The Changing CO_2 Seasonal Cycle

Contribution from the Agricultural Green Revolution

Ning Zeng

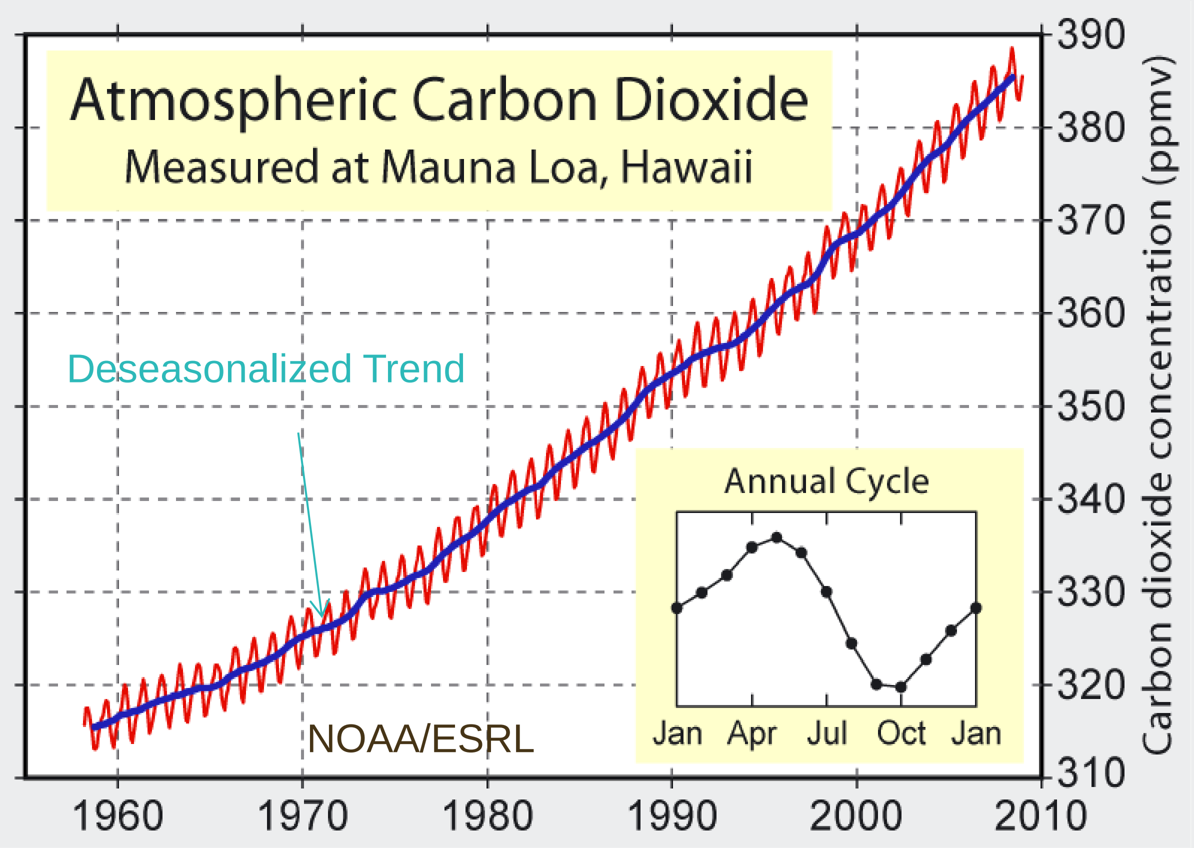
Dept. Atmospheric and Oceanic Science and
Earth System Science Interdisciplinary Center
University of Maryland

With F. Zhao, J. Collatz, E. Kalnay, T. West, R. Salawitch, L. Guanter

The Keeling Curve

Major signals:

- Trends (long-term change)
- Seasonal cycle
- Interannual-decadal variabilities, to a lesser degree



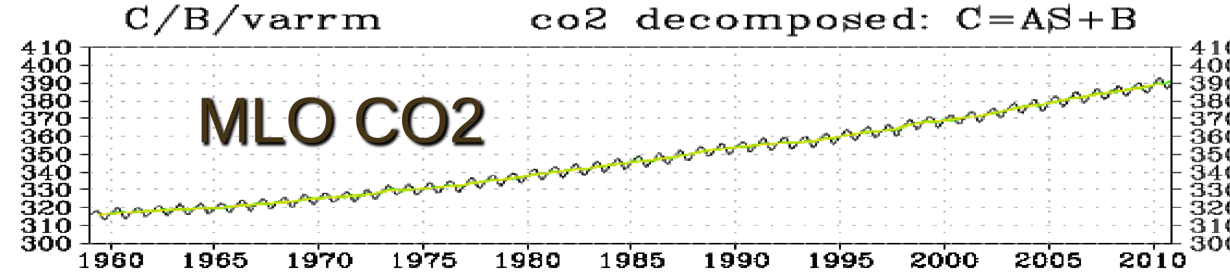
Mean seasonal cycle:

- Max in May, min in October
- CO2 drawdown for 5 months.
- Not symmetric, not exactly sinusoidal
- Seasonal amplitude (max-min) ~ 6 ppm

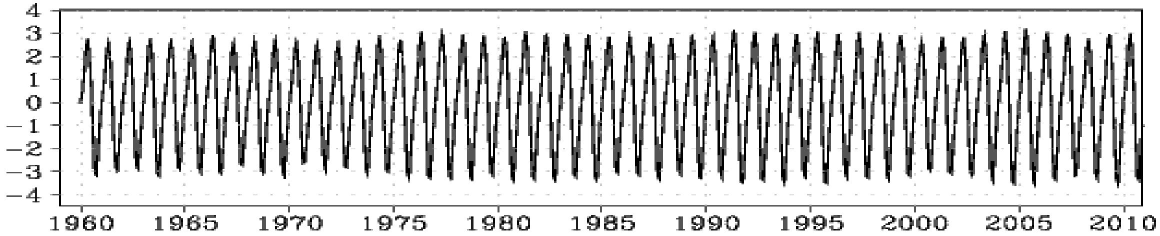
How to calculate CO2 seasonal amplitude (CSA) and its change
Deconstructing a legendary time series

$$CO2(t) = A(t)\,S(t^*) + B(t)$$

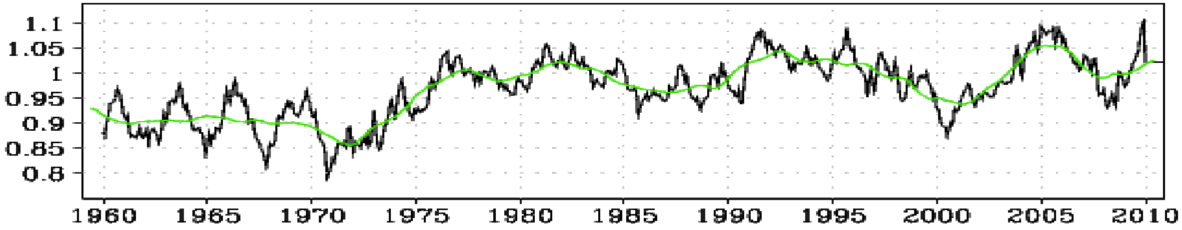
CO2(t) – Original CO2
S(t*) – An ‘average’ seasonal cycle (fixed: varying seasonally, but does not change from year to year)
A(t) – Amplitude of the seasonal cycle that may vary with time
B(t) – Trend (diseasonalized); low frequency as well as high frequency signal



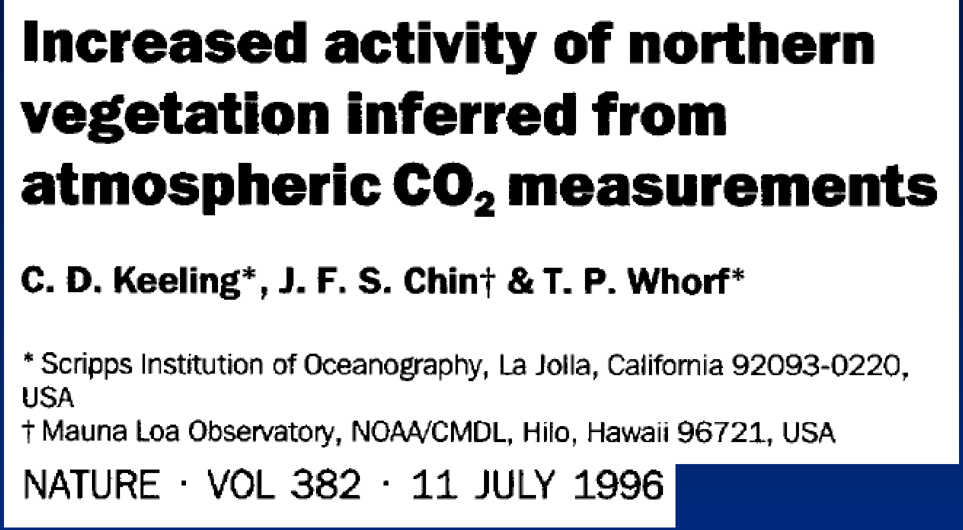
Detrended: A(t) S(t*)



Amplitude of Seasonal cycle A(t)



1961-1970 min in Oct
2001-2010 min in Sep



Increased activity of northern vegetation inferred from atmospheric CO_2 measurements

C. D. Keeling*, J. F. S. Chin† & T. P. Whorf*

* Scripps Institution of Oceanography, La Jolla, California 92093-0220, USA
† Mauna Loa Observatory, NOAA/CMDL, Hilo, Hawaii 96721, USA

NATURE · VOL 382 · 11 JULY 1996

The amplitude of CO2 seasonal cycle increased by 20% at MLO, 40% at Barrow from 1960-1995

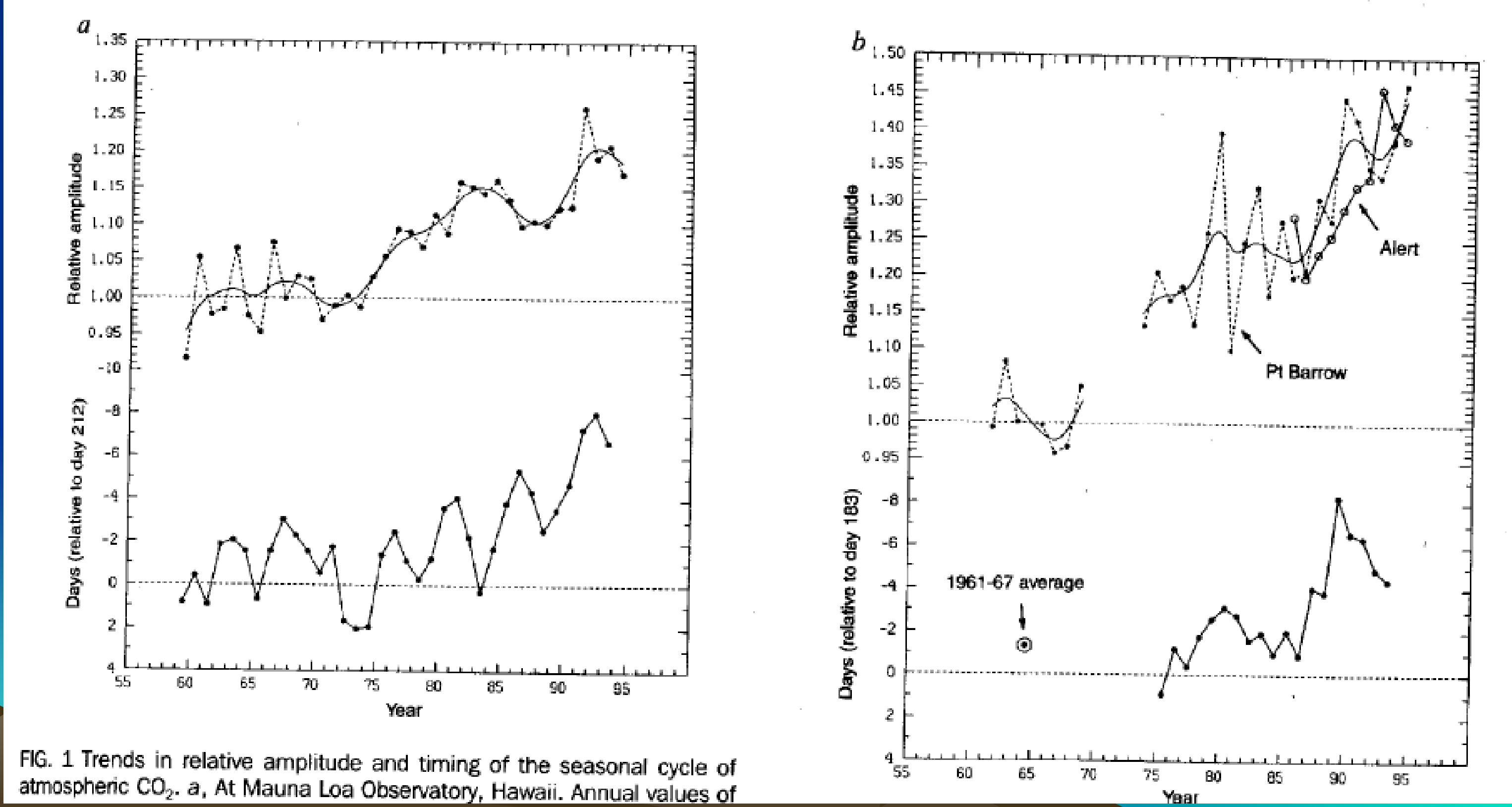


FIG. 1 Trends in relative amplitude and timing of the seasonal cycle of atmospheric CO_2. *a*, At Mauna Loa Observatory, Hawaii. Annual values of

Also:
Pearman and Hyson, 1981
Cleveland, 1983
Bacastow et al., 1985

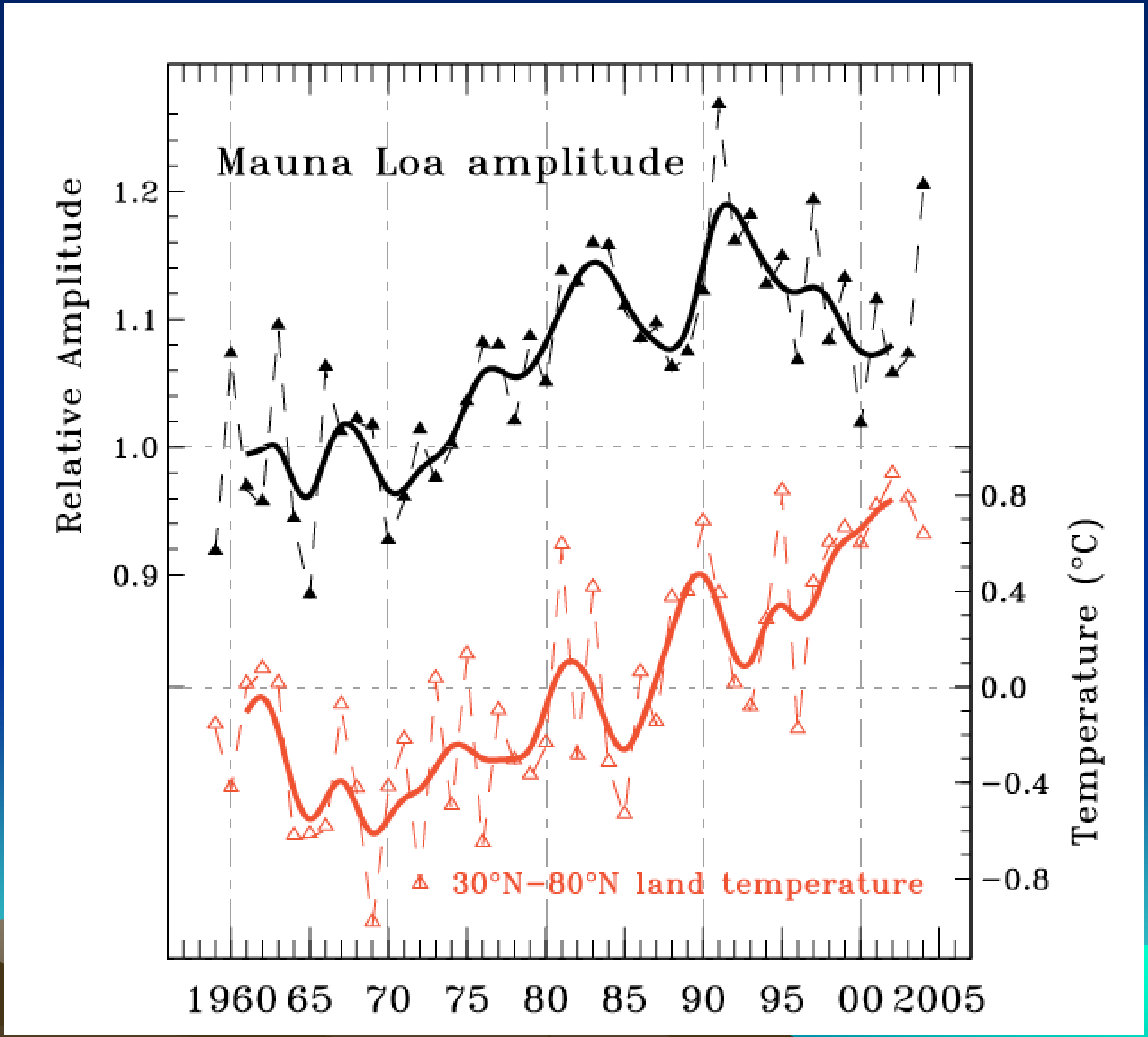
The changing carbon cycle at Mauna Loa Observatory

Wolfgang Buermann*[†], Benjamin R. Lintner[‡§], Charles D. Koven*, Alon Angert*[¶], Jorge E. Pinzon[‖], Compton J. Tucker[‖], and Inez Y. Fung*,**

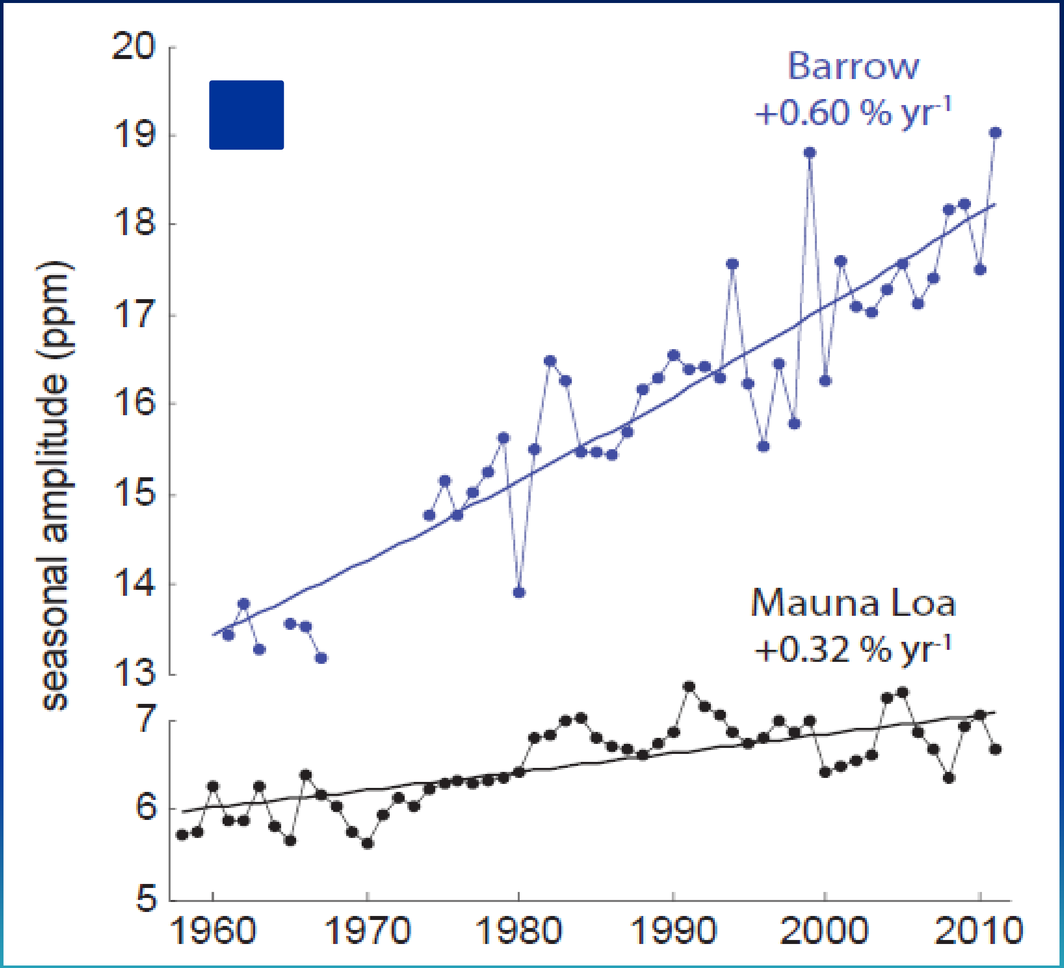
*Berkeley Atmospheric Sciences Center and [‡]Department of Geography, University of California, Berkeley, CA 94720; and [‖]National Aeronautics and Space Administration/Goddard Space Flight Center, Greenbelt, MD 20771

PNAS | March 13, 2007 | vol. 104 | no. 11 | 4249–4254

But
CO2 seasonal amplitude
decreased in the 1990s



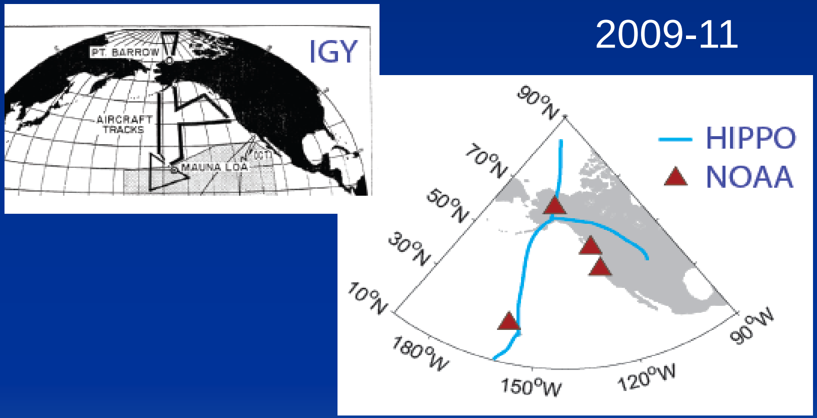
The seasonal amplitude of CO_2 has increased by 35% at Barrow and 15% at Mauna Loa since 1960



Comparison of aircraft data can now assess whether these trends are representative of the large-scale pattern

1958-61

2009-11



Graven et al., Science, 2013

Keeling et al. 1996; Keeling et al. 1968; Wofsy et al. 2011; C. Sweeney unpub. data

Our analysis: Data/model products

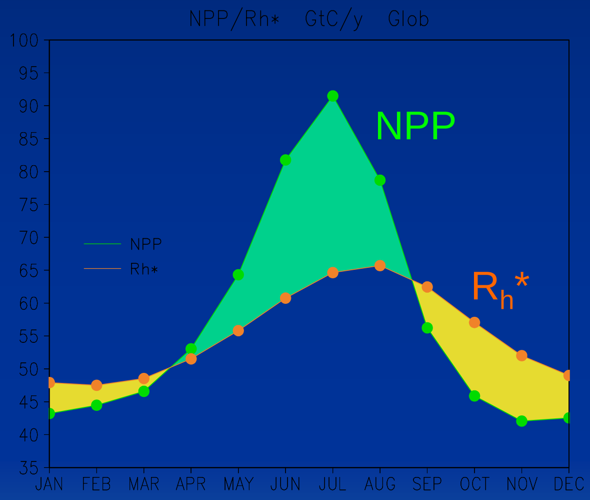
- MLO CO2
- Global CO2 index based on 20+ marine stations (NOAA/ESRL)
- Atmospheric inversions v3.4 (MPI/Jena)
- CarbonTracker 2011 (NOAA/ESRL)
- Terrestrial carbon models: VEGAS (UMD) + LPJ + ORCHIDEE
- Statistics (population, land use, crop production etc.)
- FLUXNET (Global network of eddy correlation towers to measure surface fluxes of evaporation, heat, CO2, etc.)

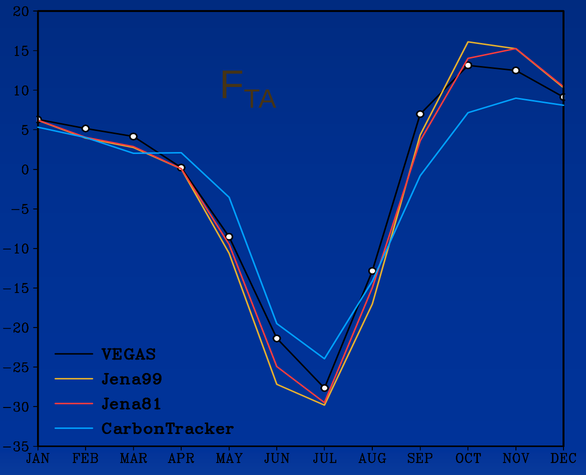
The mean CO2 seasonal cycle I

The dominance of Northern Hemisphere vegetation

- Vegetation takes up atmospheric CO2 during spring/summer growing season, while respiration and decomposition has a much weaker seasonal cycle

- $F_{TA} = R_h^* - NPP$





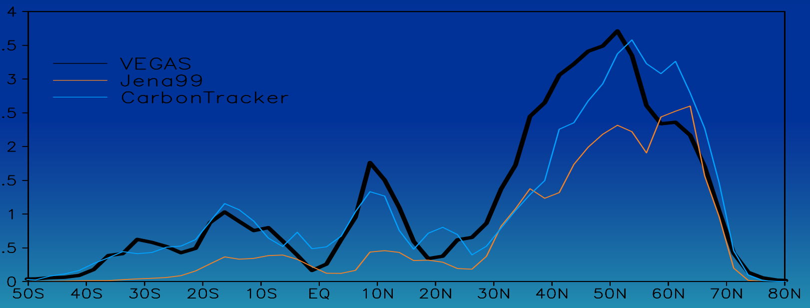
F_{TA} -- Net land-atmosphere carbon flux

R_h^*-- Respiration extended (including heterotrophic respiration, fire and other losses).

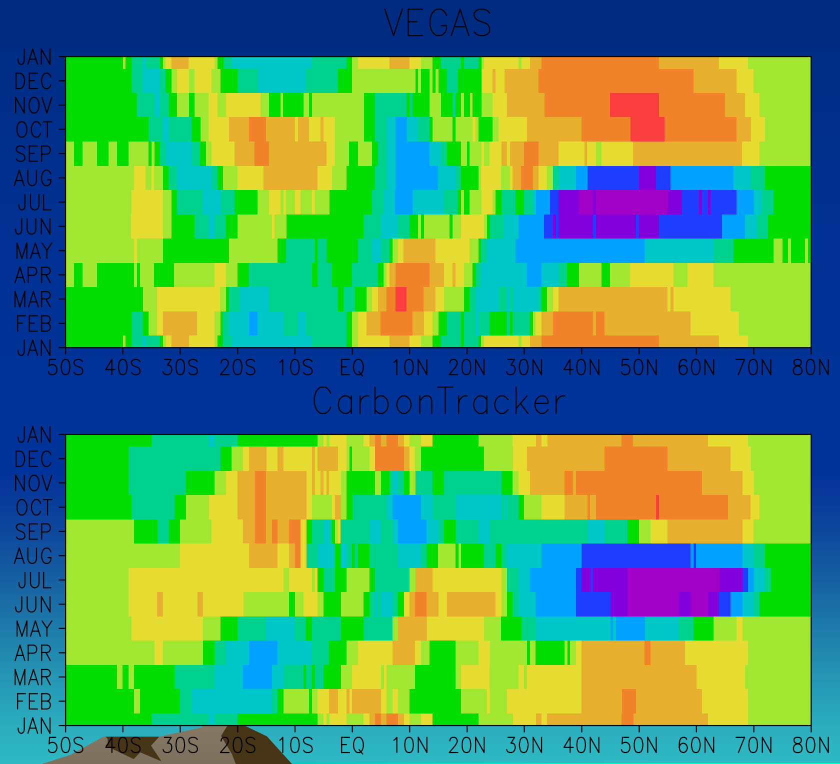
The mean CO2 seasonal cycle II

Comparison of mechanistic model with atmospheric inversions

Latitudinal distribution of F_{TA} seasonal amplitude (SA)



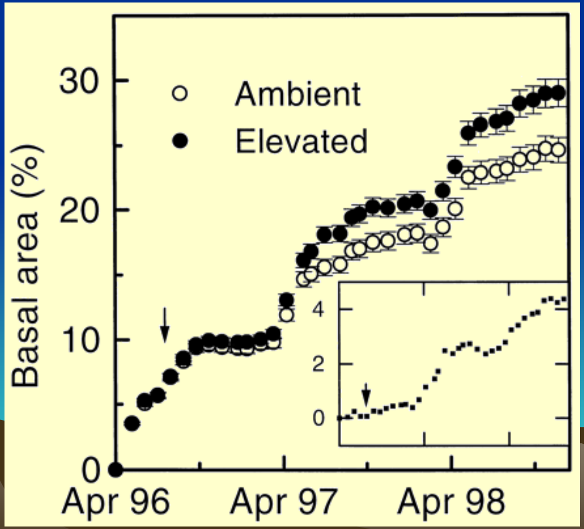
Latitude-time evolution of F_{TA}



What caused CSA increase?
CO2 fertilization+N,P

- Estimated contribution (Kohlmeier et al., 1989) for the CSA increase
  - CO2 (25%, based on lab), N/P deposition another 10-20%
  - May be even smaller given the recent understanding of the strength of the CO2 fertilization effect

FACE Experiments
(Free Air CO2 Enrichment)



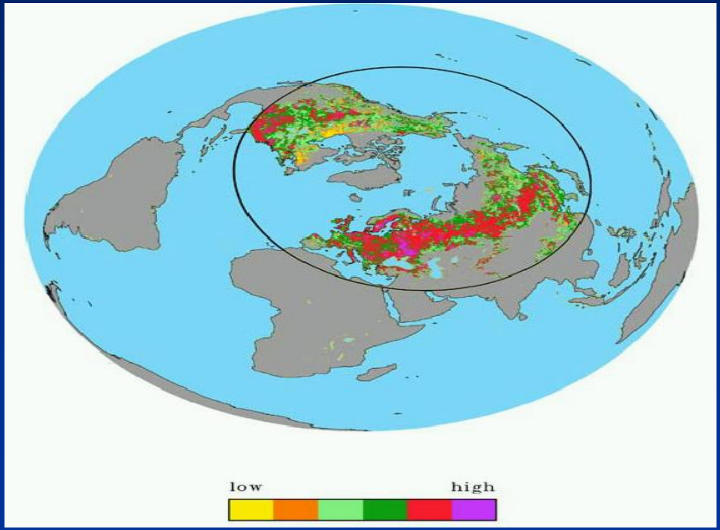
DeLucia et al., Science, 1999

Schlesinger et al., Nature, 2001

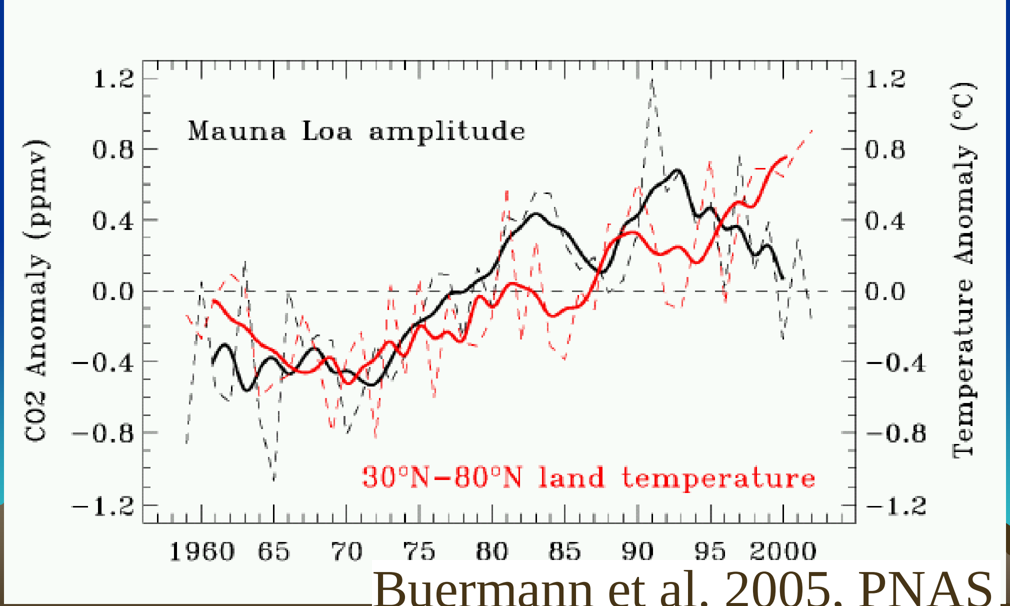
What caused CSA increase?
High-latitude warming

Estimated contribution (Keeling et al., 1996) for the CSA increase

- 10-25%, based on NPP dependence on temperature



Greening of the high latitude due to warming that leads to higher NPP, higher CO2 drawdown during growing season



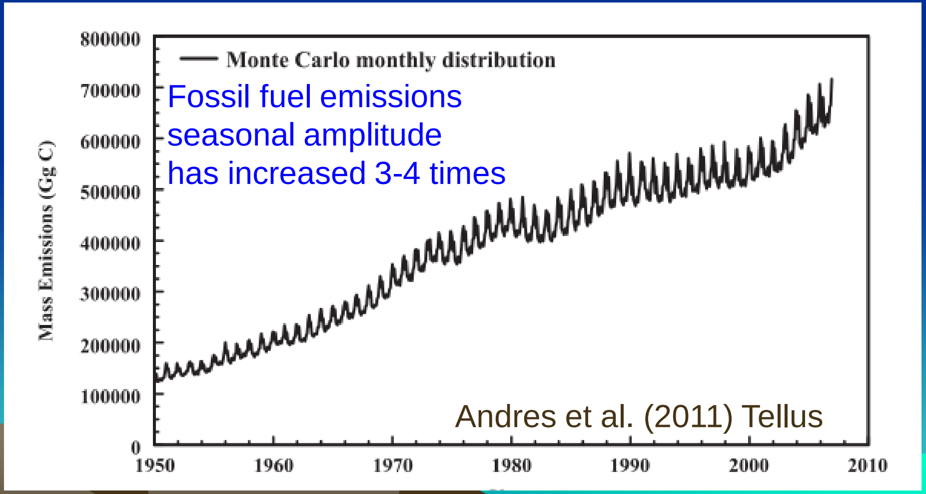
Buermann et al. 2005, PNAS

1970-80s: Increase: warming?
1990s on: Level-off/decrease: drought?

Proposed causes of CSA increase
Other factors

- FFE and ocean 5% (Kohlmeier et al., 1989)

All together (land+ocean+FFE), about 60% can be explained with the combination of the above mechanisms



Fossil fuel emissions seasonal amplitude has increased 3-4 times

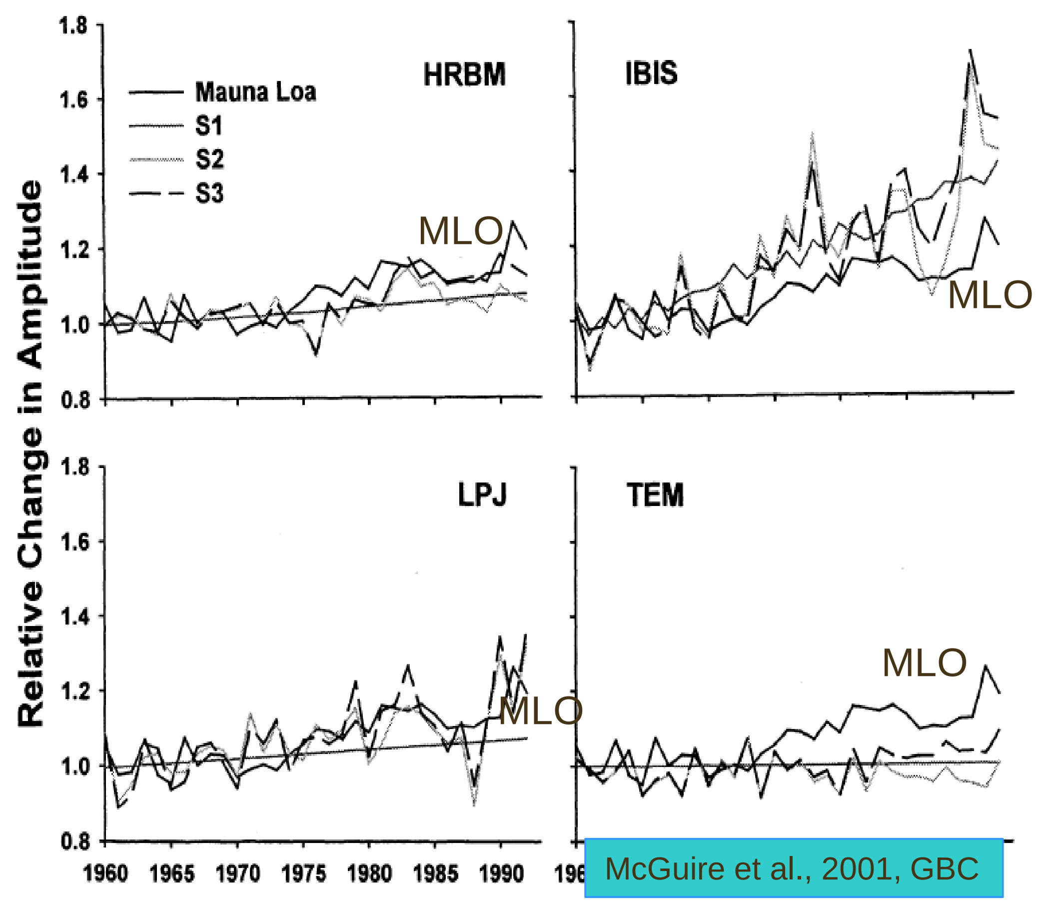
Andres et al. (2011) Tellus

Testing these hypotheses with mechanistic models (CCMLP)

- Terrestrial carbon models driven by
  - CO2 (S1)
  - CO2+Climate (S2)
  - CO2+Climate+Land use (S3)

- Results
  - 3 of the 4 models simulated larger than observed CSA increase, one almost none
  - Dominated by CO2 fertilization
  - Climate effect is uncertain
  - Land use contributed slightly to CSA increase in 3 models

How does this compared to the 60% estimate above?



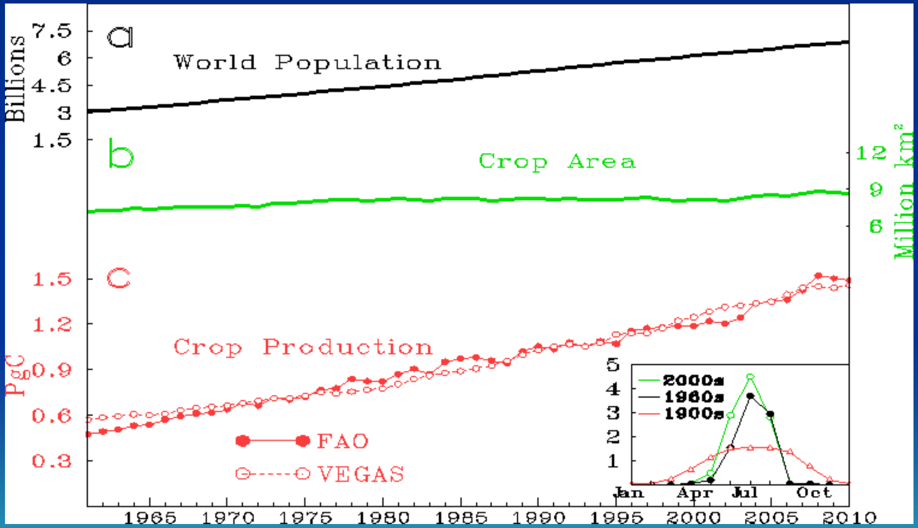
McGuire et al., 2001, GBC

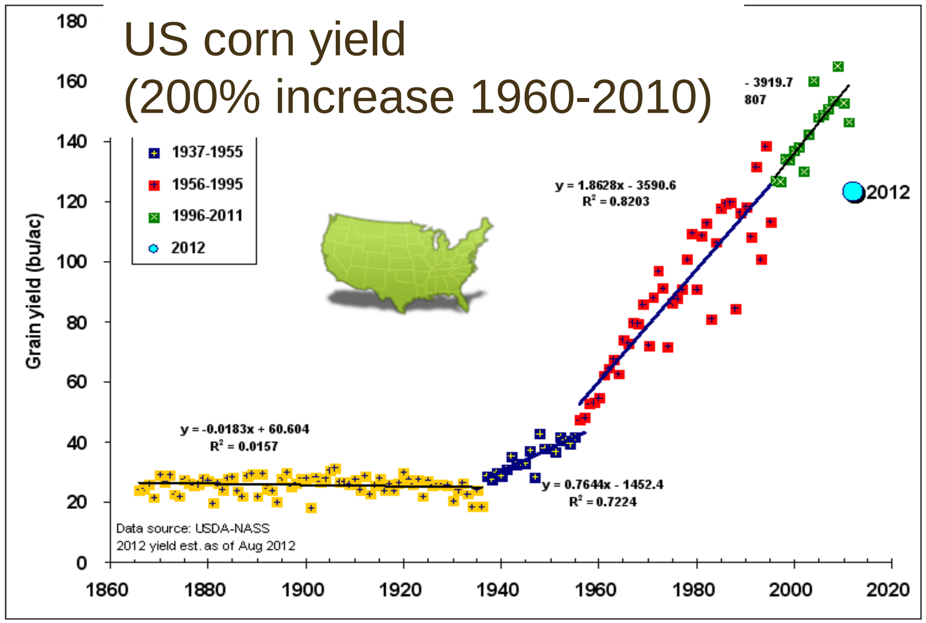
CCMLP: the “Grand Slam” Project, McGuire et al., 2001

A closer look at land use

Not just land cover change, but also management intensity

- Over the last 5 decades (1961-2010)
  - World population increased from 3 to 7 billion (130%)
  - Crop production increased from 0.5 to 1.5 PgC/y (200%)
  - Crop area 7.2 to 8.7 Mkm2 (20%)





Hoerling et al., BAMS 2014

In comparison, cropland area hardly increased

China vs. US: Yield

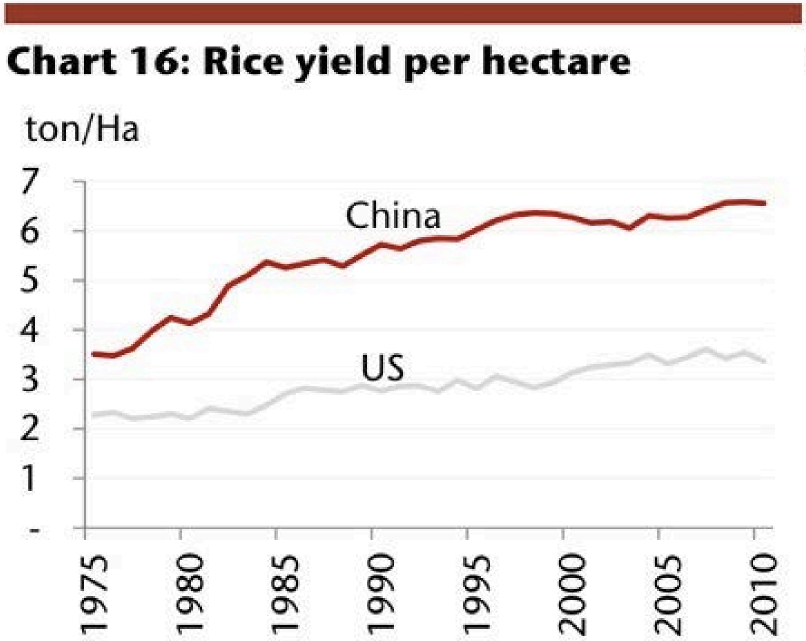


Chart 16: Rice yield per hectare

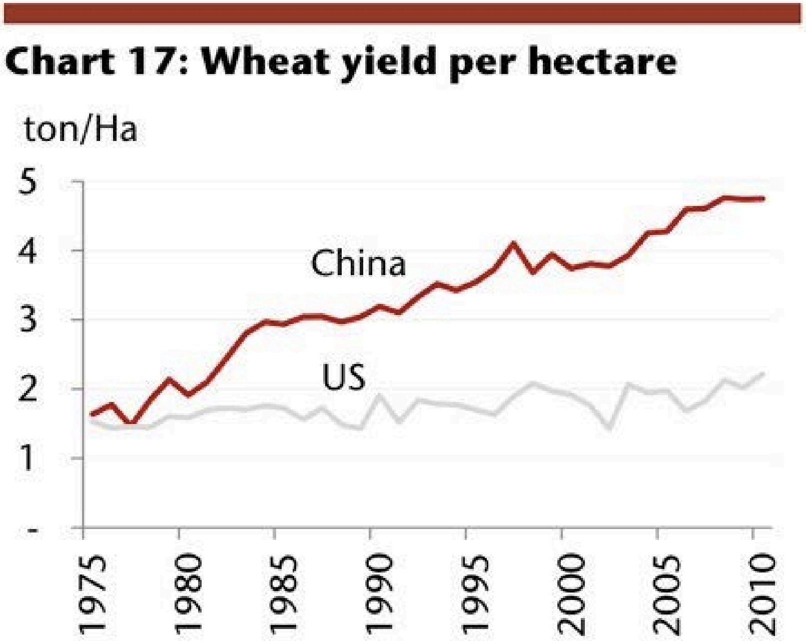


Chart 17: Wheat yield per hectare

Yield: China is 2 times higher
Fertilizer use per hectare: China is three times higher

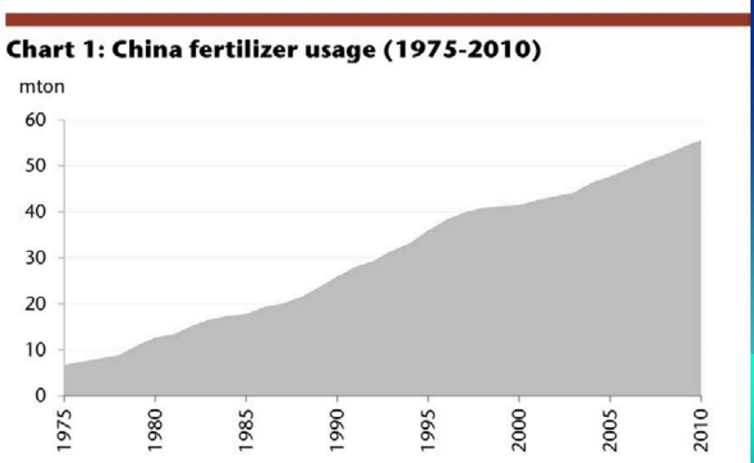


Chart 1: China fertilizer usage (1975-2010)

Can intensification of agriculture contribute to CSA increase?

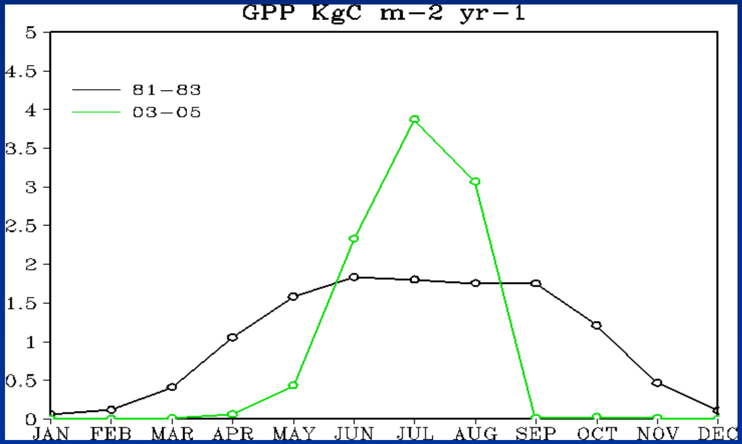
- Global NPP is 60 PgC/y, of which about 6-8 PgC/y is human appropriated NPP (HANPP)
- Now assume HANPP doubled as the result of the agricultural Green Revolution since 1960, so that ΔNPP=3 PgC/y
- Further assume that seasonal characteristics (shape/phase) of NPP and Rh do not change (e.g., Randerson et al., 1999)

This leads to a NPP change of 3/60=5% change, 1/3 of observed CSA increase at MLO

Test this hypothesis in a mechanistic model…

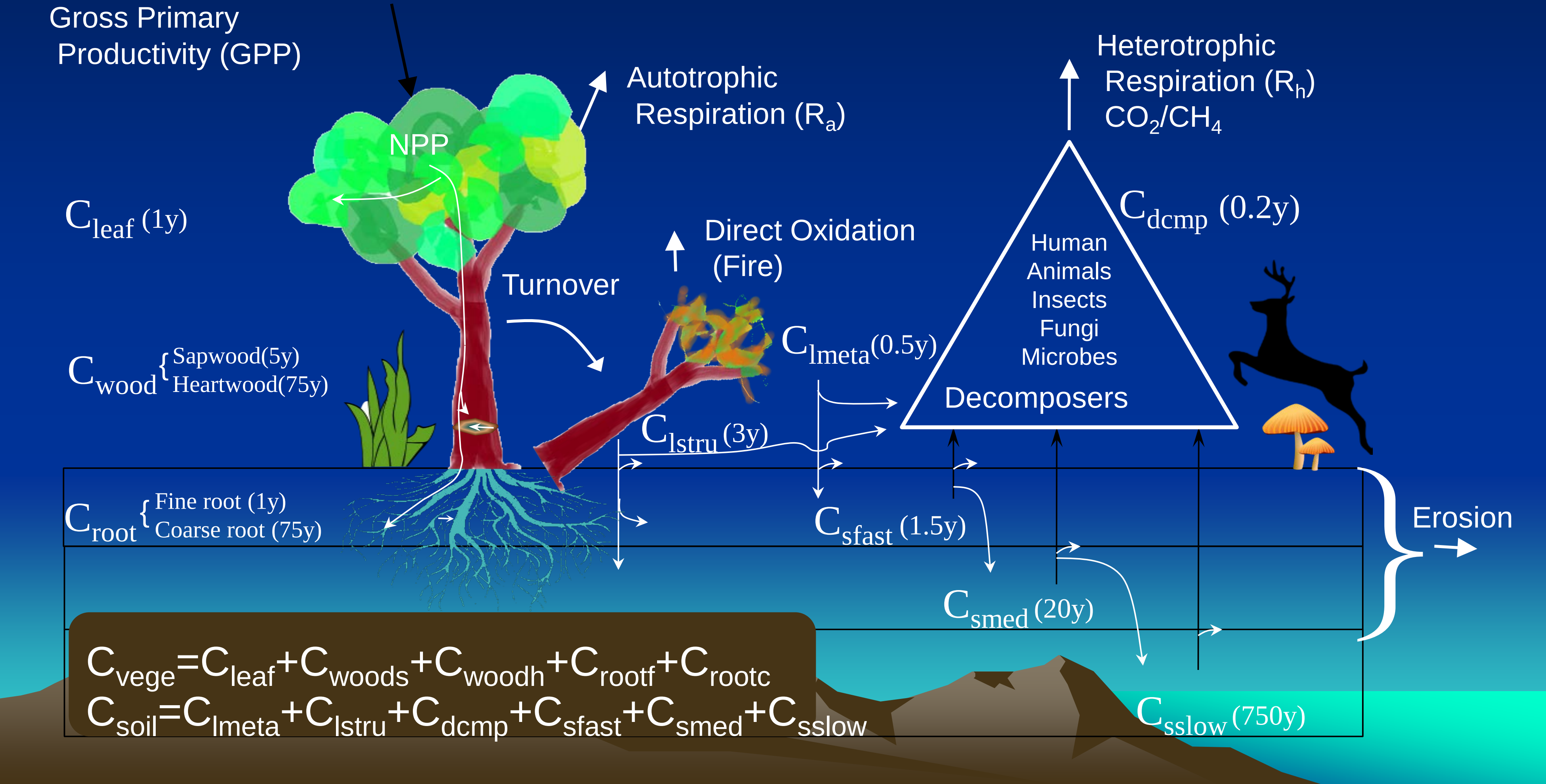
Modeling agriculture in VEGAS

- One generic crop functional type that represents an average of the 3 dominant crops: maize, wheat, and rice



- Avoiding large amount of input data and parameters in a typical crop model that are not available for the timescale of interest
- Our target is to capture the 1st-order effects on global carbon cycle
- First such attempt in global carbon cycle models

The VEgetation-Global Atmosphere-Soil Model (VEGAS)



Gross Primary Productivity (GPP)

NPP

Autotrophic Respiration (R_a)

C_{leaf} (1y)

C_{wood} {Sapwood(5y), Heartwood(75y)

C_{root} {Fine root (1y), Coarse root (75y)

Turnover

Direct Oxidation (Fire)

C_{lmeta}(0.5y)

C_{lstru} (3y)

C_{sfast} (1.5y)

C_{smed} (20y)

C_{sslow} (750y)

Heterotrophic Respiration (R_h) CO_2/CH_4

C_{dcmp} (0.2y)

Human
Animals
Insects
Fungi
Microbes

Decomposers

Erosion

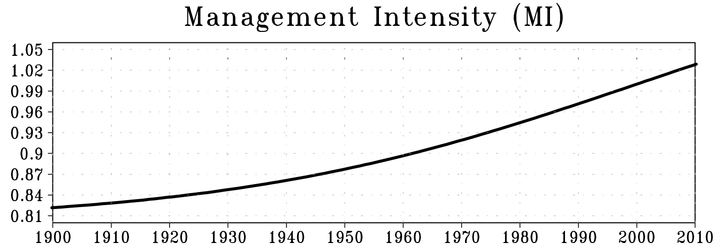
$$C_{vege}=C_{leaf}+C_{woods}+C_{woodh}+C_{rootf}+C_{rootc}$$

$$C_{soil}=C_{lmeta}+C_{lstru}+C_{dcmp}+C_{sfast}+C_{smed}+C_{sslow}$$

Cropland management change over time

---Modeling the Agricultural Green Revolution

- Three major factors changed over time and are thought to have contributed equally to increase in agricultural productivity in the later half of the 20th century (Sinclair, 1998)
  - High-yield cultivars
  - Fertilizer/pesticide
  - Irrigation



- Due to lack of data, simple rules are used. A management intensity factor (MI) due to cultivar and fertilizer enhanced productivity is a function of space (M_1, regional difference) and time:

$$MI = M_0 M_1 \left(1 + 0.2\tanh\left(\frac{year - 2000}{70}\right)\right)$$

- Irrigation enhances GPP by a ‘gentle’ enhancement of the soil moisture dependent function:

$$\beta = 1 - \frac{1 - w_1}{W_{irrg}}$$

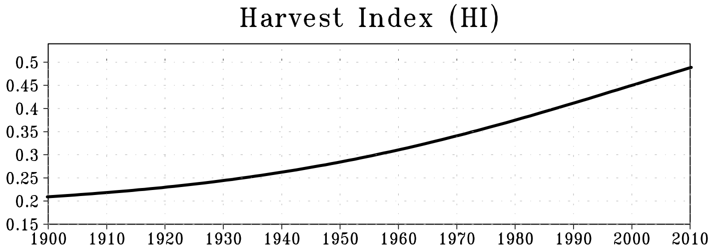
Planting and havesting

Harvest Index (HI) change over time

- Planting is allowed whenever climate condition is suitable, .e.g. due to spring warming in cold/temperate climate, i.e., “potential crop”
  - Captures much of temperate agriculture
  - Doesn’t get winter wheat which grows earlier
- Harvest occurs when leaf area index (LAI) growth rate slows to a threshold
  - May lead to double crop in some tropical regions
- After harvest, grain goes into a harvest pool while the remainder goes to the two litter pools. The harvest grain is laterally transported according to population density and trade
- Harvest Index (HI) is the ratio of grain and total above ground biomass.

$$HI_{crop} = 0.45(1+0.6\tanh(\frac{year-2000}{70}))$$

HI is 0.45 in 2000, and 0.31 in 1960: result of high yield cultivar



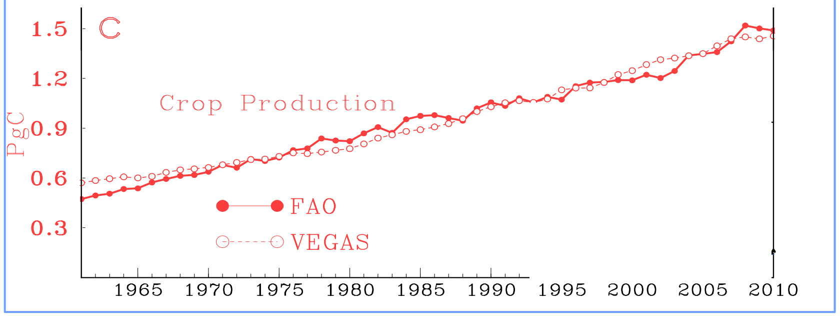
Deforestation, crop abandonment and regrowth

- A sub-grid mesh to represent age-structure without change of model structure: an idea explored and developed over last 10 years.
- A 0.5x0.5 resolution simulation is represented by a mosaic at 0.125x0.125 resolution, so that each grid contains 16 sub-grids, representing 16 cohorts of different age.
- Final results are aggregated back to 0.5x0.5 degree resolution.
- Results can also be provided on finer resolution, and in fact the finer resolution is closer to reality (such as from high resolution remote sensing product) than the cropland fractional coverage information provided in a typical land use dataset that based on statistics.

Validation of crop simulation in VEGAS

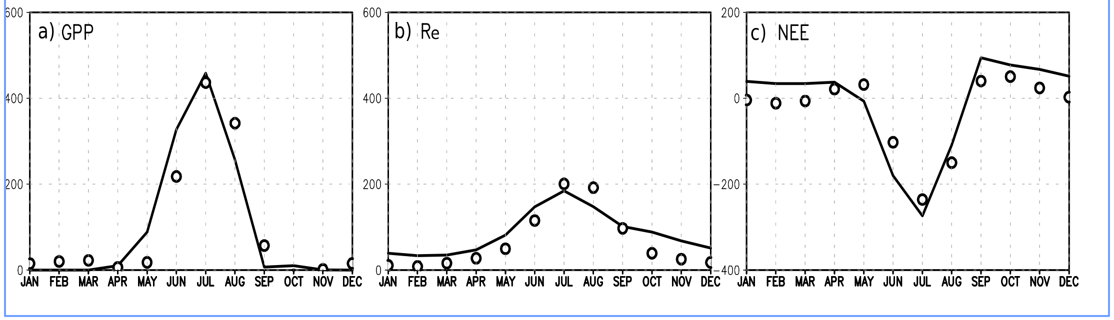
(Simulation: TRENDY protocol: forced by climate, CO2, and land use)

1. Crop production increased by 0.8, compared to FAO by 1 PgC/y



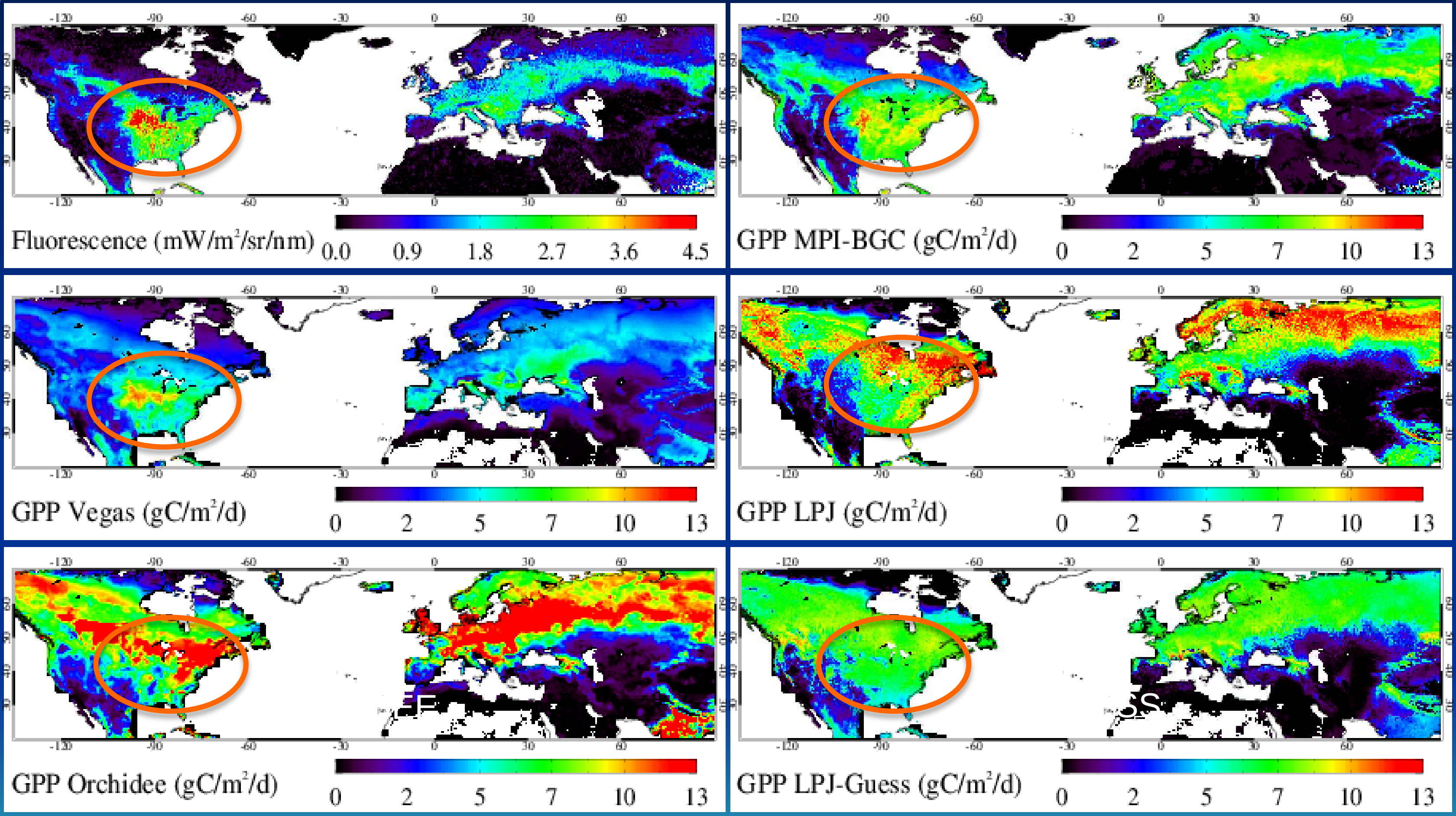
2. Simulated crop NPP_{crop} is 6.2 PgC/y, compared to HANPP 6-8 PgC/y (Vitousek et al., 1986; Haberl et al., 2006)

3. Comparison of VEGAS with FLUXNET measurement at Bondville, Illinois



Sun-induced Chlorophyll fluorescence (SIF):
Comparison with GPP from data-driven estimates MTE of MPI-Jena
and 4 TRENDY carbon models (LPJ, ORCHIDEE, LPJ-GUESS and VEGAS)

July 2009

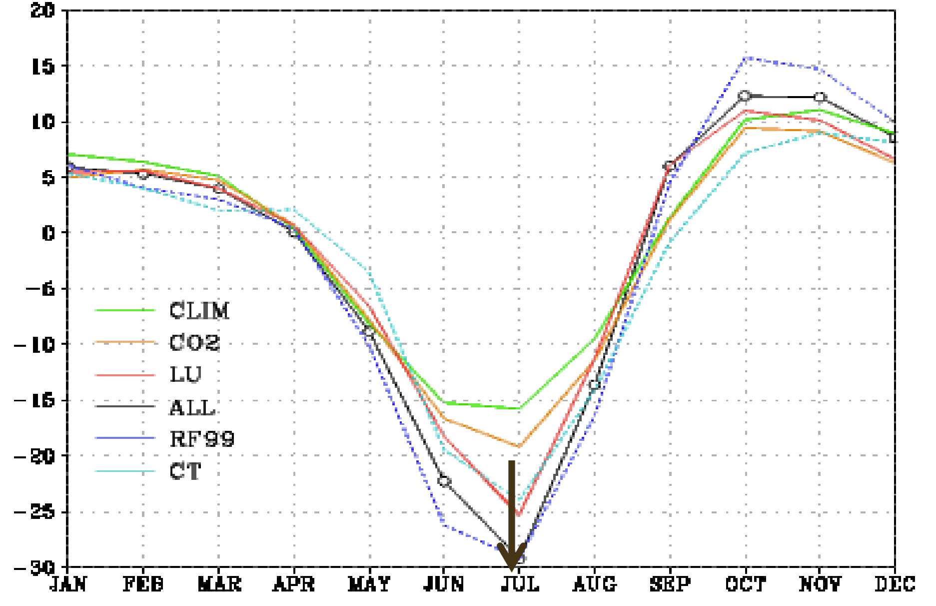


Most models miss the high productivity in agricultural region, except for one…

Guanter et al. (2014), PNAS

Impact of agriculture on modeled seasonal cycle

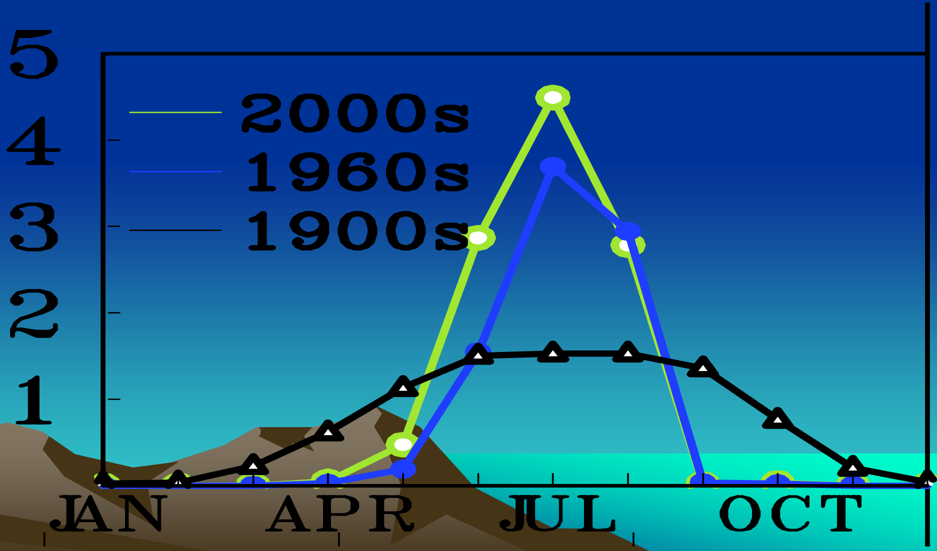
Mean seasonal cycle has a larger drawdown during growing season (~20%)



Seasonal characteristics change

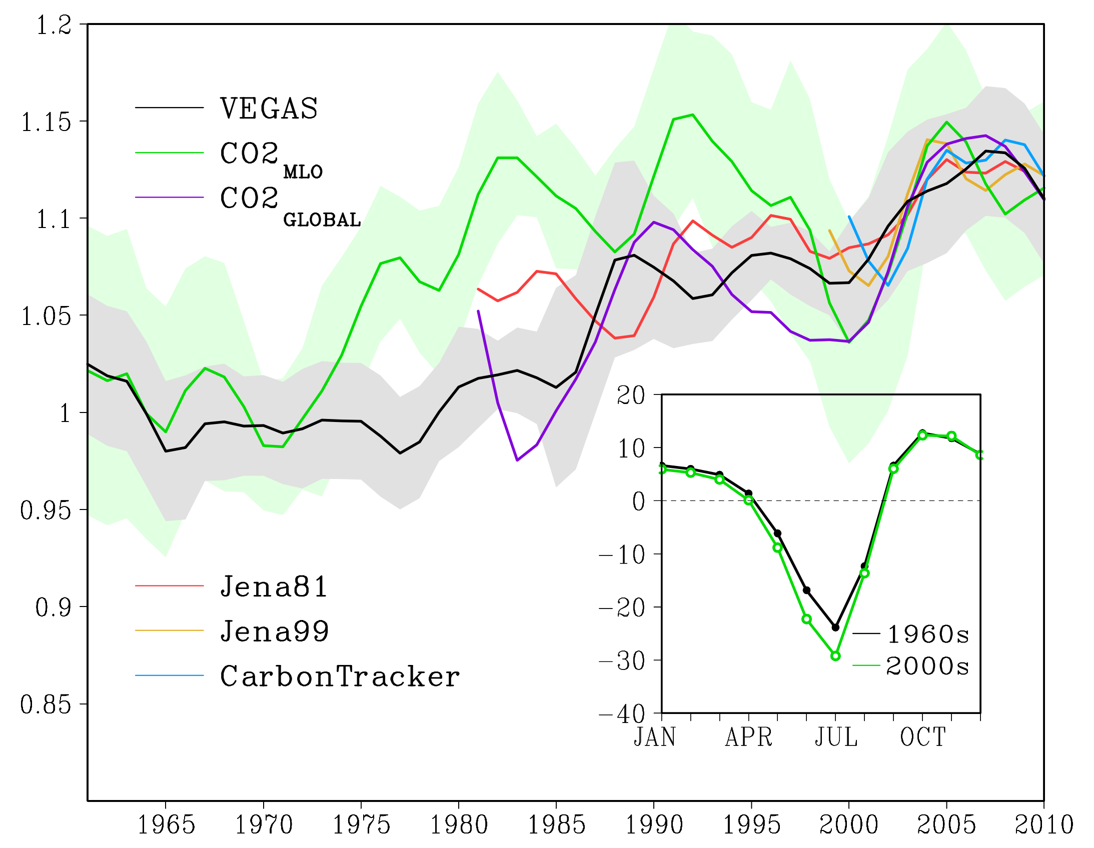
GPP change at a US Midwest location

1900s – Natural vegetation
1960s - Agriculture
2000s – Agriculture intensified



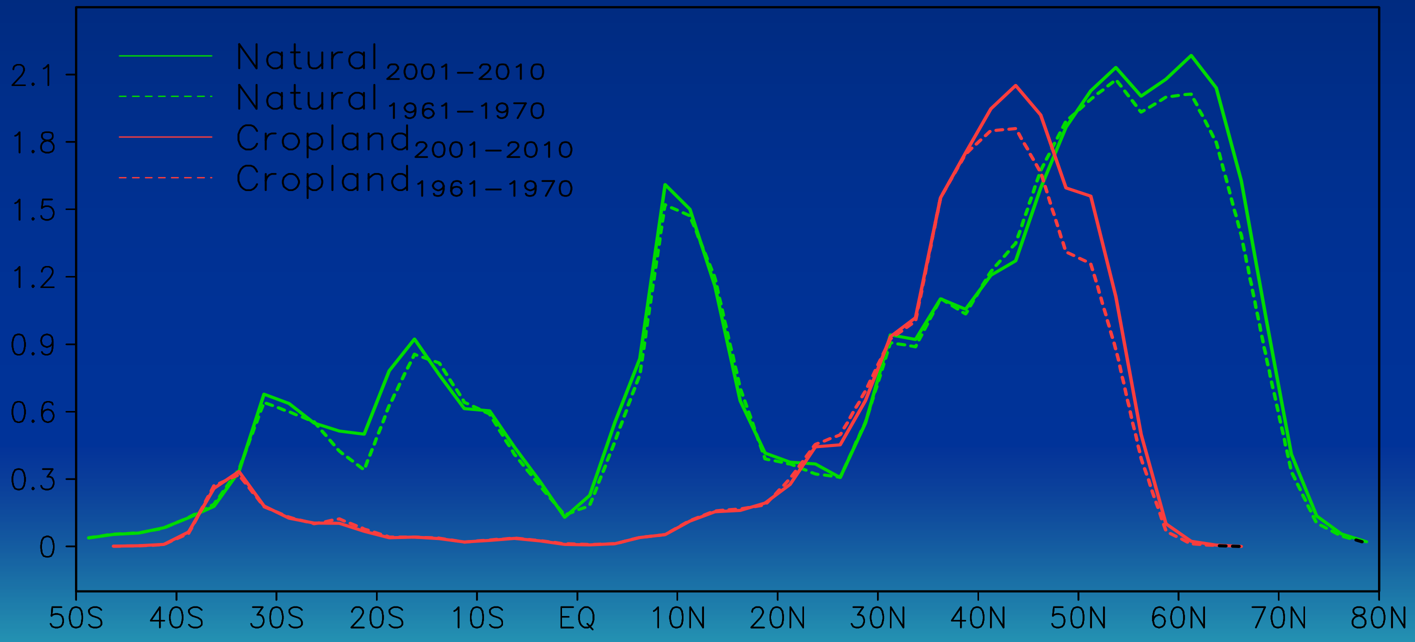
Change in CSA 1961-2010

- A long-term increase in seasonal amplitude (SA) by about 15% (MLO CO2g and VEGAS F_{TA})
- Large dacadal (interannual filtered out) variability
- Good (but not great) agreement on both trend and decadal variability among model, CO2 (MLO and GlOBAL), inversions (MPI/Jena and CarbonTracker)
- Compared to the 1960s, 2000s has a larger drawdown in NH spring/summer; early by about 10 days
- Corresponding to an stronger mean carbon sink by 1.6 PgC/y

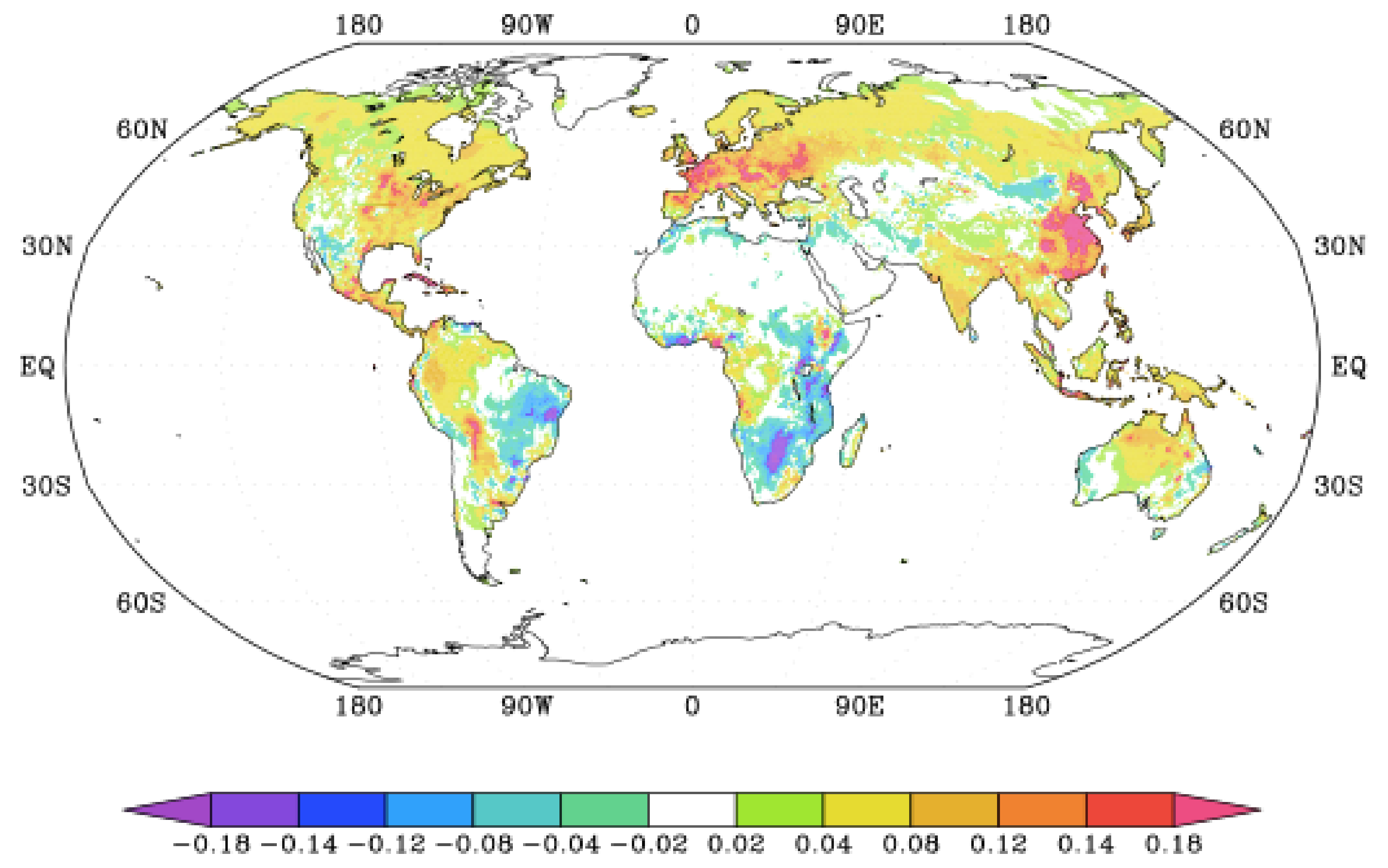


Zeng et al., 2014, Nature, revised

Separating cropland and natural vegetation

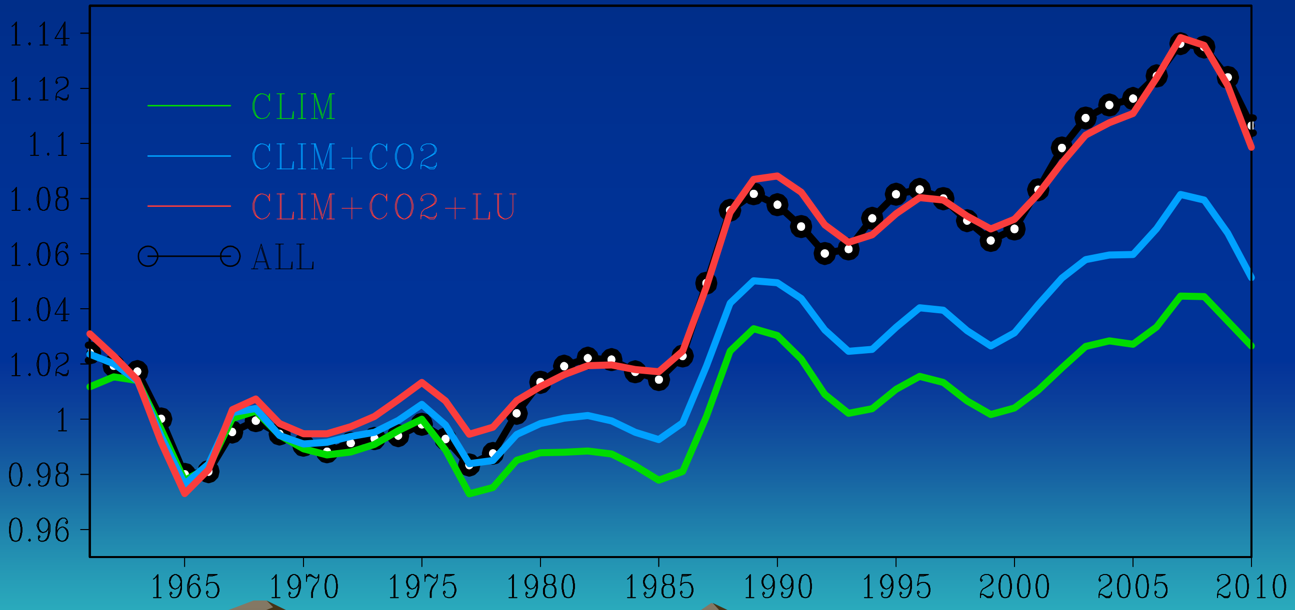


1961-2010 trend in NPP



Sensitivity experiments

CLIM: Climate only
CO2: CO2 fertilization only
LU: Land use and management



Conclusion

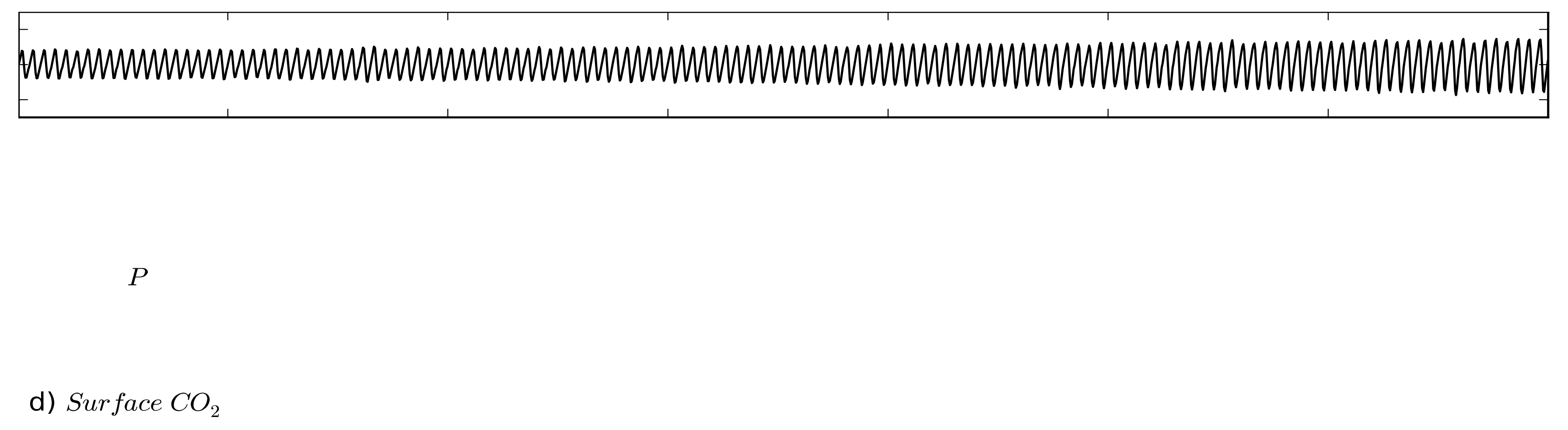
- The basic rhythm of the biosphere: seasonal ‘breathing’ has been changing: 15% increase in CSA with large decadal-interannual variations
- CO2 fertilization, high latitude warming contributed
- We suggest a missing link: the intensification of agriculture

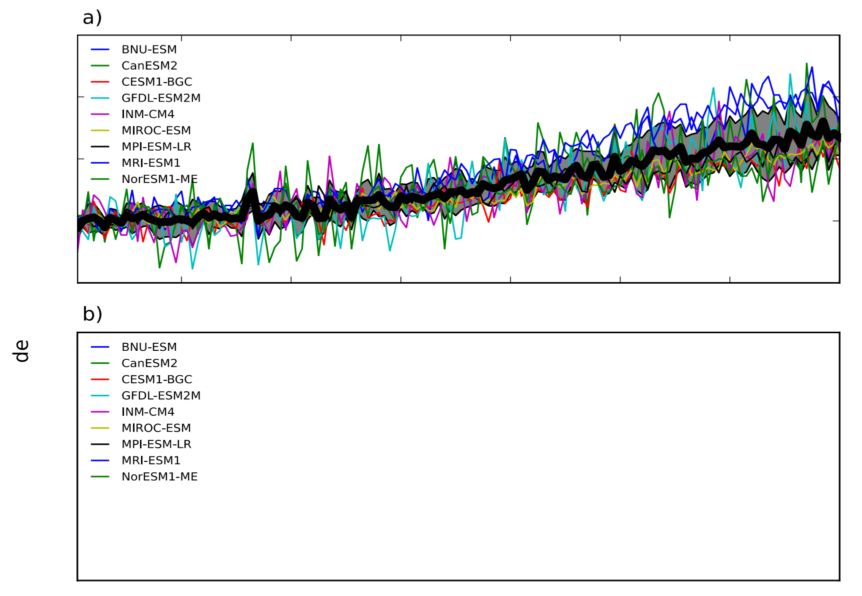
* Human impact on the biosphere/climate is complex

Question: How is this ‘enhanced’ activity related to the mean land carbon sink?

Thank you!

CMIP5 ESM model projections

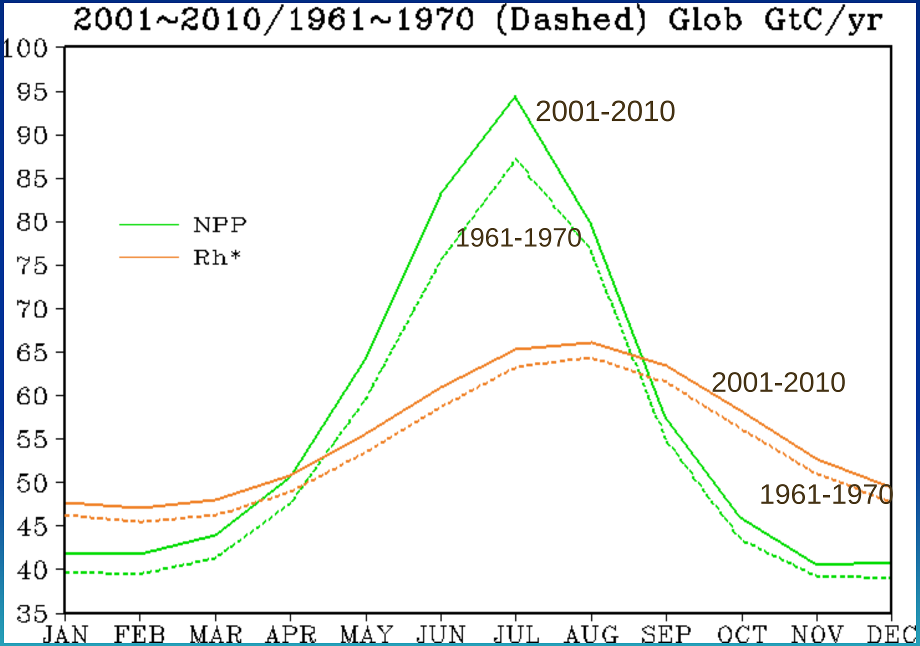


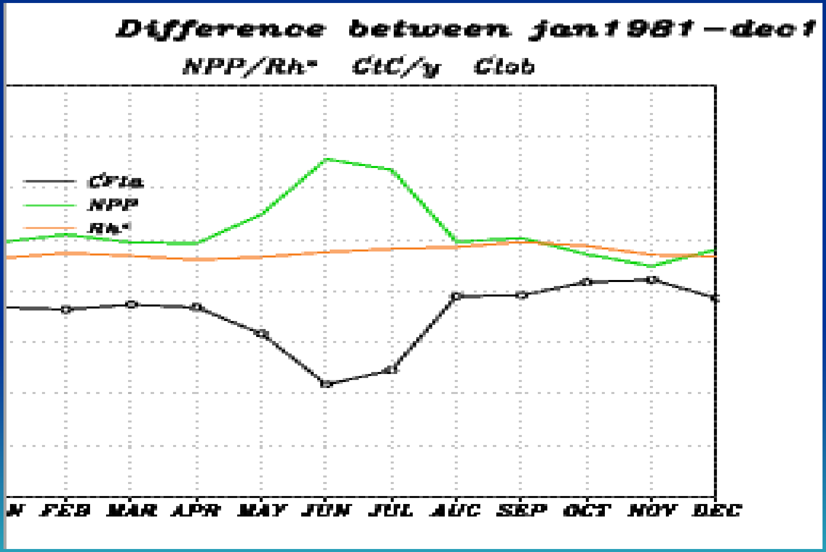


- CO_2 seasonal amplitude increase by 74% over 120 years
- The trend of minimums has a larger magnitude than the trend of maximums
- The surface CO_2 amplitude increase estimated by the models is lower than ESRL's global CO_2 estimate, however the changes of amplitude are similar

Zhao and Zeng, ESDD, 2014

NPP vs. R_h*


2001~2010/1961~1970 (Dashed) Glob GtC/yr
100
95
90
85
80
75
70
65
60
55
50
45
40
35
NPP
Rh*
2001-2010
1961-1970
2001-2010
1961-1970
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC


Difference between jan1981 –dec1
NPP/Rh* GtC/y Glob
CFla
NPP
Rh*
N
FEB
MAR
APR
MAY
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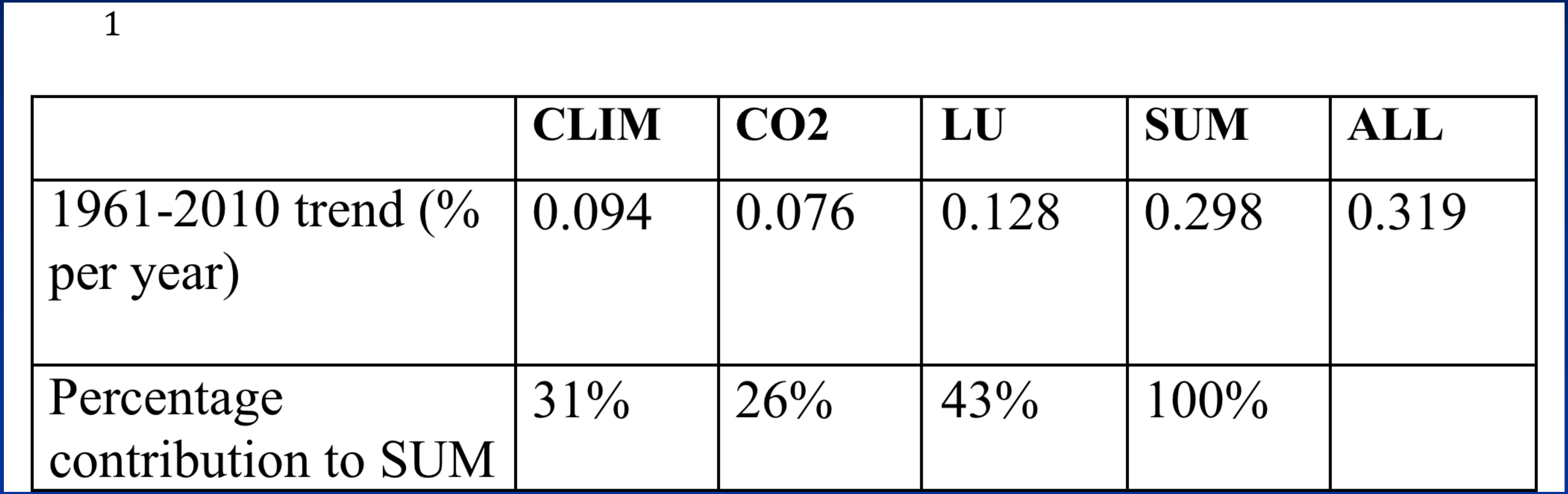
AUG
SEP
OCT
NOV
DEC

Summary

- Land

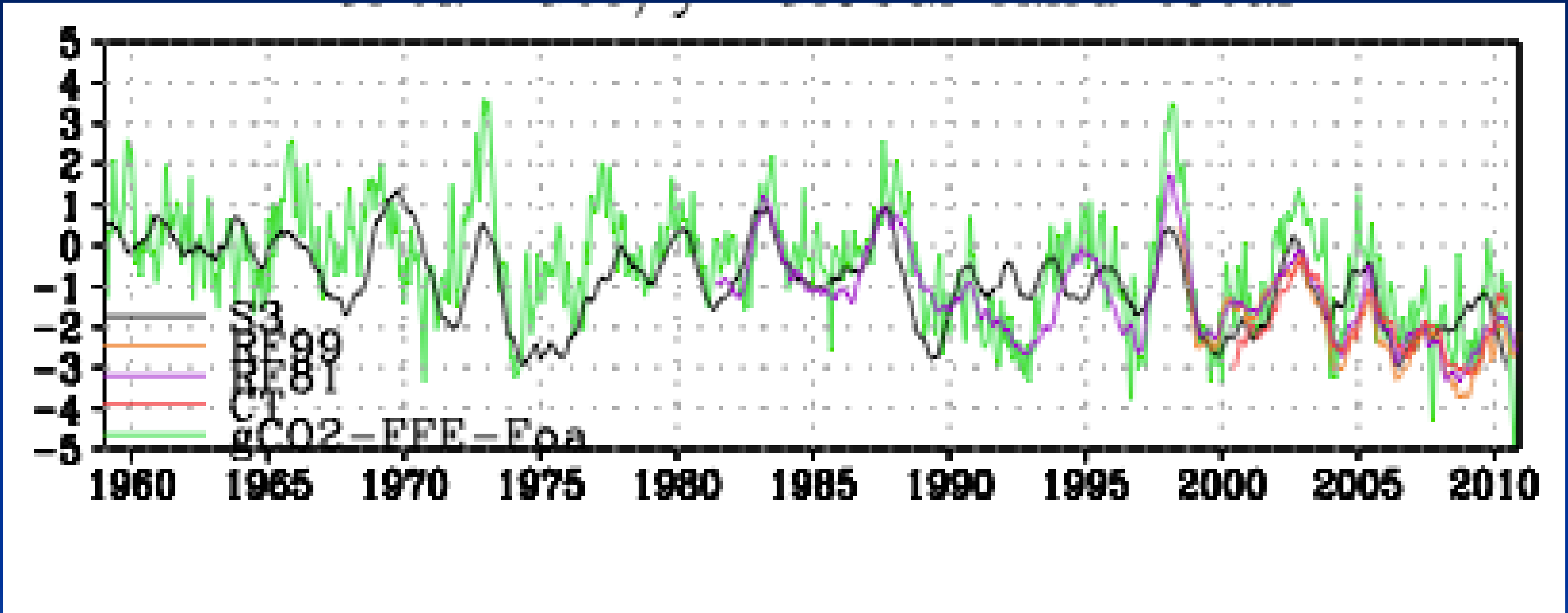


	CLIM	**CO2**	**LU**	**SUM**	**ALL**
1961-2010 trend (% per year)	0.094	0.076	0.128	0.298	0.319
Percentage contribution to SUM	31%	26%	43%	100%	

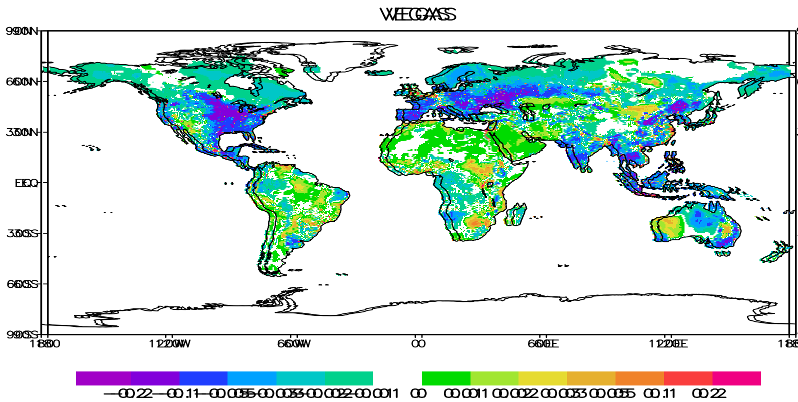
- Ocean/FFE: some influence

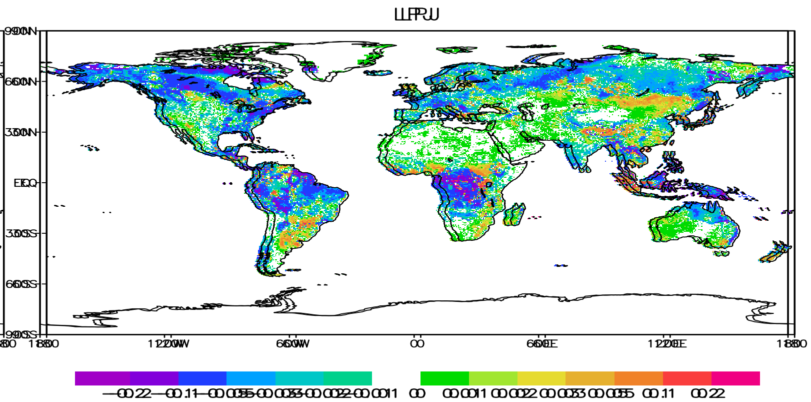
Mean sink and trends

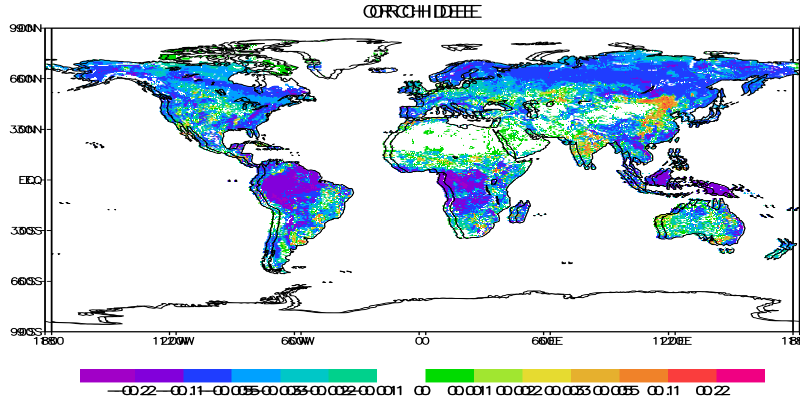
---More model simulation results

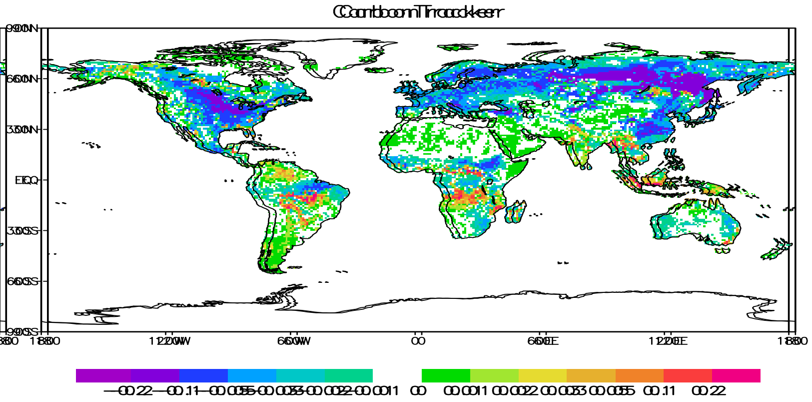


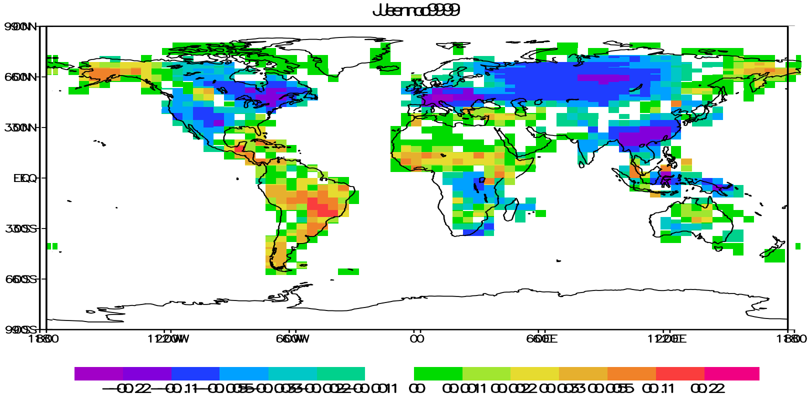
Interannual variability and long-term trend (deseasonalized)









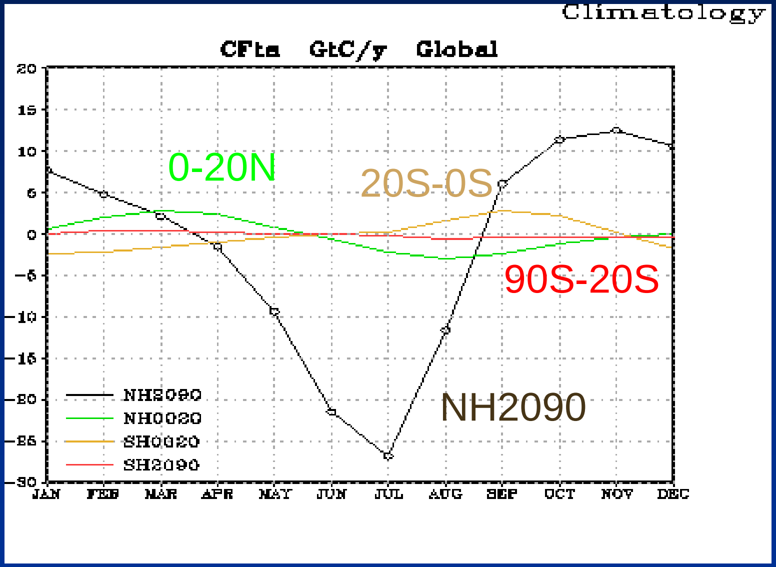


Land-atmo flux F_{TA} (2001-2010)
Multi-models and inversions

Spatial patterns of carbon sinks are highly uncertain!

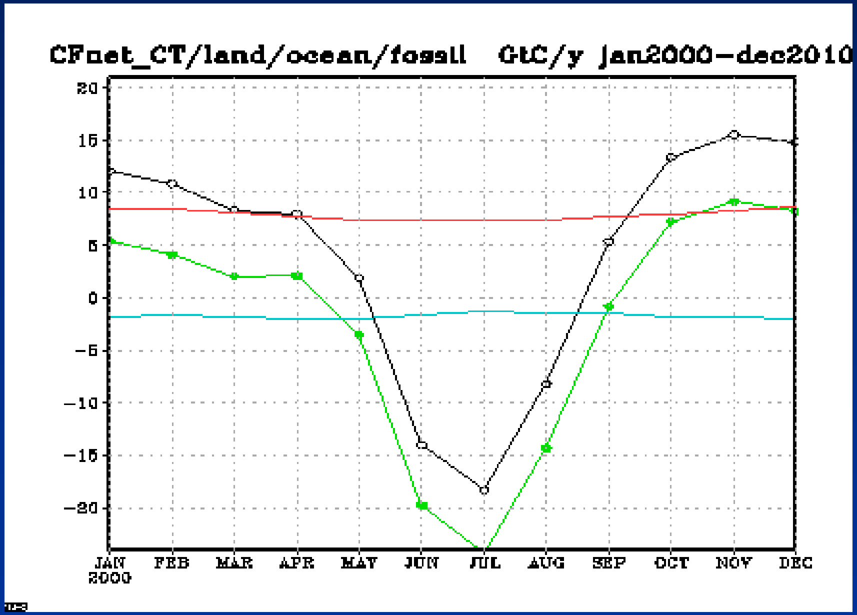
The mean CO2 seasonal cycle II
The Tropics and the Southern Hemisphere

- The Southern Hemisphere land mid-high latitude region has a seasonal cycle opposite of the Northern Hemisphere, but the total amount of biospheric production is much smaller than NH due to the smaller land area in the SH
- The tropical vegetation has small seasonal cycle because growth is largely year round
- Subtropical land off the equatorial zone, wet and dry seasons caused by the movement of the ITCZ and monsoons leads to modest seasonal changes but the regions north and south of the equator are out of phase so they largely cancel each other out



The mean CO2 seasonal cycle III
Ocean and fossil fuel

- Atmosphere CO2 growth rate (CO2g=dCO_2/dt) is determined by Fossil fuel emissions (FFE), ocean and land fluxes:



$$CO2g = F_{net} = F_{FE} + F_{OA} + F_{TA}$$

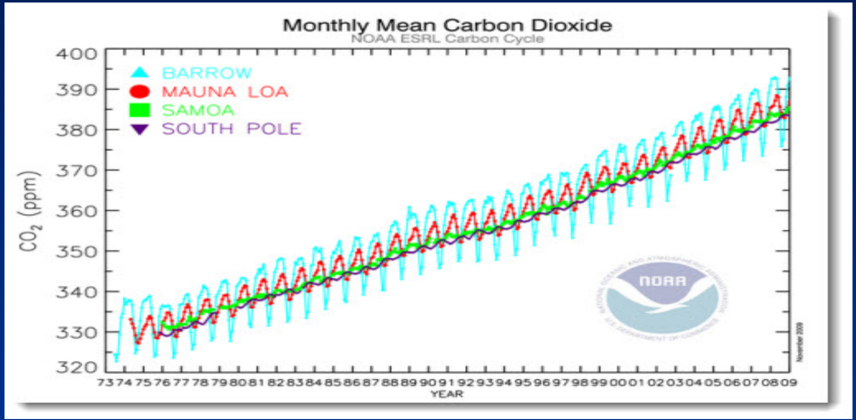
- Fossil fuel emissions has a small seasonal cycle, broadly in phase with terrestrial flux. Similar to vegetation, NH dominates over SH also for FFE because of the larger population in the NH.
- Oceanic CO2 flux has a small seasonal cycle that is probably opposite of terrestrial.

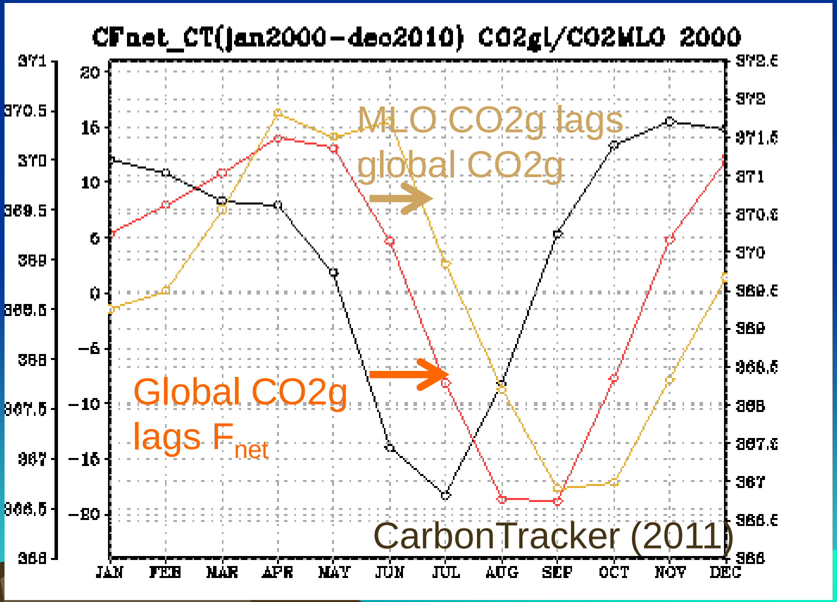
The mean CO2 seasonal cycle IV

Atmospheric transport

- The CO2 seasonal cycle at different site can be drastically different. This reflects the source distribution, but also importantly, the atmospheric transport: fast in the zonal direction (several days), but relatively slow in the meridional direction. In particular, cross-equator mixing is on the order of 1 year
- Phase lag between surface-atmosphere flux and CO2 concentration. The July max in F_{net} corresponds to the fastest drawdown of CO2, but not the minimum of CO2 itself. Instead, the minimum of CO2 is reached when F_{net} is zero in October. Because NH vegetation growing season is concentrated in the summer, the seasonal cycle is not symmetric: CO2 decreases only from May-September, with major decreases in only 3 months June-August.

$$dCO2_{global}/dt = F_{net}$$





MLO CO2g lags global CO2g

Global CO2g lags F_{net}

CarbonTracker (2011)