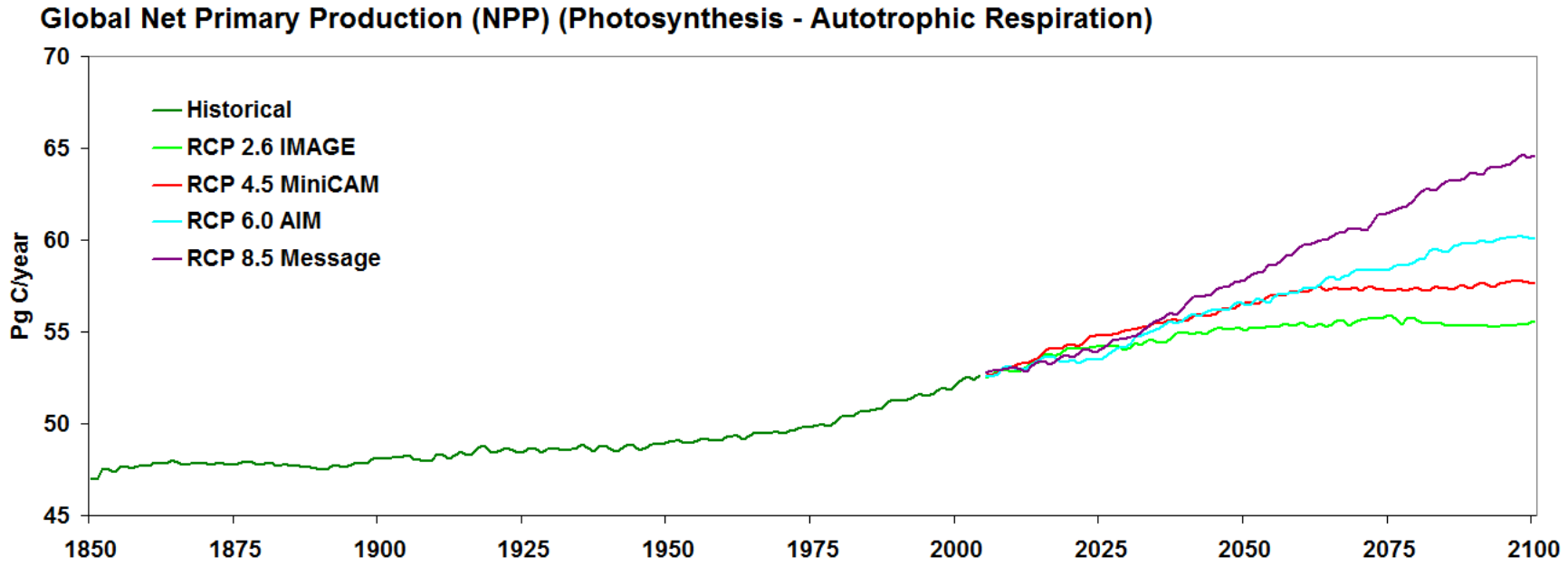

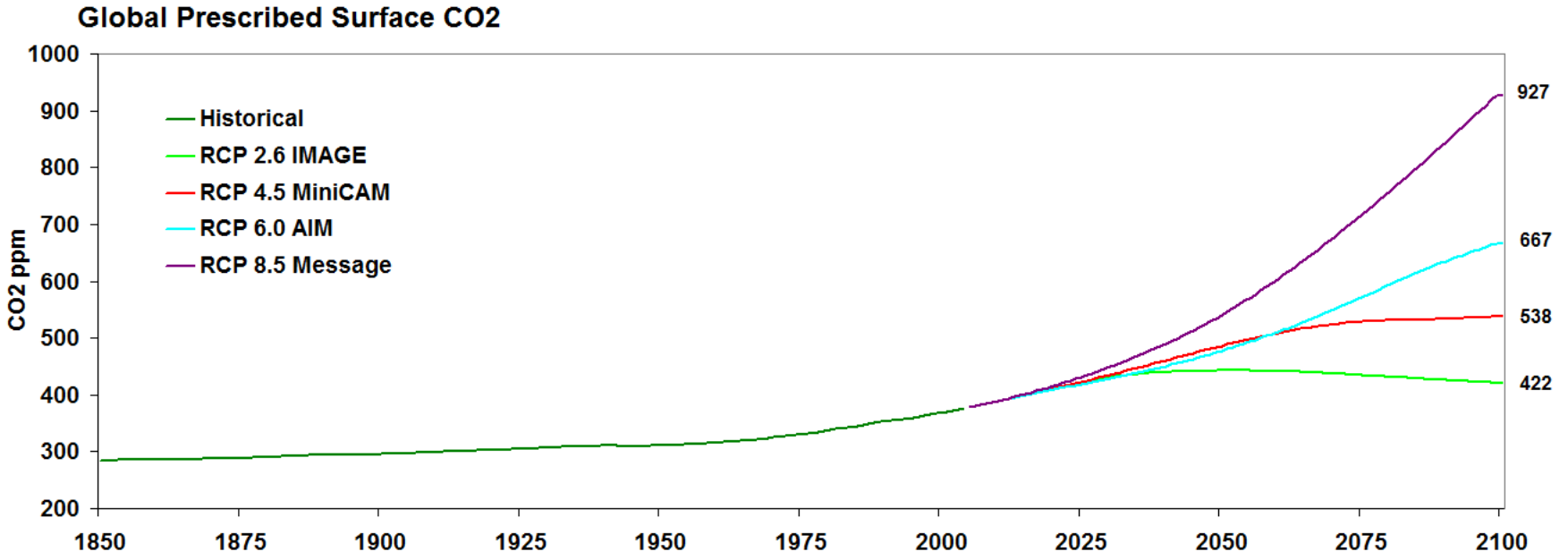

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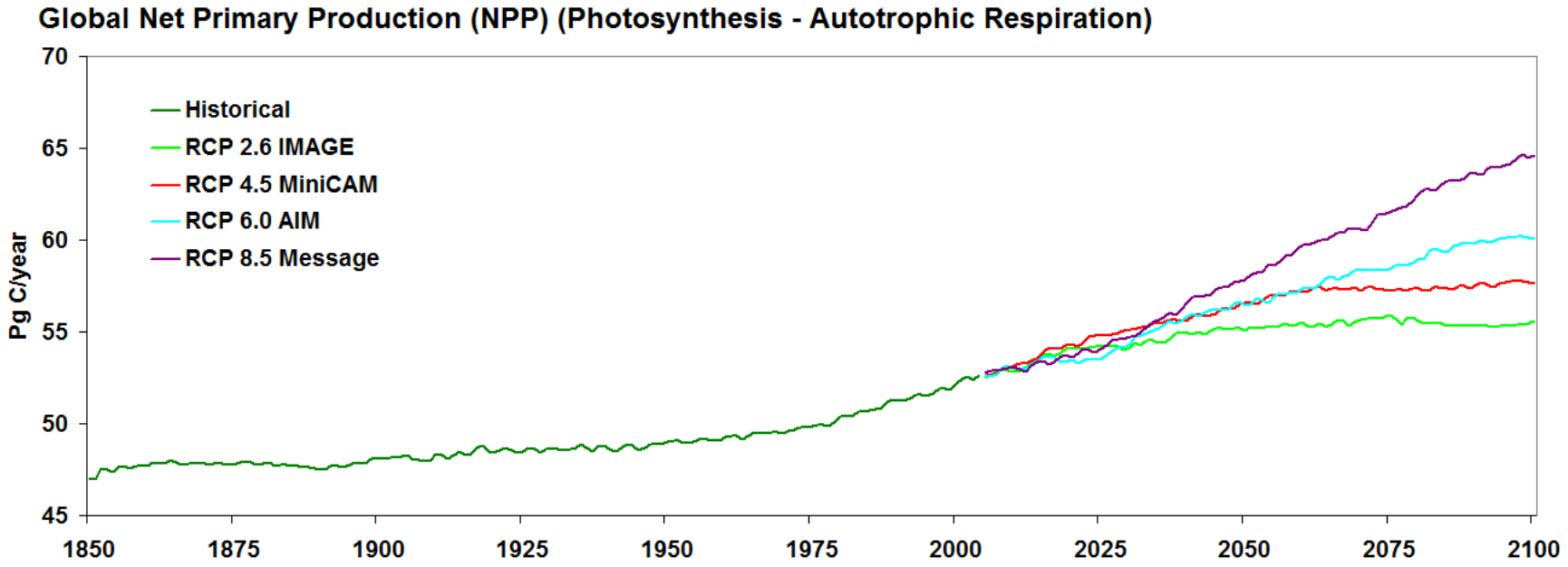

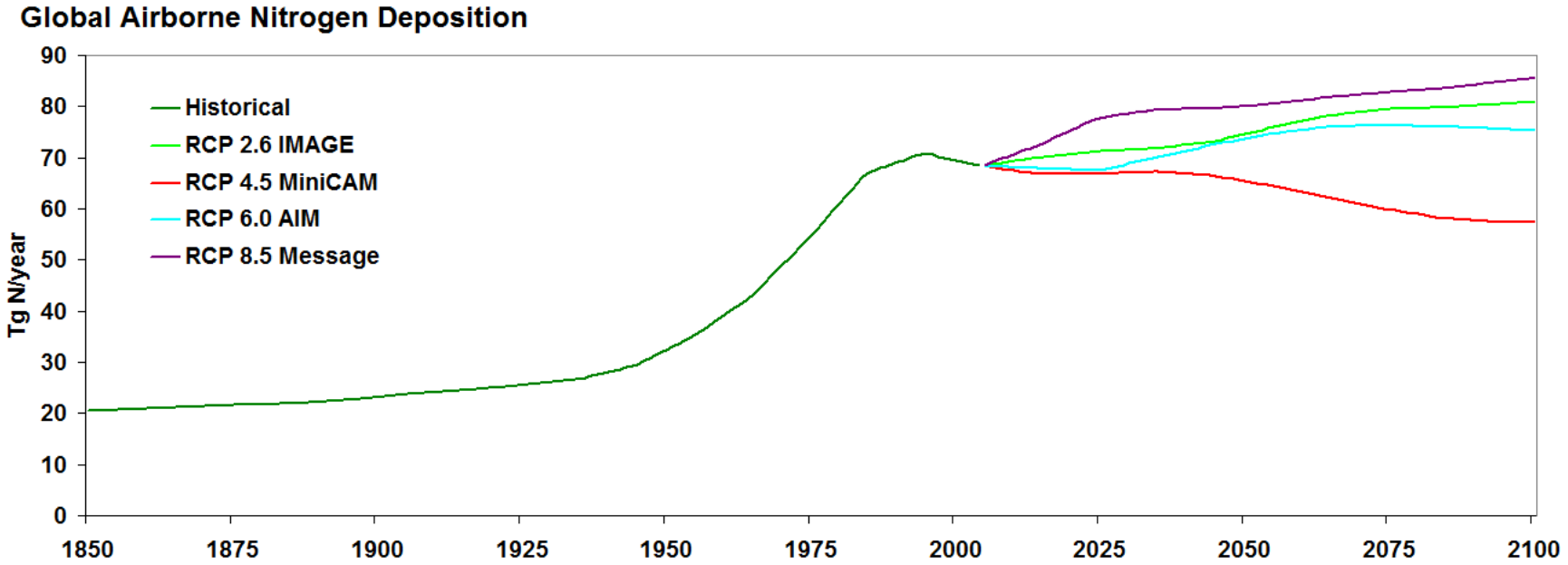

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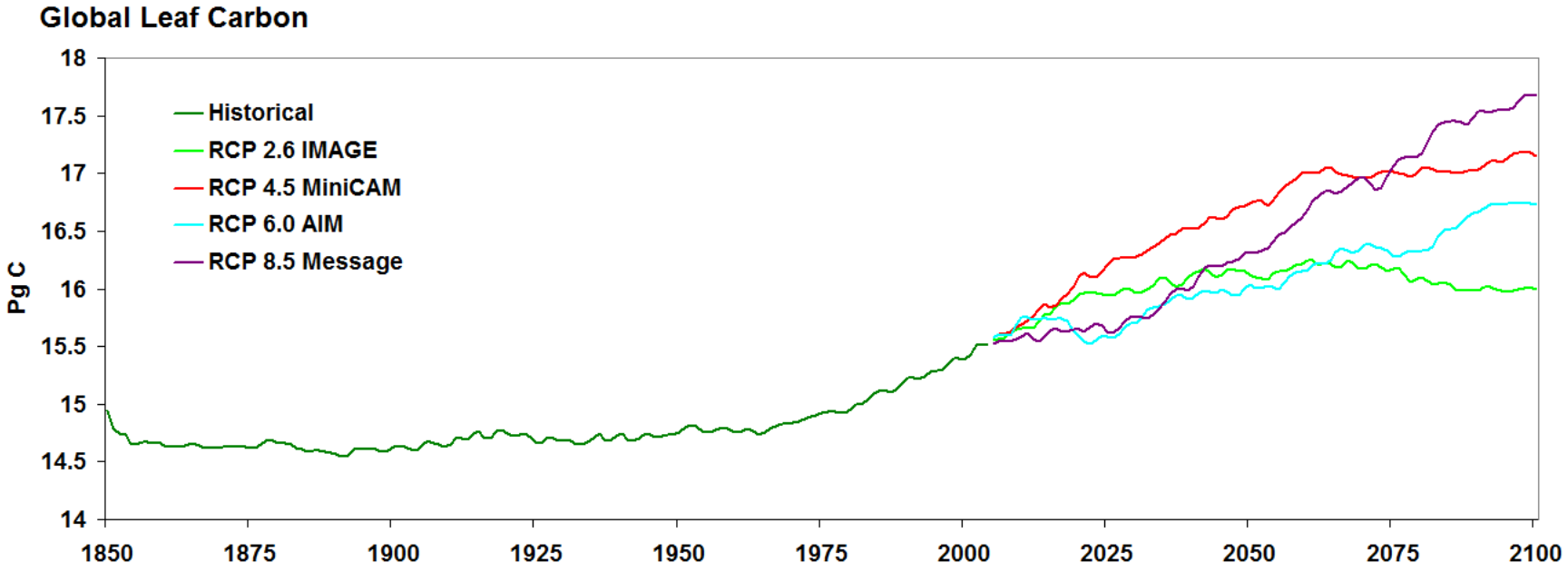
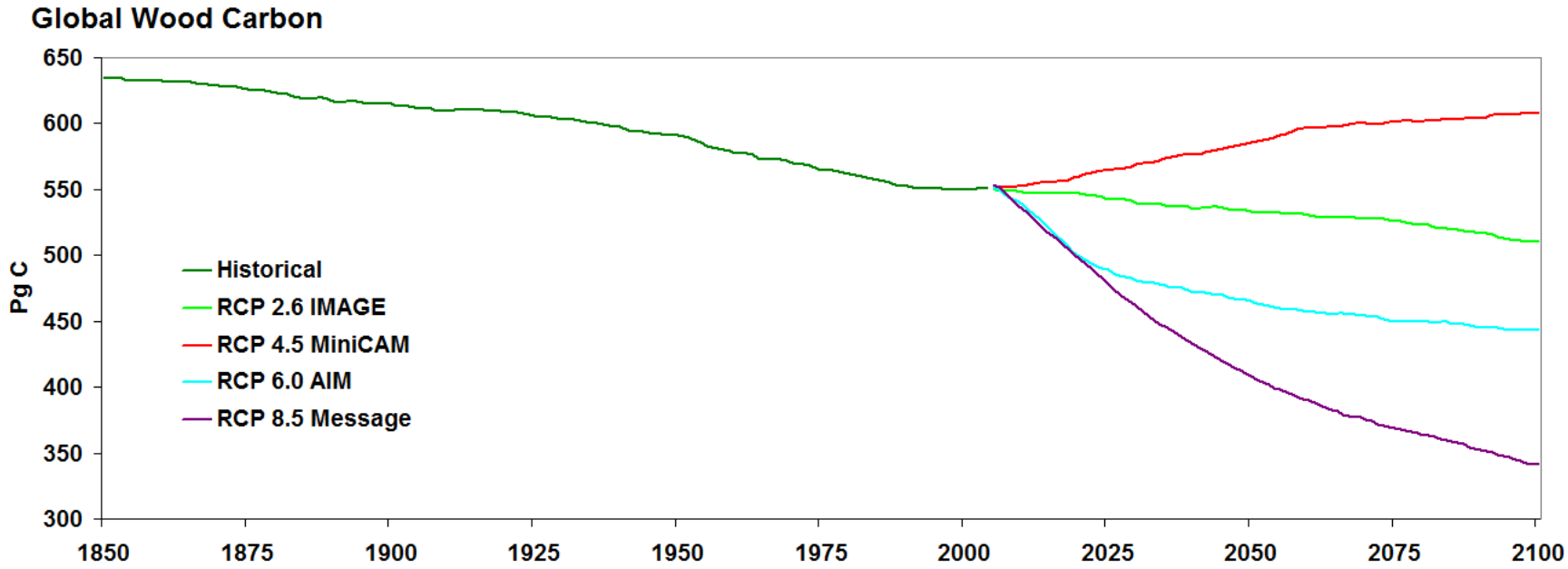
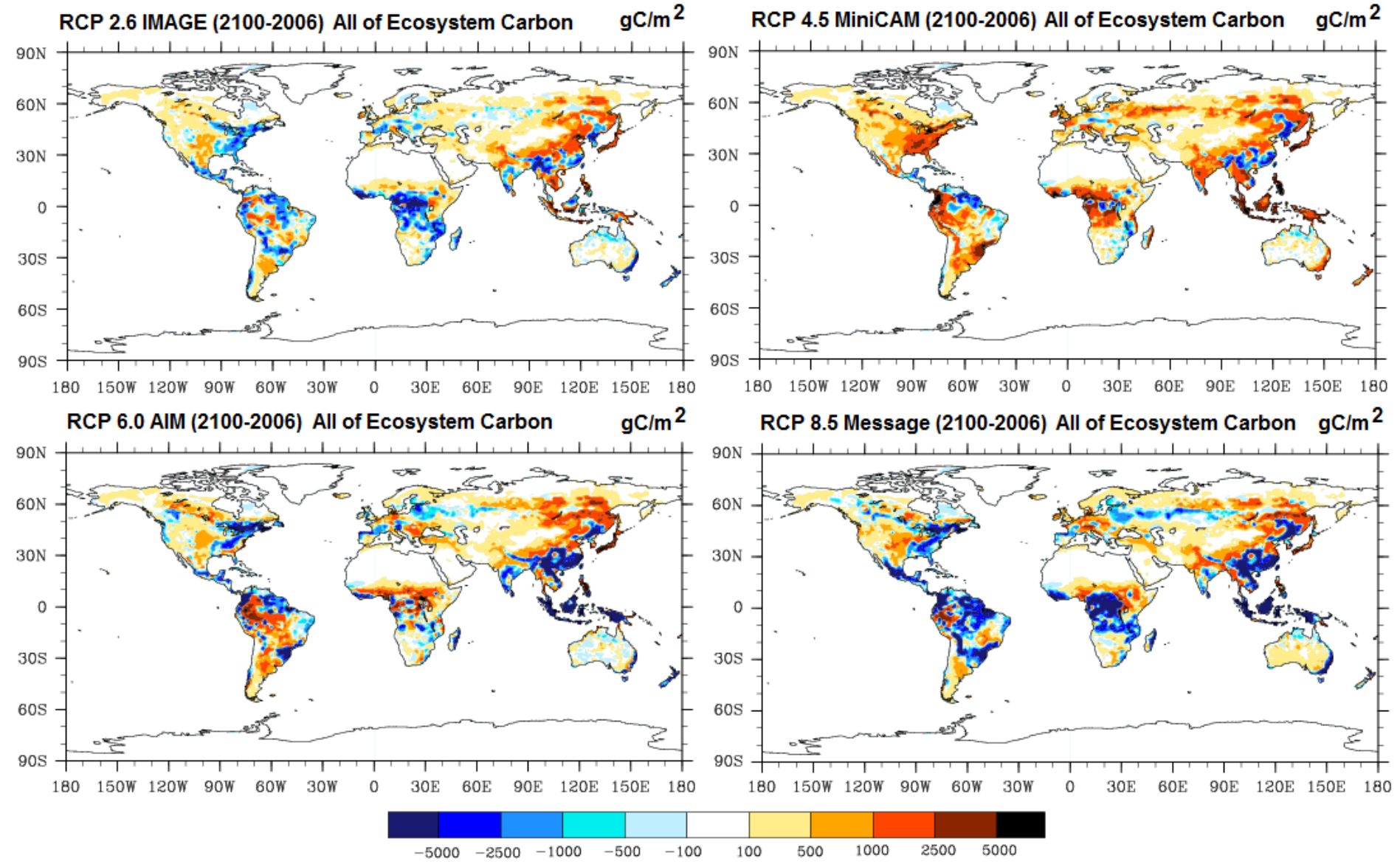




6. LCC in CCSM 4 – Coupled Climate & Prescribed CO2



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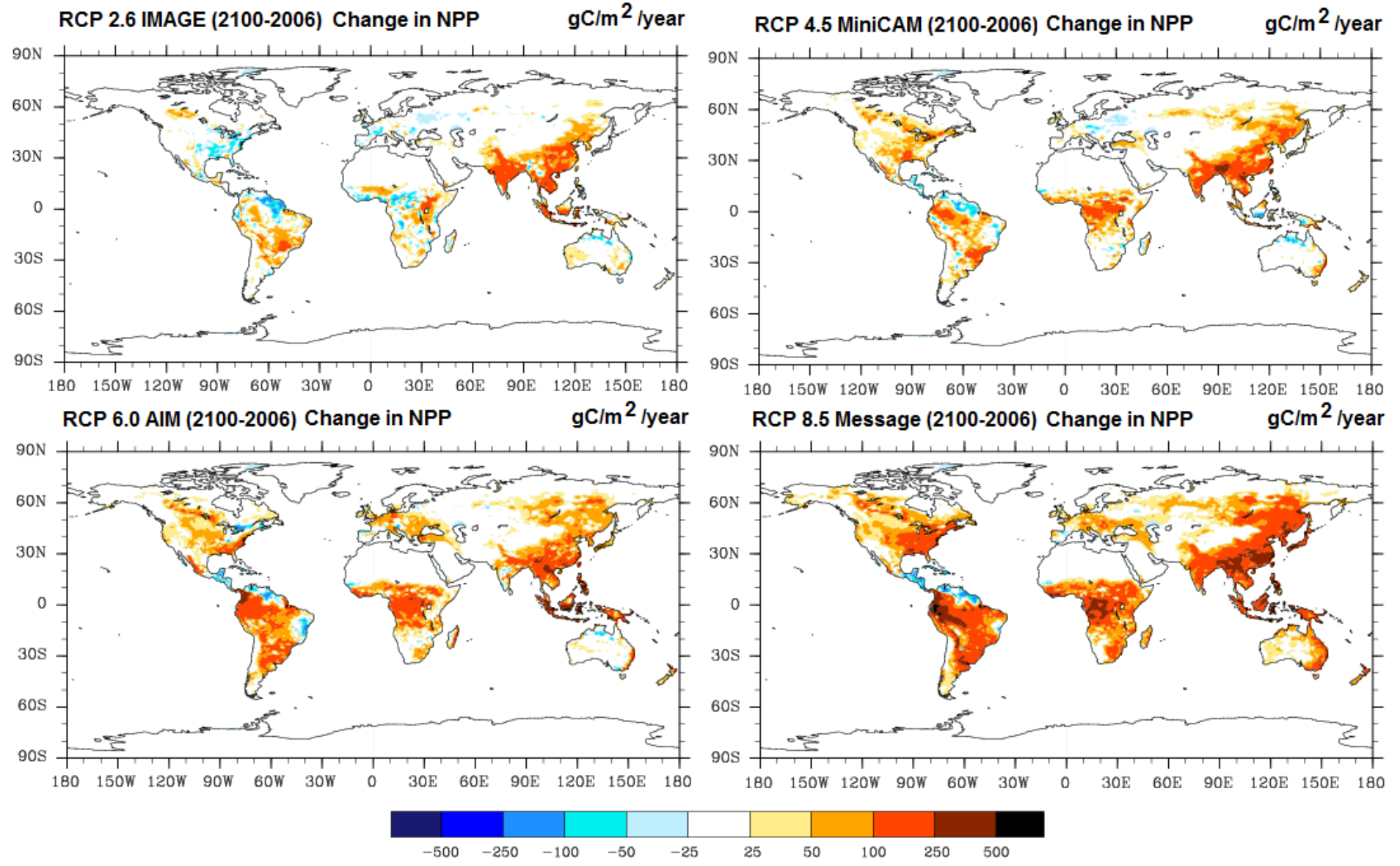
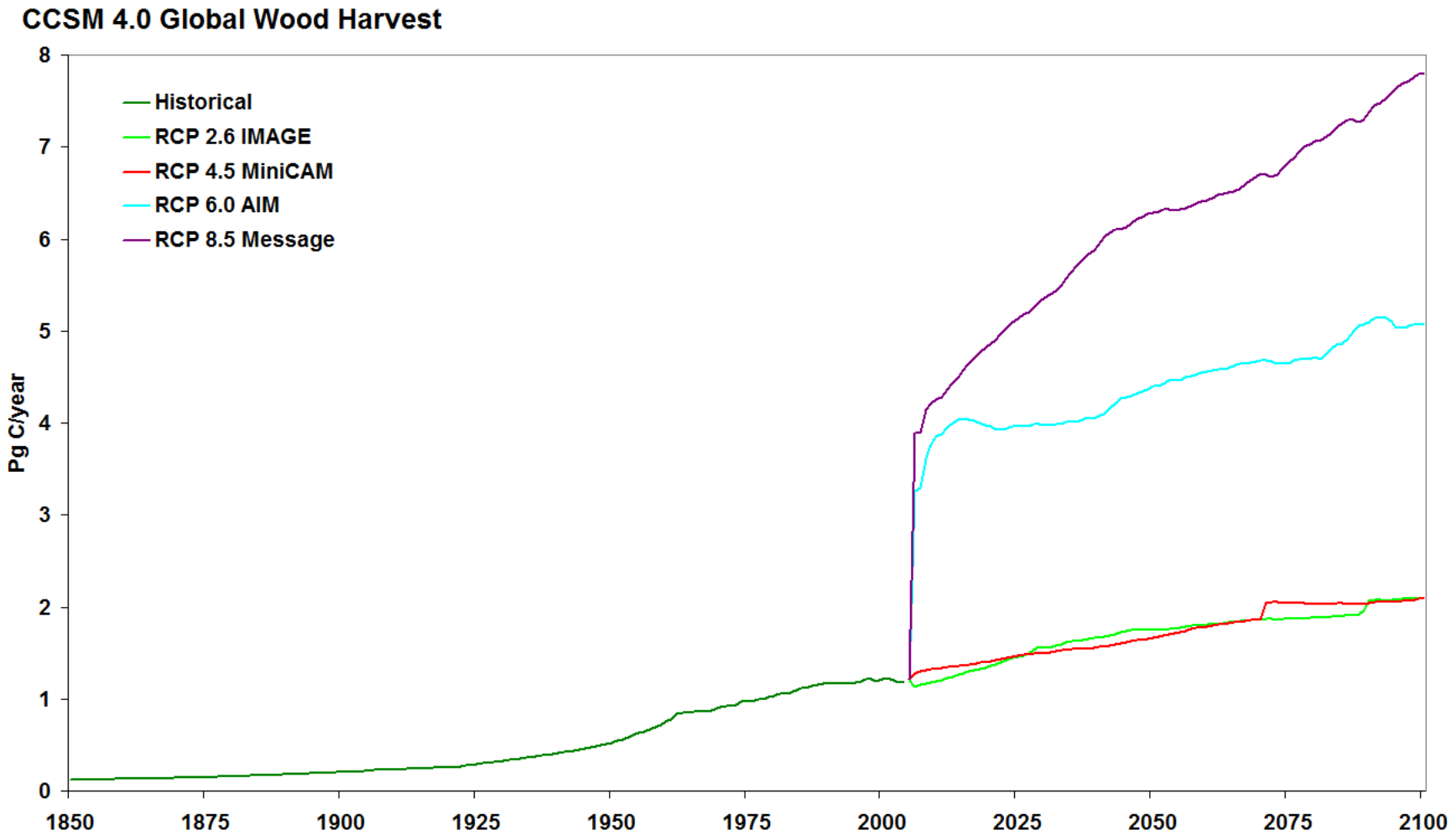
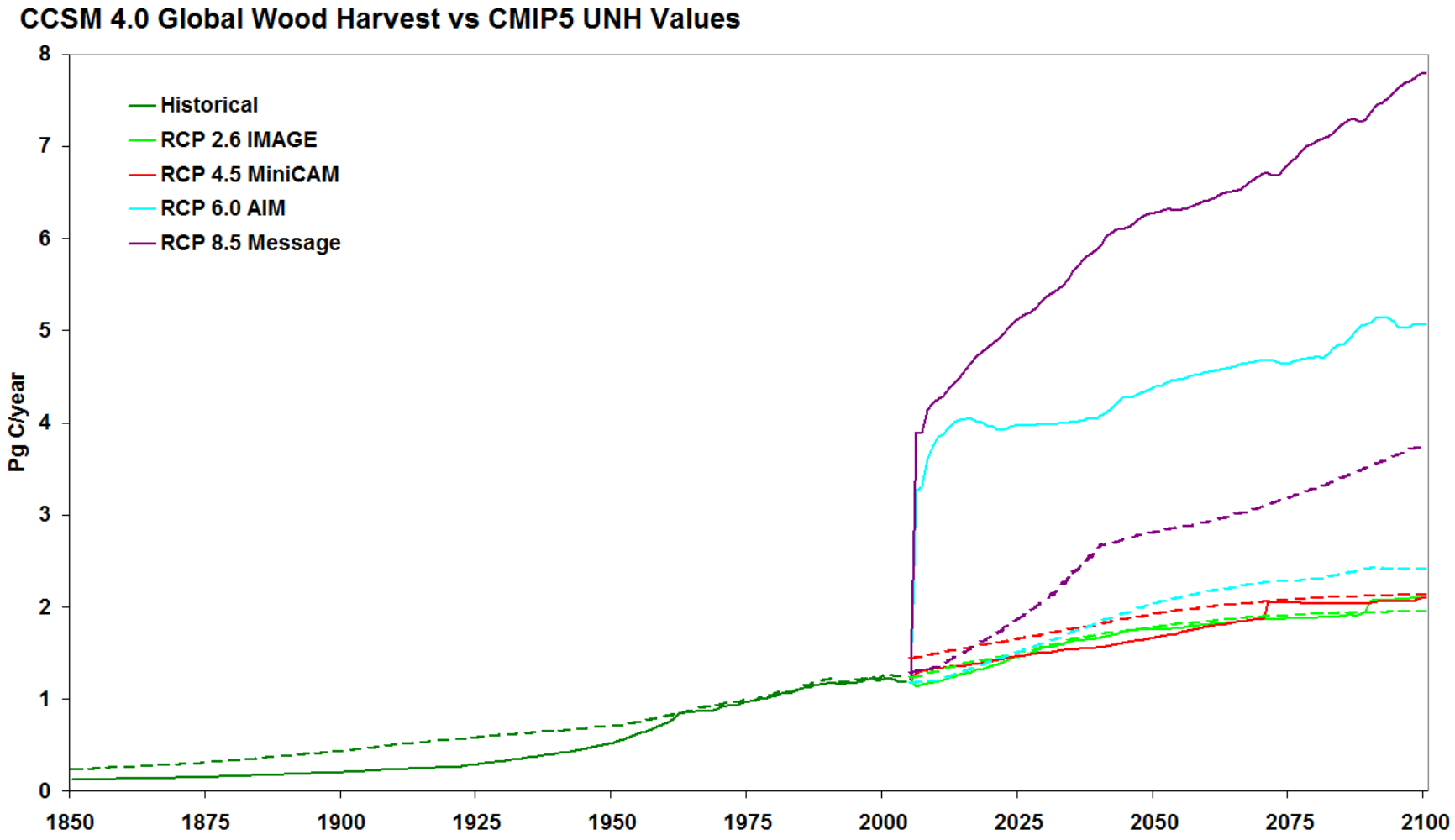


6. LCC in CCSM 4 – Coupled Climate & Prescribed CO2



7. CMIP5 Wood Harvest in CCSM 4.0 vs UNH Prescribed



7. CMIP5 Wood Harvest in CCSM 4.0 vs UNH Prescribed

1. The Historical, RCP 2.6 and RCP 4.5 time series all have good agreement for carbon harvested in CCSM 4.0 with the Tree PFT wood harvest parameters and the UNH prescribed wood carbon harvest.

2. RCP 6.0 and RCP 8.5 both have very large differences.

3. The relationships between the UNH harvest area and the wood carbon prescription reflect differences in standing amounts of wood carbon and differences in harvest intensities for the different time series.

4. To ensure that the amount of carbon harvested in the RCP 6.0 and RCP 8.5 climate simulations is consistent with the UNH carbon harvest we need to scale the Tree PFT wood harvest parameters by the implied wood harvest intensity

7. CCSM 4.0 vs UNH Wood Harvest – Carbon

CMIP5 Total Carbon of Wood Harvest for Historical and RCP Time Series (PgC).

CCSM 4.0 (UNH) values: < 50% < 80% 80-120% >120% >150%

Time Series	Primary Forest	Primary Non Forest	Secondary Mat Forest	Secondary Yng Forest	Secondary Non Forest	All Harvest
Historical 1850-2005	55.8 (71.2)	1.0 (1.6)	7.7 (9.7)	9.9 (16.0)	3.4 (3.0)	77.7 (101.5)
RCP 2.6 Image	72.1 (66.0)	2.5 (2.2)	28.4 (18.4)	43.8 (59.1)	16.4 (19.0)	163.1 (164.6)
RCP 4.5 MiniCAM	73.8 (75.2)	0.8 (0.8)	29.4 (25.3)	46.7 (63.6)	14.2 (14.7)	164.9 (179.6)
RCP 6.0 AIM	47.7 (41.1)	10.7 (3.9)	305.0 (101.0)	2.9 (6.3)	53.0 (32.9)	419.2 (185.2)
RCP 8.5 Message	79.5 (60.2)	11.8 (7.1)	404.7 (116.8)	6.3 (5.1)	81.3 (63.8)	583.6 (253.0)

7. CCSM 4.0 vs UNH Wood Harvest – Intensity

CMIP5 Wood Harvest Intensity for Historical and RCP Time Series (kgC/m^2).

CCSM 4.0 (UNH) values: < 50% < 80% 80-120% >120% >150%

Time Series	Primary Forest	Primary Non Forest	Secondary Mat Forest	Secondary Yng Forest	Secondary Non Forest	All Harvest
Historical 1850-2005	7.1 (9.1)	0.1 (0.2)	7.3 (9.2)	1.0 (1.6)	0.2 (0.1)	1.6 (2.1)
RCP 2.6 Image	9.4 (8.6)	0.8 (0.7)	13.6 (8.8)	0.7 (1.0)	0.3 (0.3)	1.2 (1.2)
RCP 4.5 MiniCAM	8.1 (8.2)	0.4 (0.4)	10.2 (8.8)	0.7 (1.0)	0.1 (0.1)	0.8 (0.8)
RCP 6.0 AIM	11.9 (10.3)	2.7 (1.0)	1.9 (0.6)	0.2 (0.4)	0.6 (0.4)	1.5 (0.7)
RCP 8.5 Message	11.7 (8.8)	1.6 (1.0)	3.4 (1.0)	1.4 (1.1)	0.4 (0.3)	1.6 (0.7)

7. CCSM 4.0 vs UNH Wood Harvest – Parameter Scaling

CMIP5 Wood Harvest Intensity Fraction for Historical and RCP Time Series.

UNH/CCSM 4.0 harvest intensity fraction : > 150% > 120% 120-80% <80% <50%

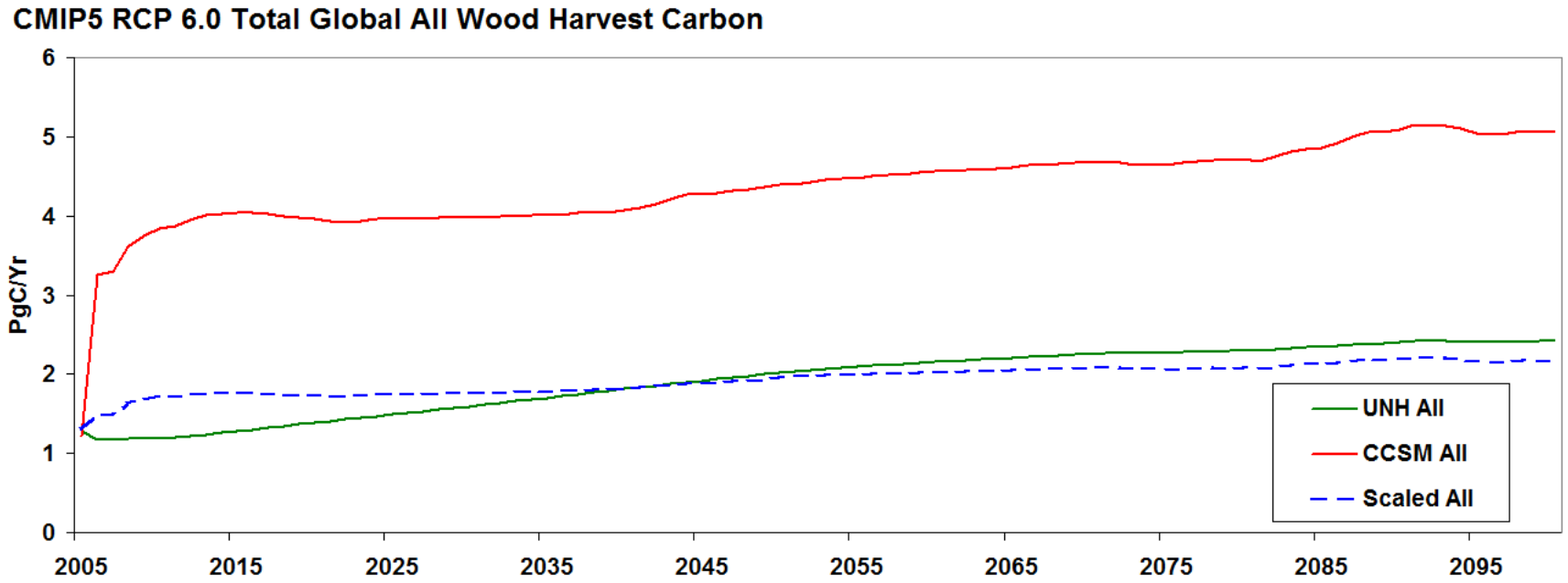
Time Series	Primary Forest	Primary Non Forest	Secondary Mat Forest	Secondary Yng Forest	Secondary Non Forest	All Harvest
Historical 1850-2005	1.28	1.70	1.27	1.62	0.87	1.31
RCP 2.6 Image	0.92	0.87	0.65	1.35	1.16	1.01
RCP 4.5 MiniCAM	1.02	0.97	0.86	1.36	1.03	1.09
RCP 6.0 AIM	0.86	0.36	0.33	2.17	0.62	0.44
RCP 8.5 Message	0.76	0.60	0.29	0.81	0.79	0.43

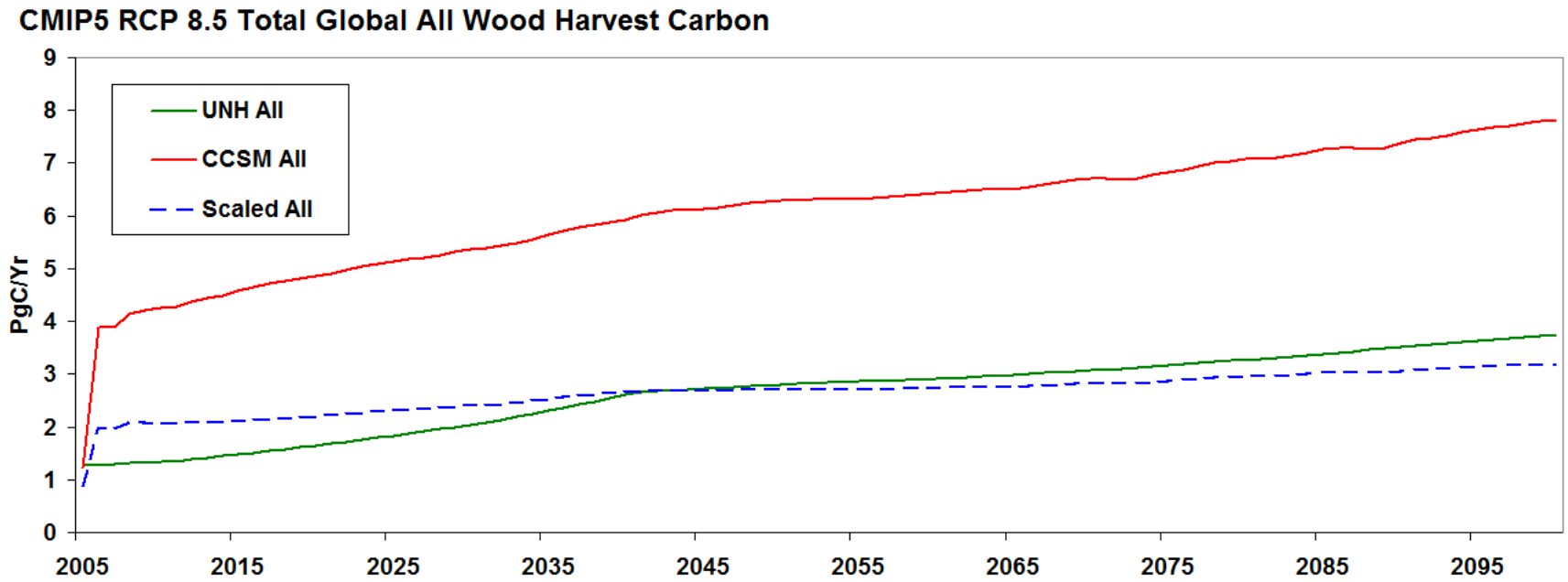
7. CCSM 4.0 vs UNH Wood Harvest – Parameter Scaling

1. The fraction of the UNH/CCSM 4.0 wood harvest intensity can be used as a scaling factor to modify the fraction of tree PFTs harvested in a grid cell in a year from the area based values

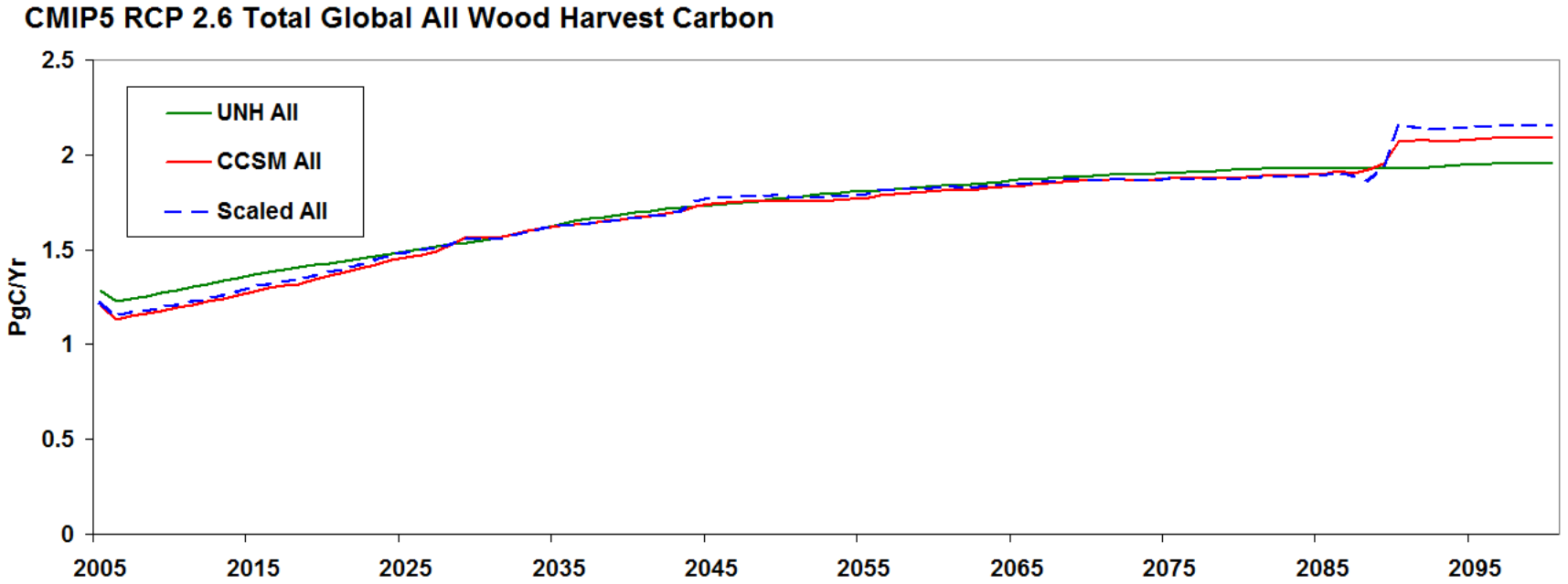
2. This can be applied to the five harvest classes for each time series as needed.

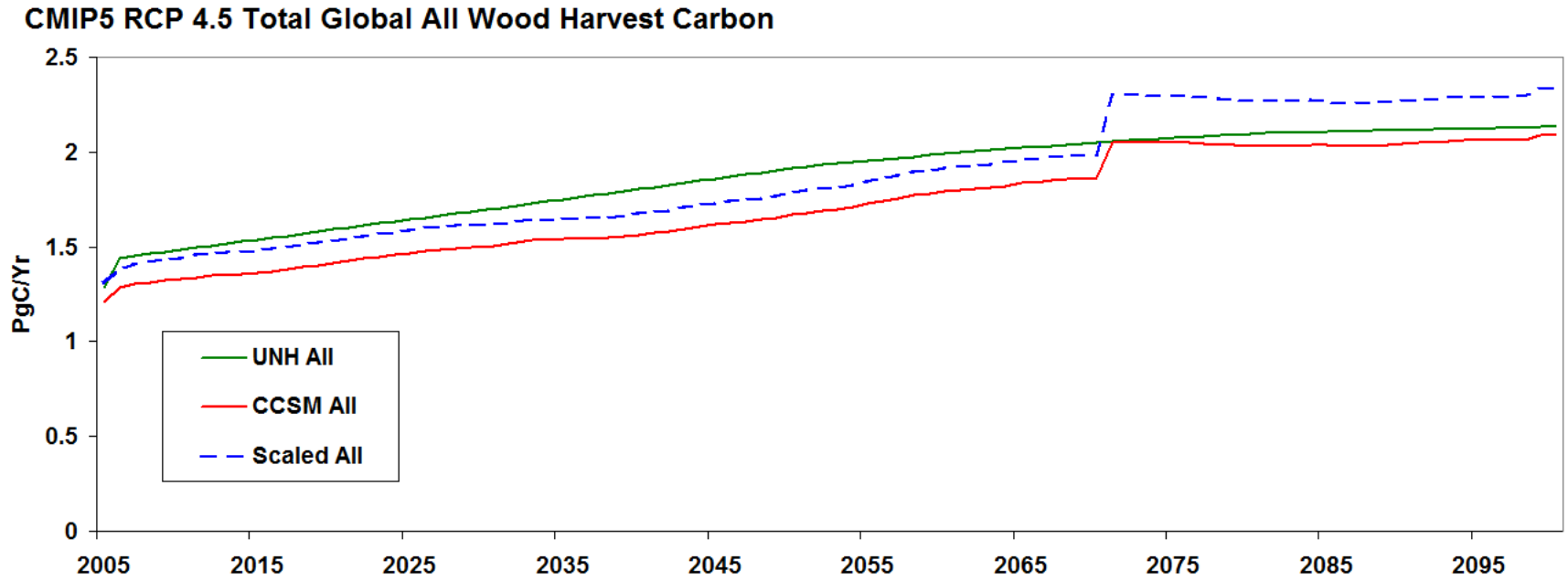
7. CCSM 4.0 vs UNH Wood Harvest – Parameter Scaling



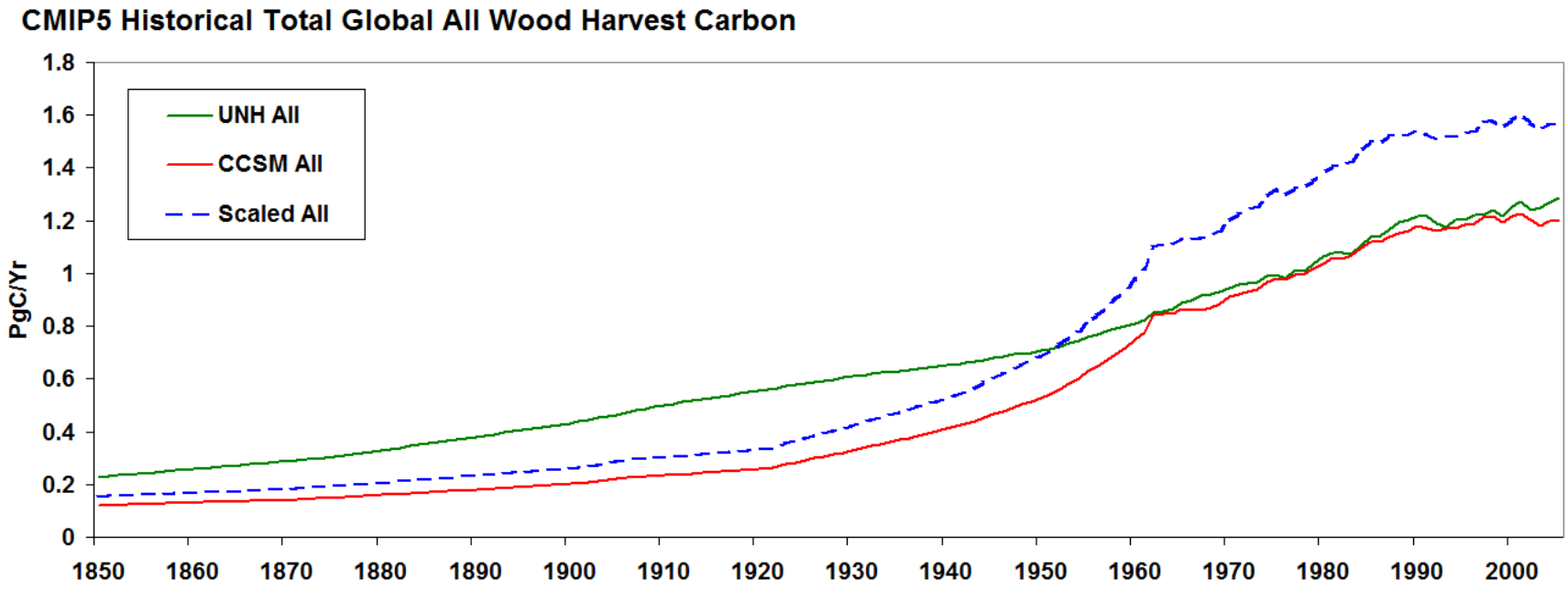


7. CCSM 4.0 vs UNH Wood Harvest – Parameter Scaling





7. CCSM 4.0 vs UNH Wood Harvest – Parameter Scaling



8. Conclusions

1. CCSM 4 (CESM 1.0) provides a global carbon climate model with CLM 4.0 including Land Cover Change and Harvesting

2. We have prescribed CMIP5 historical and RCP Land Cover Change and Harvesting in CLM parameters for all experiments

3. CCSM 4 simulates carbon fluxes in good agreement with other global estimates of Land Cover Change and Forestry

4. Analysis of transient land carbon fluxes demonstrate the competing influences between Land Cover Change, CO2 fertilization, Nitrogen Deposition, and climate

5. Wood Harvest Parameters for RCP 6.0 and RCP 8.5 need to be scaled to represent the different harvest intensities used in these Integrated Assessment Models

8. Continuing Investigation

1. Attribution studies are being undertaken with historical single forcing experiment to identify the individual impacts of LCC, CO2 fertilization, N Deposition, and Climate

2. The attribution studies provide a more robust frame for isolating biogeophysical impacts of land cover change