The Science and Ecology of Carbon Offsets

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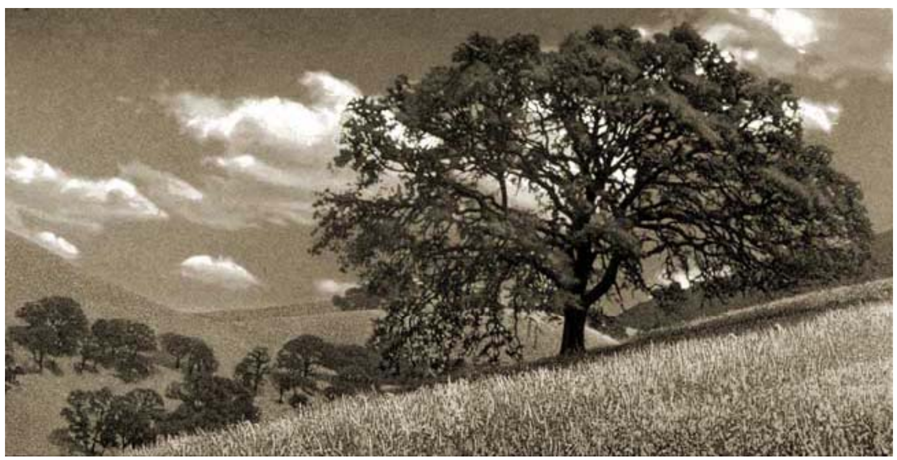


2007 Max Planck Institute for Biogeochemistry, Jena

If Papal Indulgences can save us from burning in Hell:
Can Carbon Indulgences Solve Global Warming?

Concluding Issues to Consider

- Vegetation operates less than ½ of the year and is a solar collector with less than 2% efficiency
  - Solar panels work 365 days per year and have an efficiency of 20%+
- Ecological Scaling Laws are associated with Planting Trees
  - Mass scales with the -4/3 power of tree density
- Available Land and Water
  - Best Land is Vegetated and New Land needs to take up More Carbon than current land
  - You need more than 500 mm of rain per year to grow Trees
- The ability of Forests to sequester Carbon declines with stand age
- There are Energetics and Environmental Costs to soil, water, air and land use change
  - Changes in Albedo and surface energy fluxes
  - Emission of volatile organic carbon compounds, ozone precursors
  - Changes in Watershed Runoff and Soil Erosion
- Societal/Ethical Costs and Issues
  - Land for Food vs for Carbon and Energy
  - Energy is needed to produce, transport and transform biomass into energy

Future Carbon Emissions: Kaya Identity

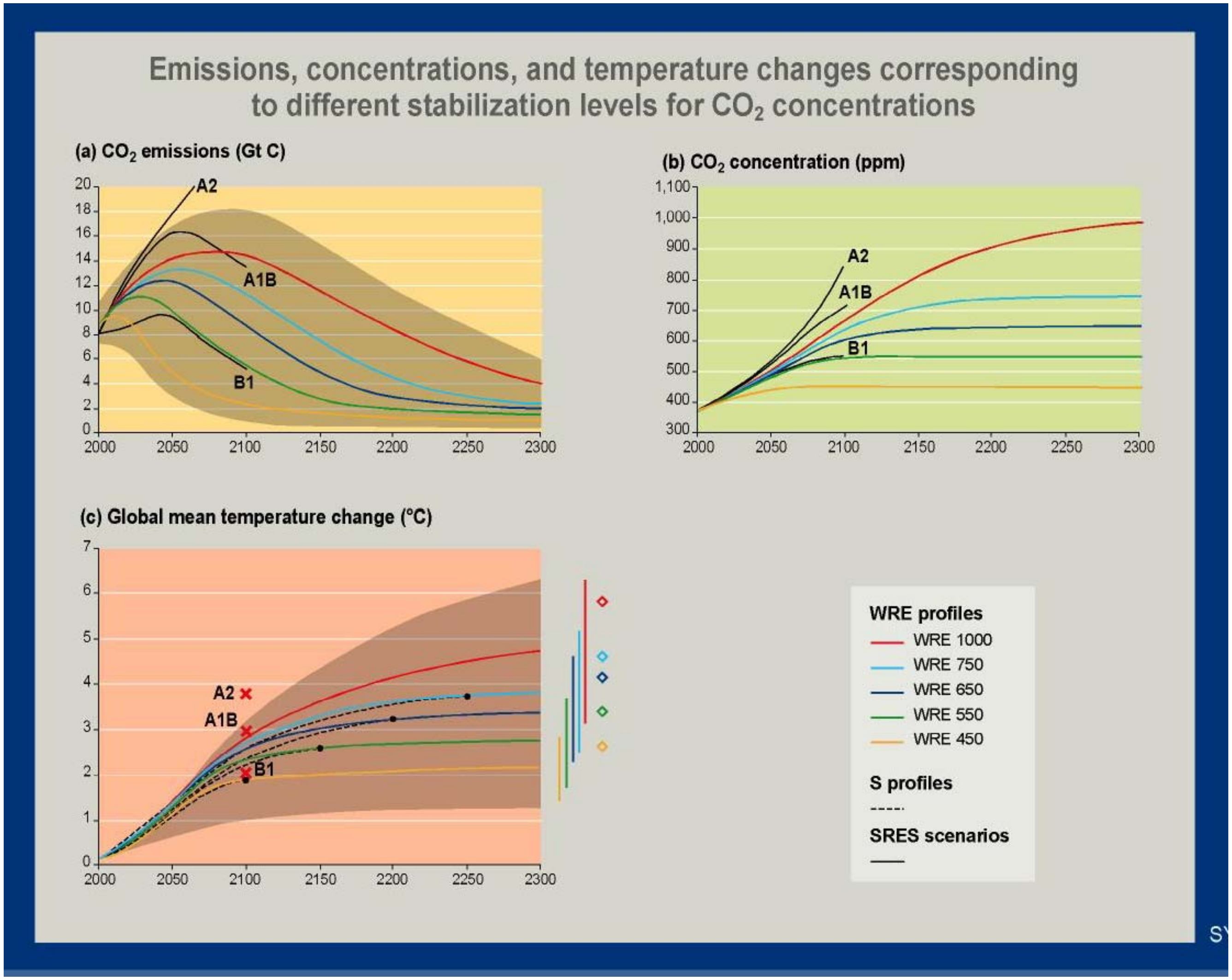
C Emissions = Population * (GDP/Population) * (Energy/GDP) * (Emissions/Energy)

- **Population**
  - Population expected to grow to ~9-10 billion by 2050
- **Per capita GDP**, a measure of the standard of living
  - Rapid economic growth in India and China
- **Energy intensity**, the amount of energy consumed per unit of GDP.
  - Can decrease with efficient technology
- **Carbon intensity**, the mass of carbon emitted per unit of energy consumed.
  - Can decrease with alternative energy

CO_2 in 50 years, at Steady-State

- 8 GtC/yr, Anthropogenic Emissions
  - 45% retention
- 8 * 50 * 0.45 = 180 GtC, integrated Flux
- Each 2.19 GtC emitted causes a 1 ppm increase in Atmospheric CO_2
- 833 (@380 ppm) + 180 = 1013 GtC, atmospheric burden
- 462 ppm with BAU in 50 years
  - 1.65 times pre-industrial level of 280 ppm
- BAU C emissions will be ~ 16 to 20 GtC/yr in 2050
- To stay under 462 ppm the world can only emit 400 GtC of carbon, gross, into the atmosphere!

We cannot Afford Steady-State or BAU:
We Must Consider the Integrated Path of Carbon Emissions

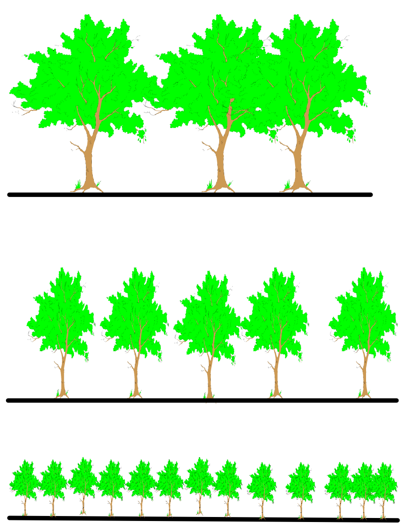


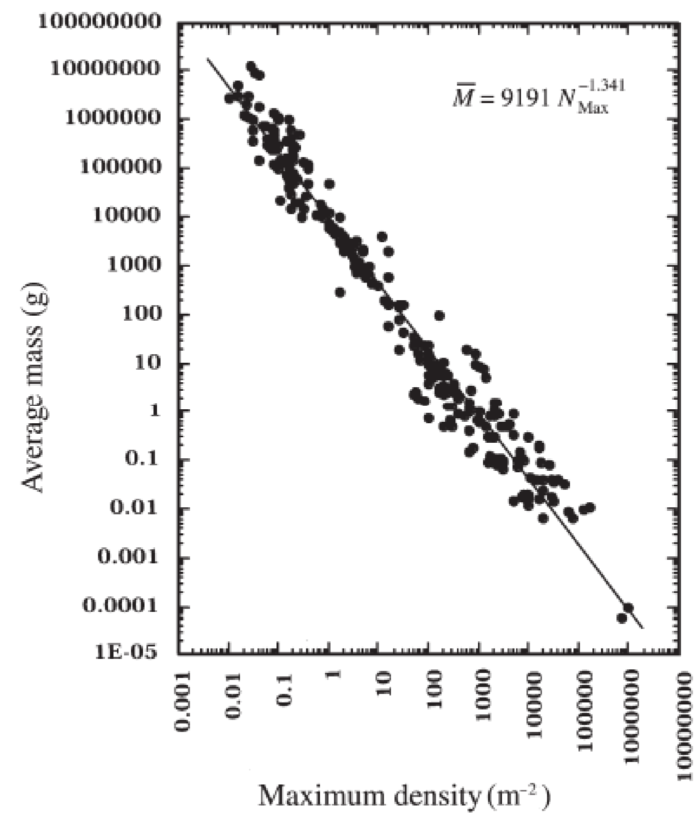
IPCC

Can we offset Carbon Growth by Planting Trees?

Yoda's Self Thinning Law

- Planting trees is may be a 'feel-good' solution, but it is not enough
  - self thinning will occur
- Energetics of Solar Capture Drives the Metabolism of the System





Enquist et al. 1998

Metabolic Scaling of Populations of Organisms

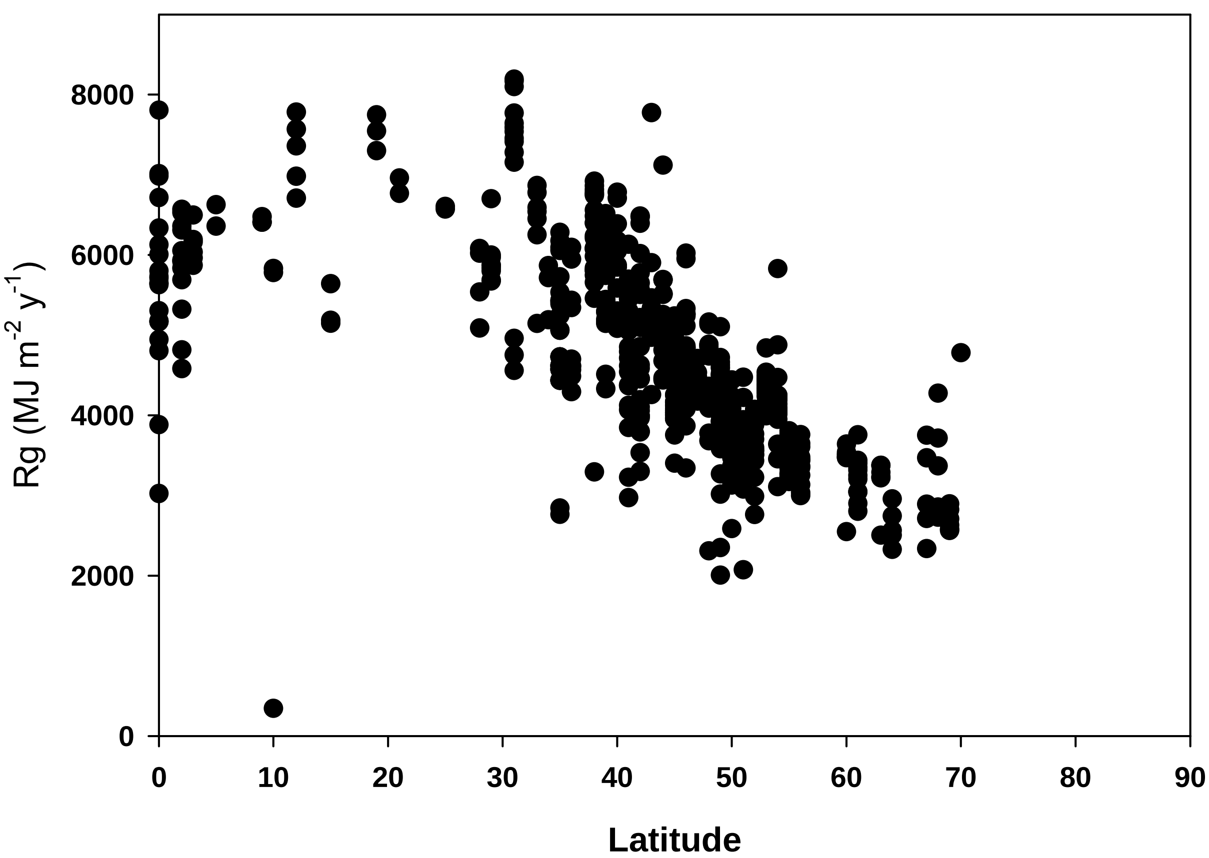
Energy flux of a population per unit area (B_t) is scale invariant with mass of the system (M):

$$B_T = N_i B_i \propto M_i^{-3/4} M_i^{3/4} = M^0$$

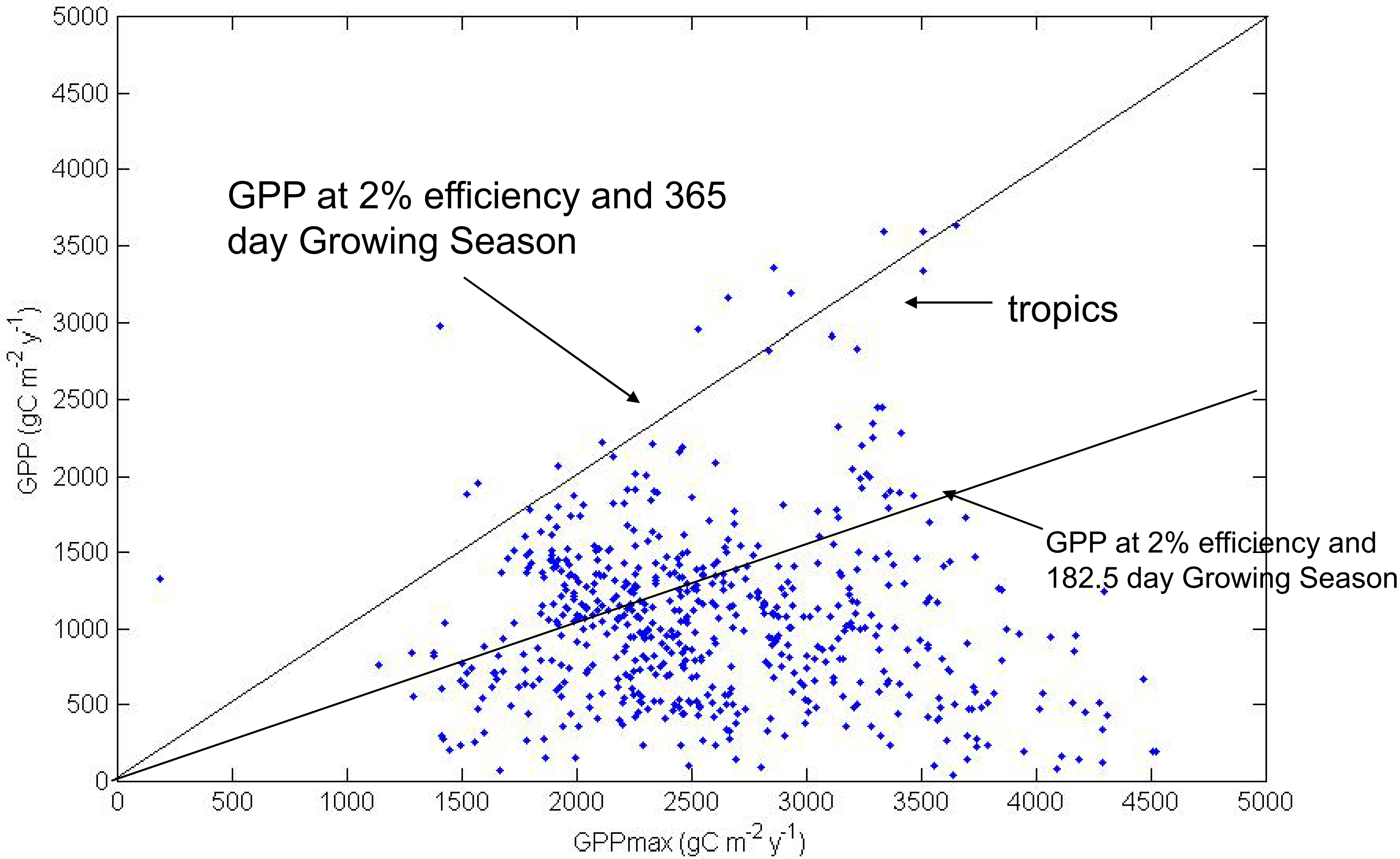
Allen et al. (2002)

Energy Drives Metabolism:
How Much Energy is Available and Where

FLUXNET database



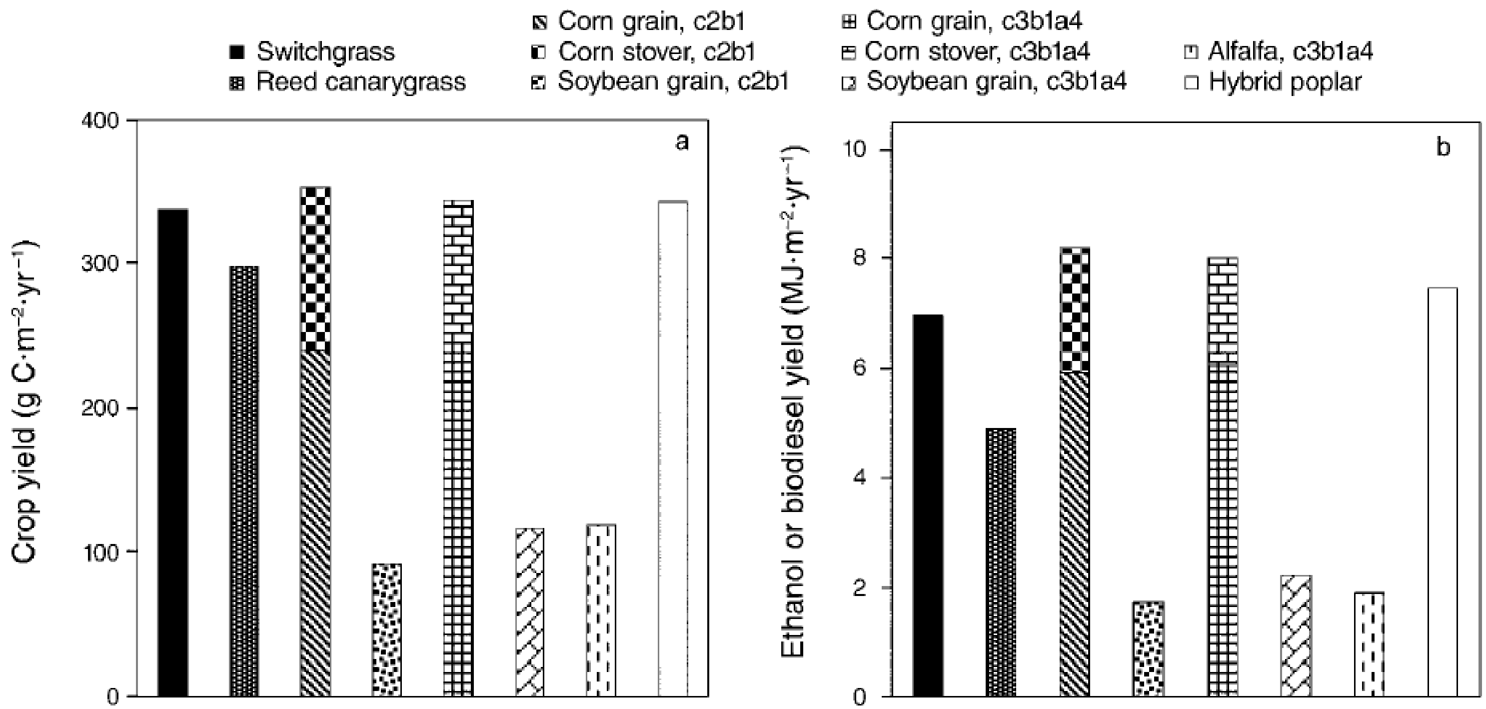
Potential and Real Rates of Gross Carbon Uptake by Vegetation: Most Locations Never Reach Upper Potential



FLUXNET 2007 Database

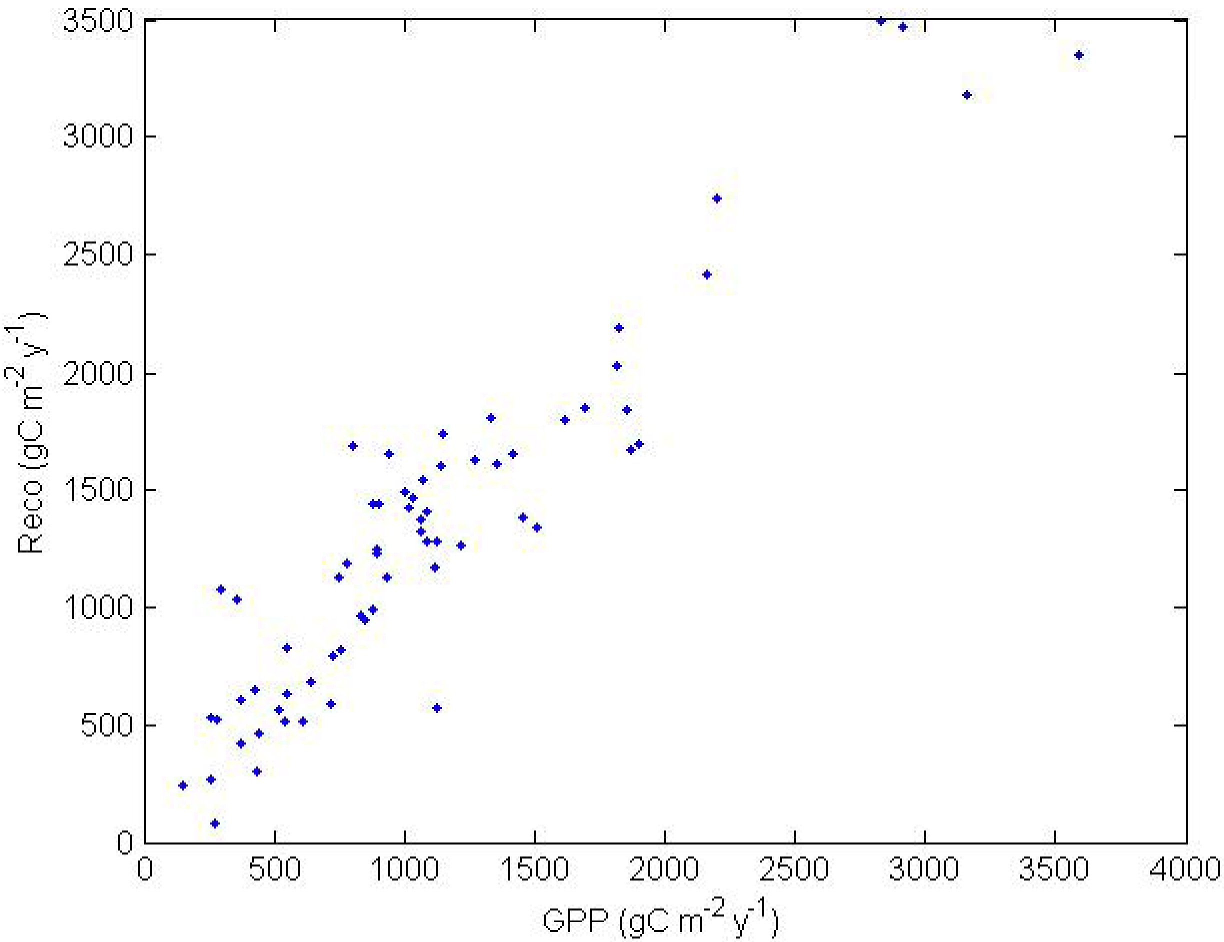
How Does Energy Availability Compare with Energy Use?

- US Energy Use: 105 EJ/year
  - 10^{18}J per EJ
  - US Population: 300 10^6
  - 3.5 10^{11} J/capita/year
- US Land Area: 9.8 10^6 km^2=9.8 10^{12} m^2 = 9.8 10^8 ha
- Energy Use per unit area: 1.07 10^7 J m^{-2}
- Potential, Incident Solar Energy: 6.47 10^9 J m^{-2}
  - Ione, CA
- A solar system (solar panels, biomass) must be 0.1% efficient, working year round, over the entire surface area of the US to capture the energy we use to offset fossil fuel consumption
- Assuming 20% efficient solar system
  - 8.11 10^{10} m^2 of Land Area Needed (8.11 10^5 km^2, the size of South Carolina)

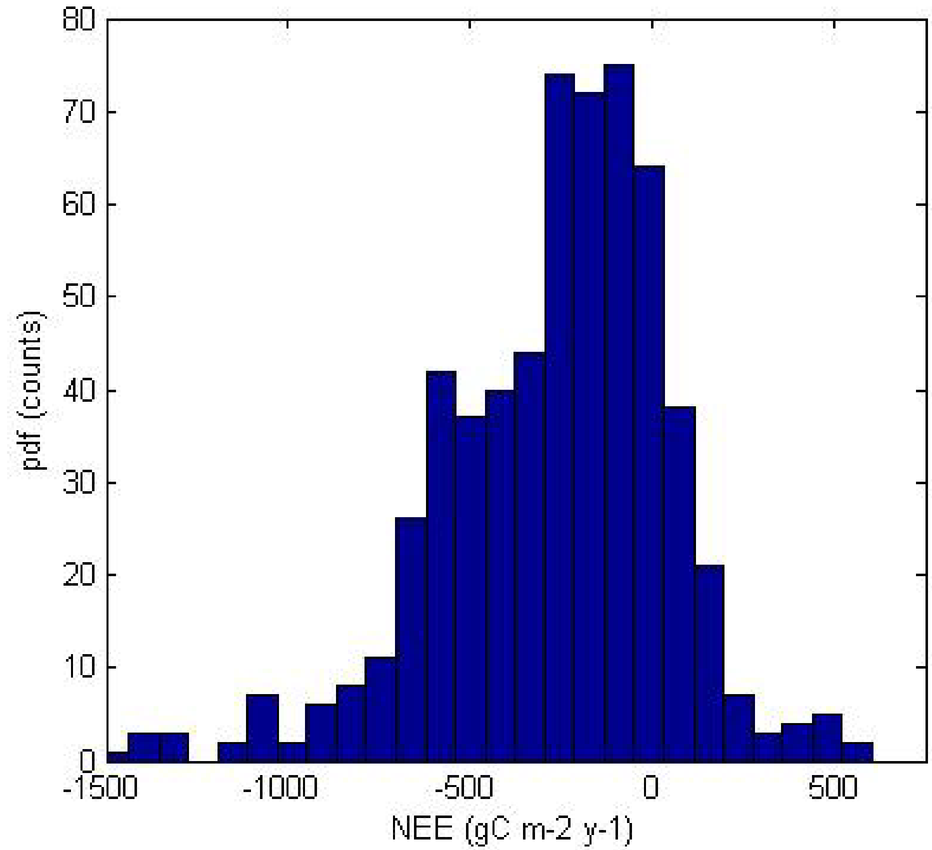


Adler et al 2007 Ecol Appl

GPP has a Cost, in terms of Ecosystem Respiration



We need to Consider Net, not Gross, CO_2 Exchange:



Fluxnet 2007 Database
180 Sites across 600+ measurement-years

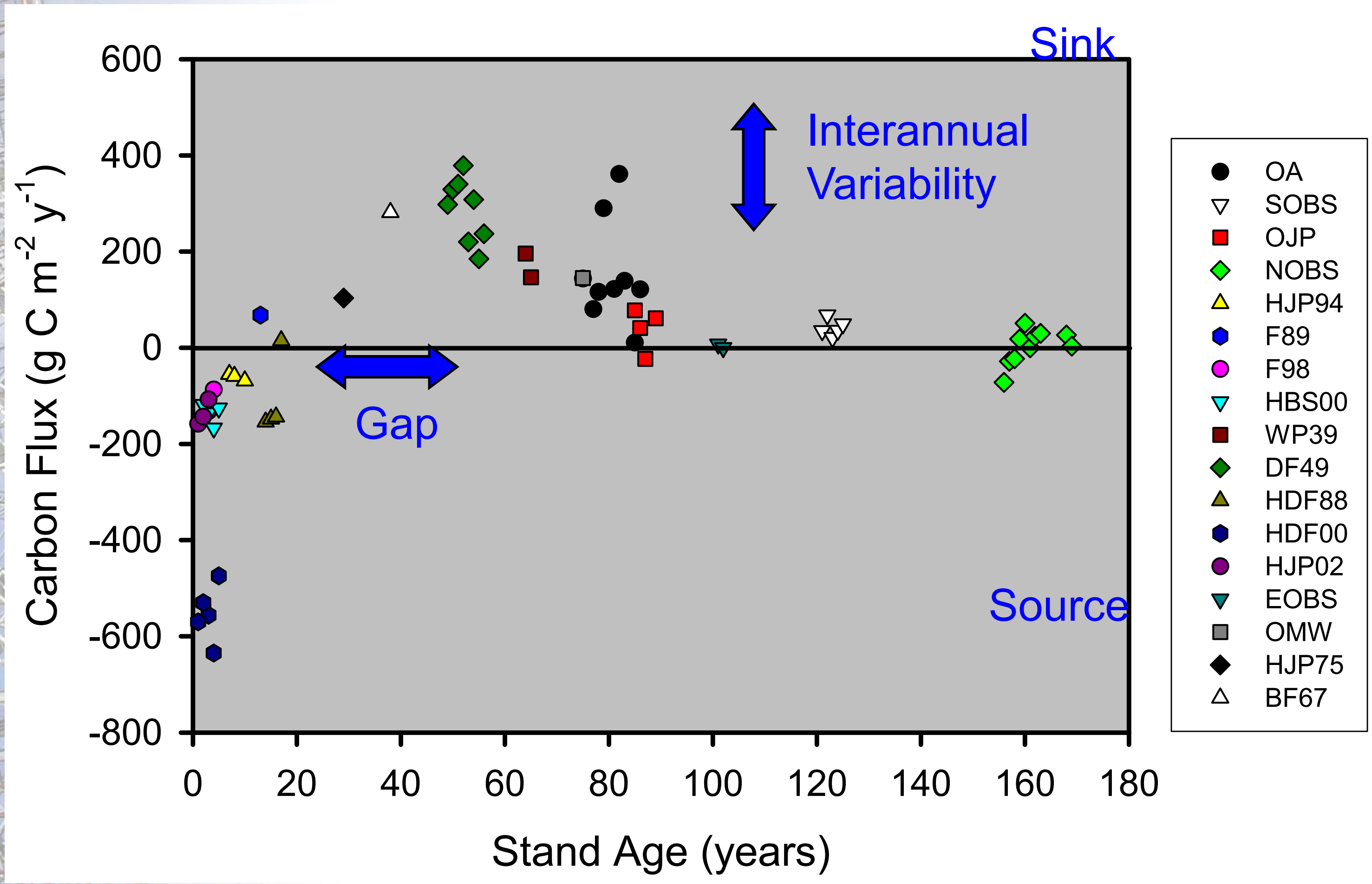
It's a matter of scale

A lot of 'trees' need to be planted to offset our profligate carbon use

- US accounts for about 25% of Global C emissions
  - $0.25*8.0\ 10^{15}$ gC = $2.0\ 10^{15}$ gC
- Per Capita Emissions, US
  - $2.0\ 10^{15}$ gC/300 10^{6} = $6.66\ 10^{6}$ gC/person
- Ecosystem Service, net C uptake, above current rates
  - ~200 gC m^{-2}
- Land Area Needed to uptake C emissions, per Person
  - $3.33\ 10^{4}$ m^{2}/person = 3.33 ha/person
- US Land Area
  - $9.8\ 10^{8}$ ha
  - $10.0\ 10^{8}$ ha needed by US population to offset its C emissions Naturally!

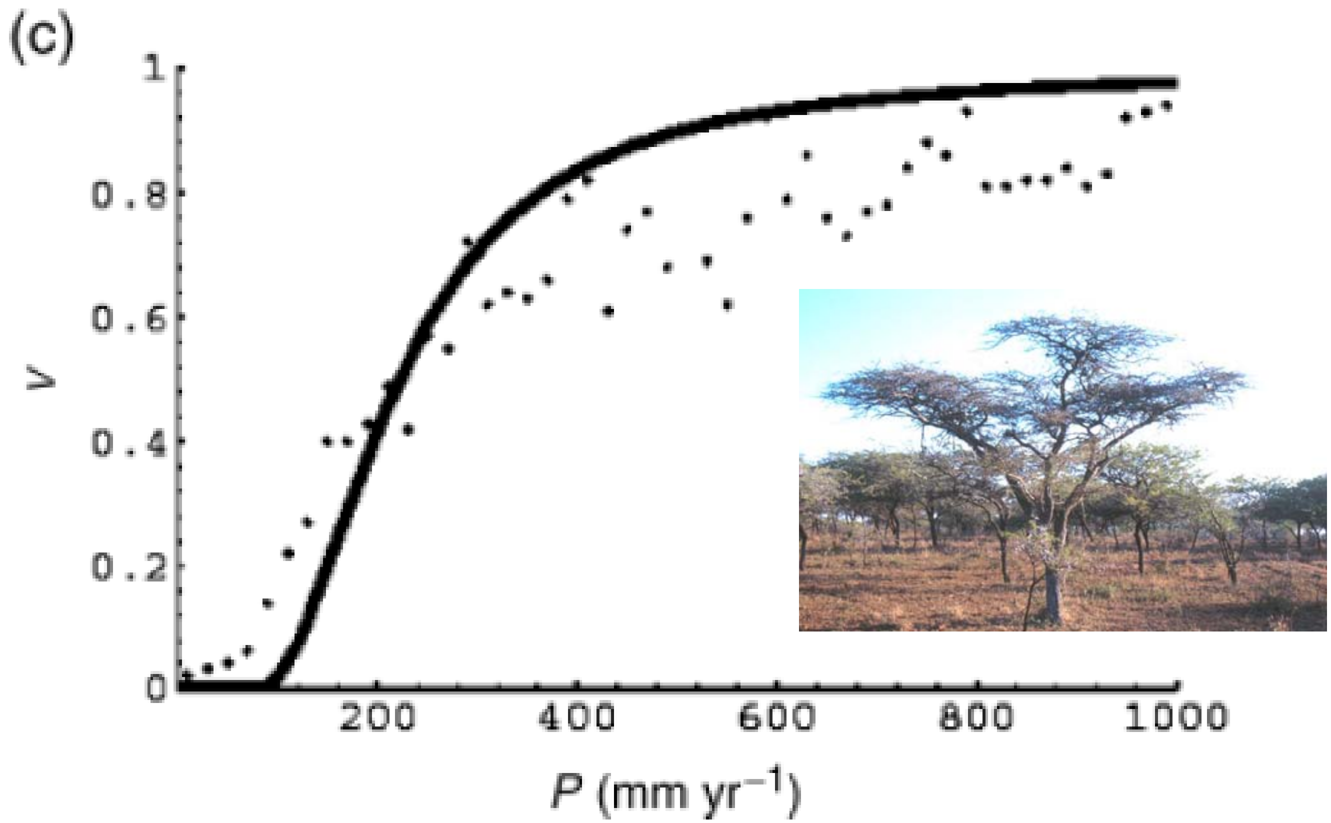
1. Carbon is Lost with Disturbance

2. Net Carbon Uptake Decline with Age



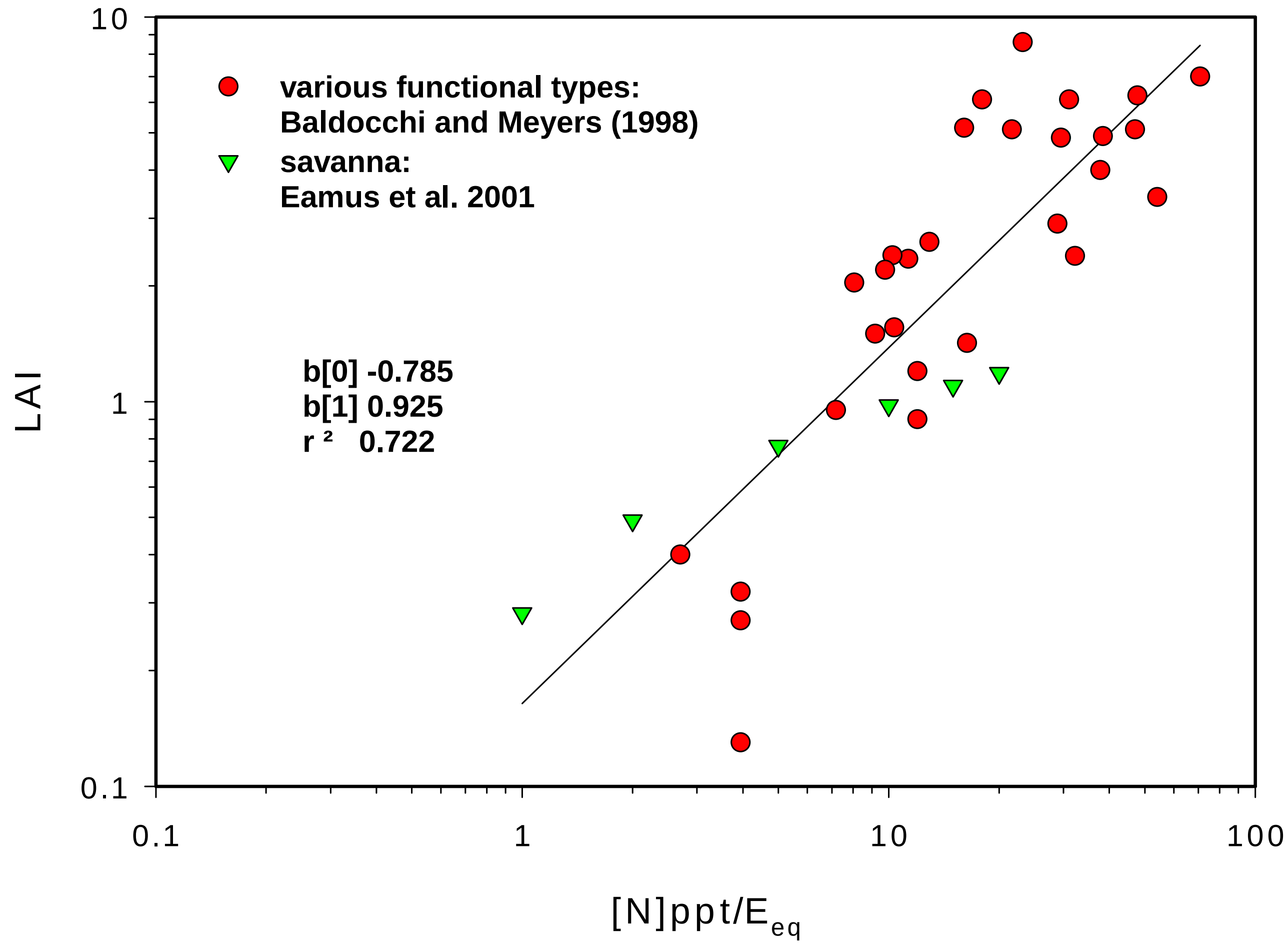
Brian Amiro 2007 AgForMet

All Land is Not Available or Arable: You need Water to Grow Trees!

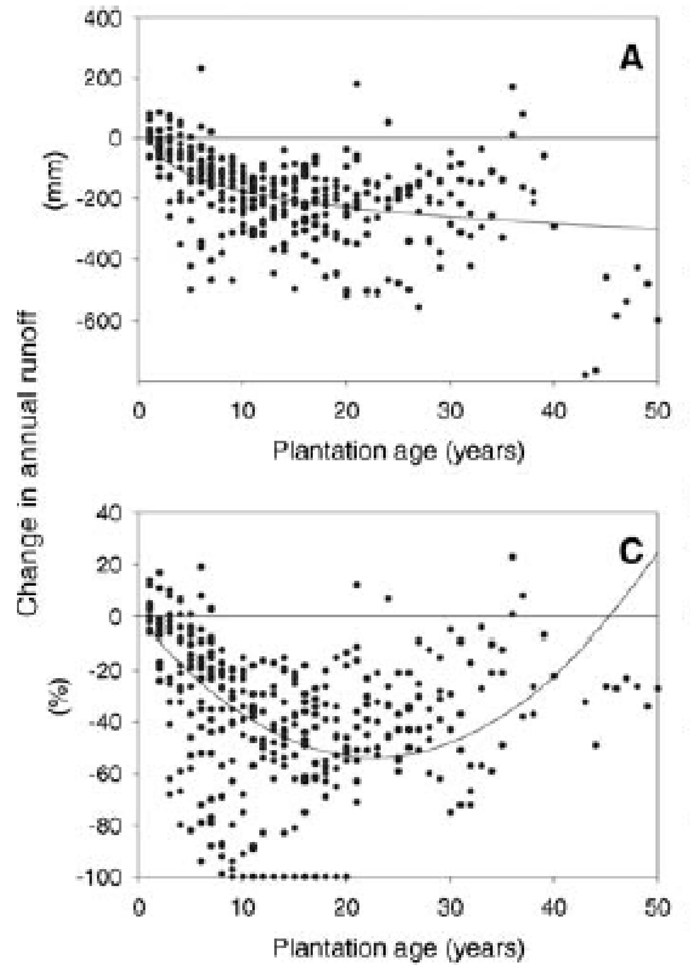


Scheffer al 2005

Leaf Area Index scales with:
Precipitation, Evaporation and Nutrition



Carbon sequestration by plantations can dry out streams

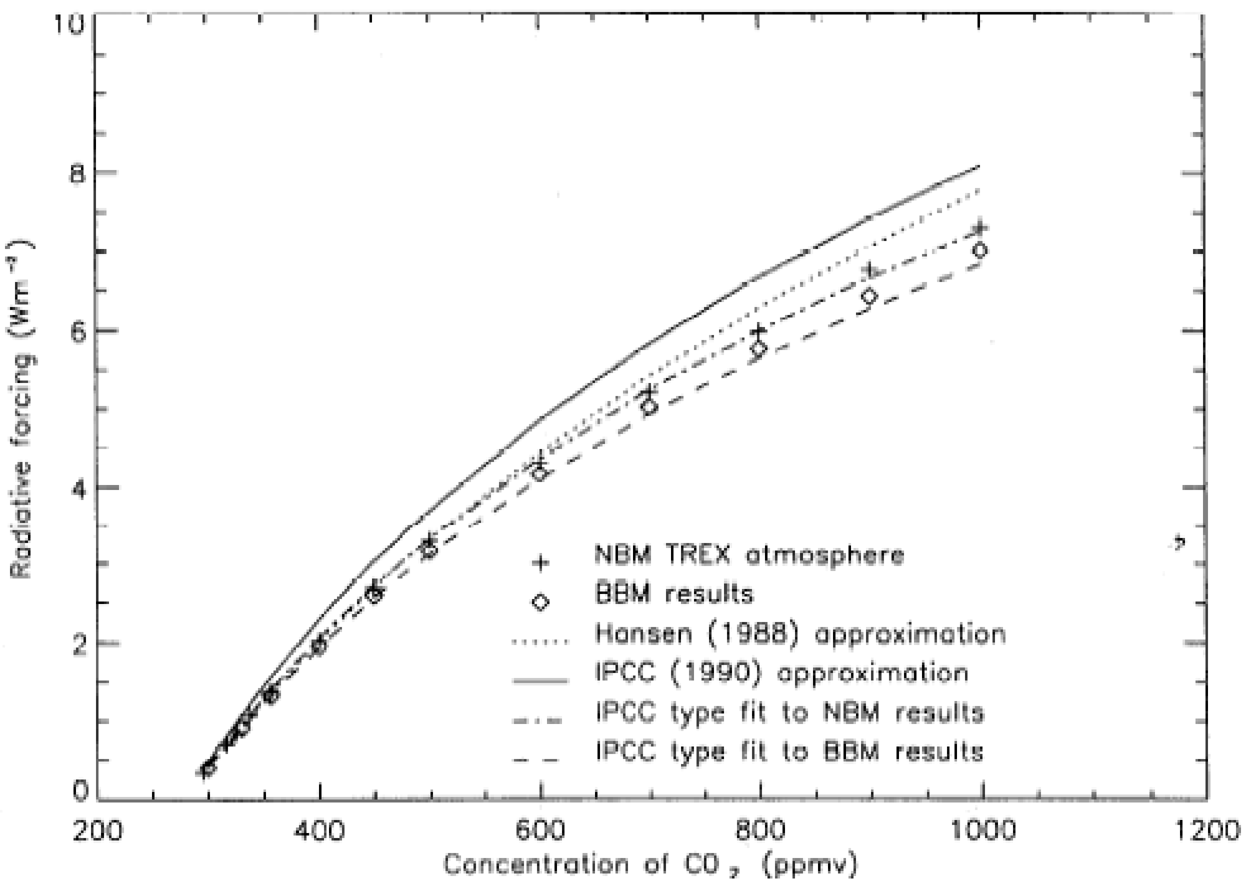


[*Jackson, et al.*, 2005, Science].

Other Complications associated with reliance on Carbon sequestration

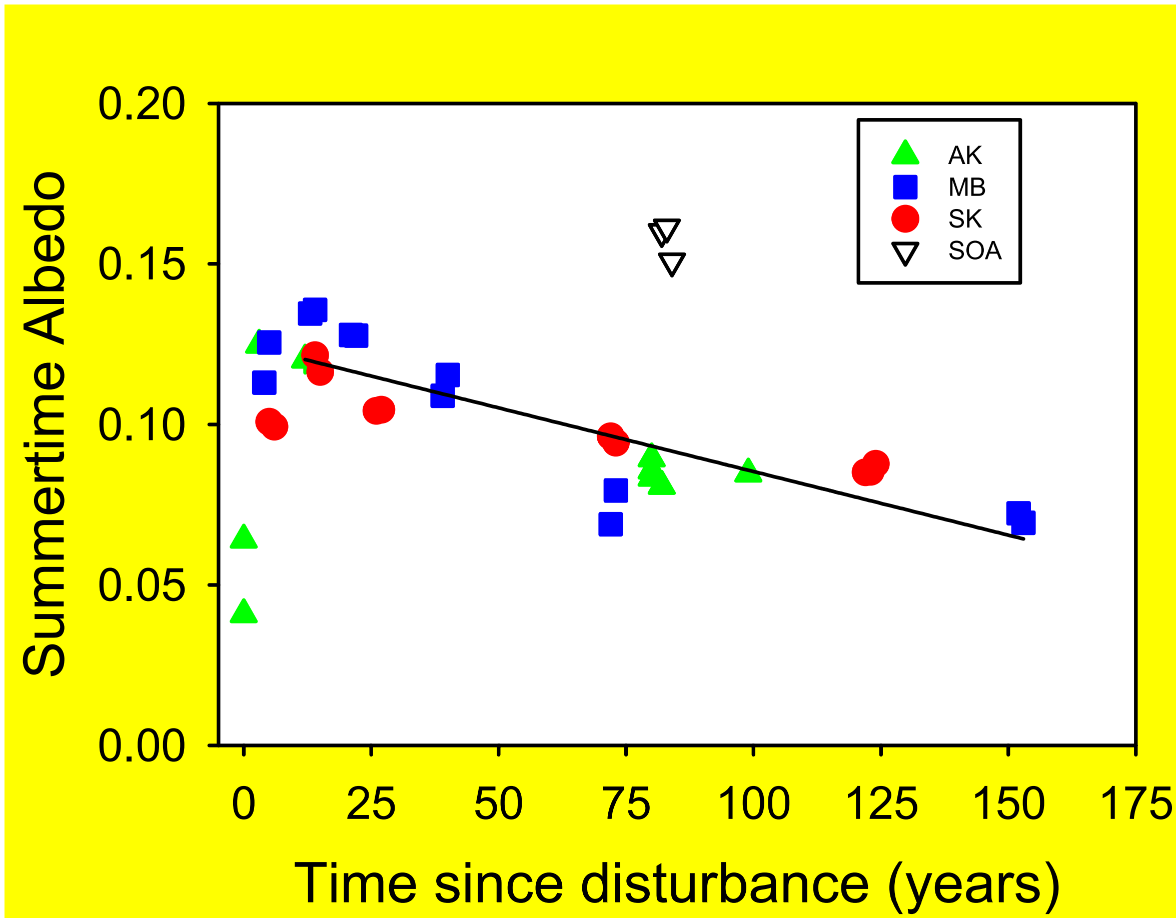
- Fire
- Nutrient Requirements
- Soil Erosion
- Ecosystem Sustainability
- Deleterious effects of Ozone, Droughts and Heat Stress
- Length of Growing Season

Energetics of Greenhouse Gas Forcing:
Doubling CO_2 provides a 4 Wm^{-2} energy increase, Worldwide

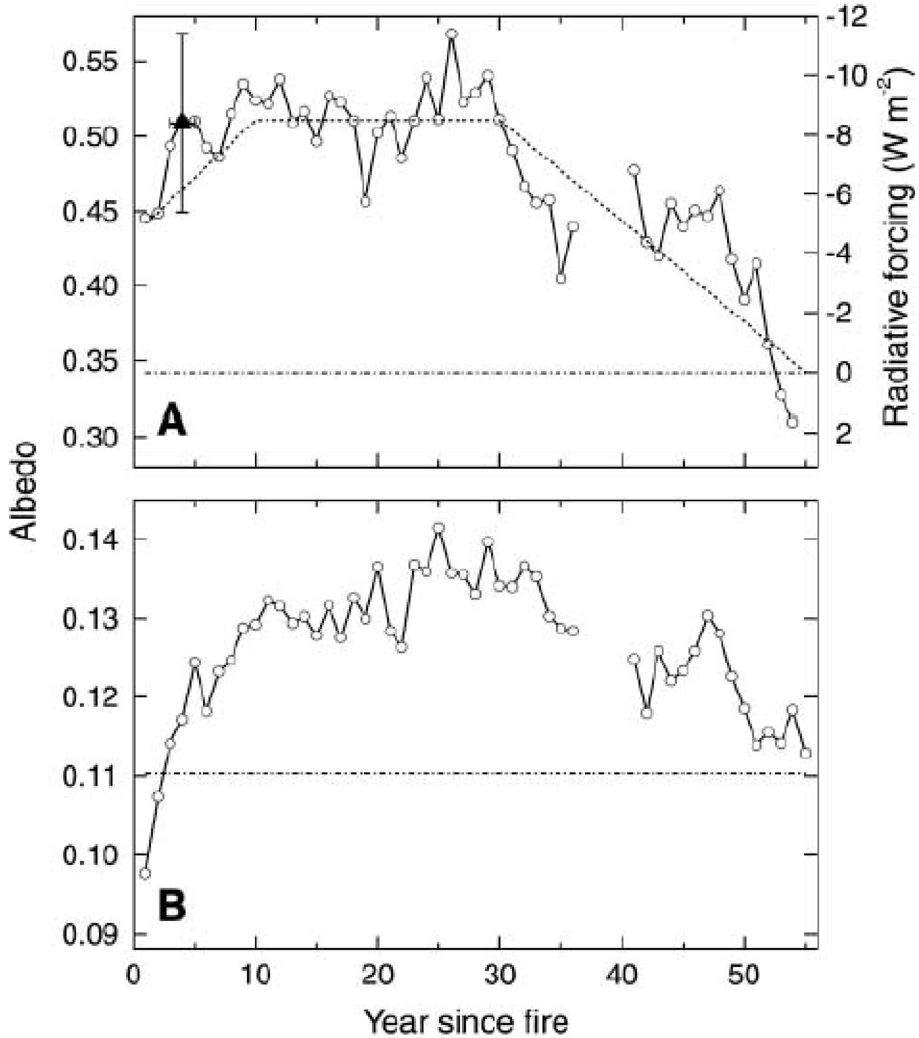


Myhre et al 1998 GRL

Its not Only Carbon Exchange:
Albedo Changes too with planting Forests



Amiro et al 2006 AgForMet



Randerson et al 2006 Science

Should we cut down dark forests to Mitigate Global Warming?:
UpScaling Albedo Differences Globally, part 1

- Average Solar Radiation: ~95 to 190 W m^{-2}
- Land area: ~30% of Earth's Surface
- Tropical, Temperate and Boreal Forests: 40% of land
- Forest albedo (10 to 15%) to Grassland albedo (20%)
- Area weight change in incoming Solar Radiation: 0.8 W m^{-2}
  - Smaller than the 4 W m^{-2} forcing by 2x CO_2
  - Ignores role of forests on planetary albedo, as conduits of water vapor that form clouds and reflect light

Should we cut down dark forests to Mitigate Global Warming?: UpScaling Albedo Differences Globally, part 2

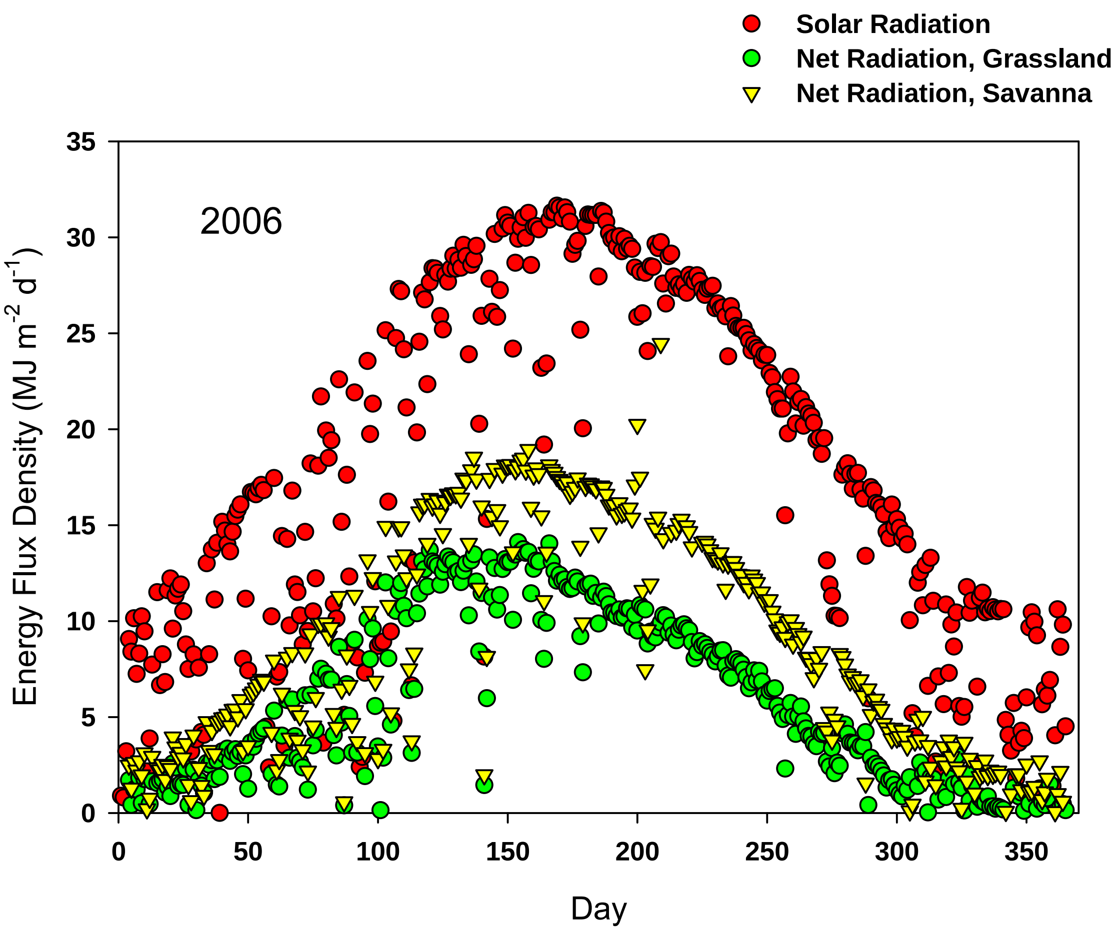
	km2	**MJ m-2 y-1**	**albedo**	**albedo**		
	area	**rad**	**change**		**wt value**	
tropical	**1.75E+07**	**6.00E+09**	**0.05**	**0.15**	**5.25E+15**	
temperate	**1.00E+07**	**5.00E+09**	**0.05**	**0.15**	**2.50E+15**	
boreal	**1.30E+07**	**4.00E+09**	**0.1**	**0.1**	**5.20E+15**	
Earth	**5.10E+08**			**sum**	**1.30E+16**	
			ave	**time/lan**	**0.805**	**W m-2**

Case Study:

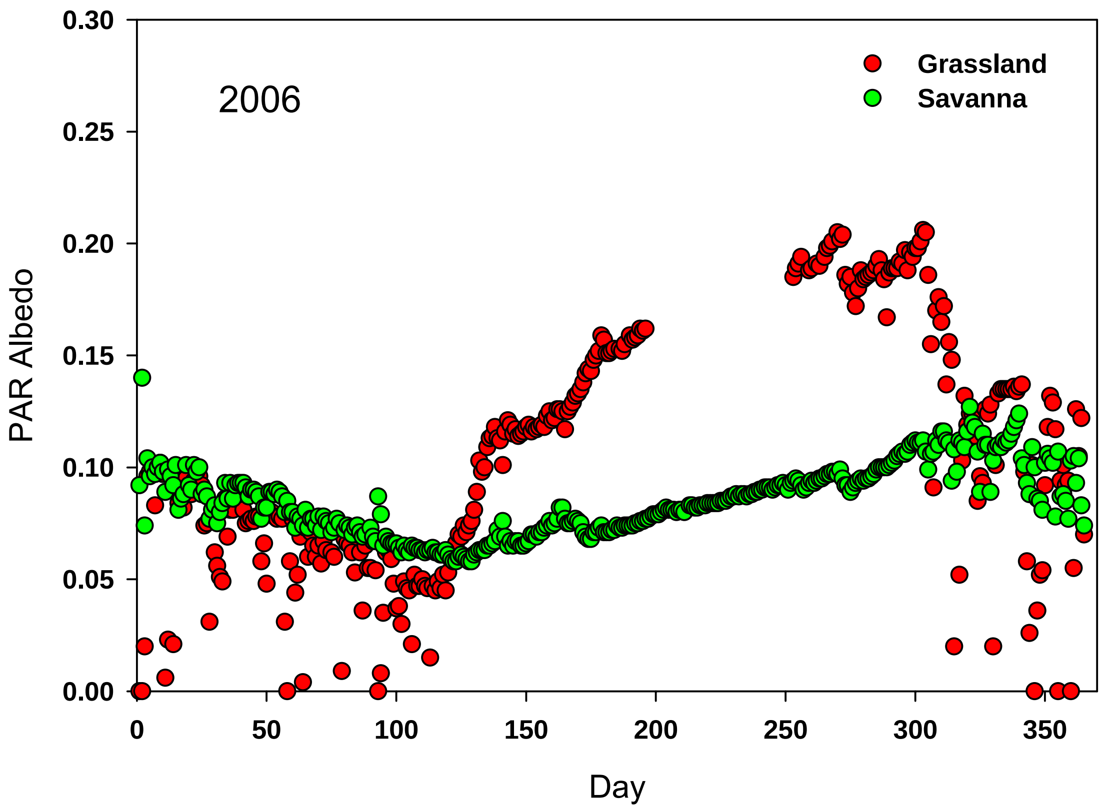
Energetics of a Grassland and Oak Savanna

Measurements and Model

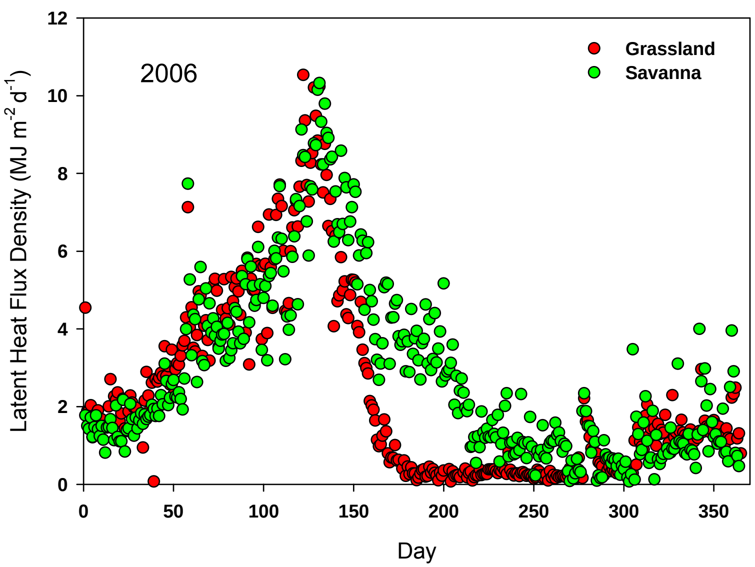
Case Study:
Savanna Woodland adjacent to Grassland

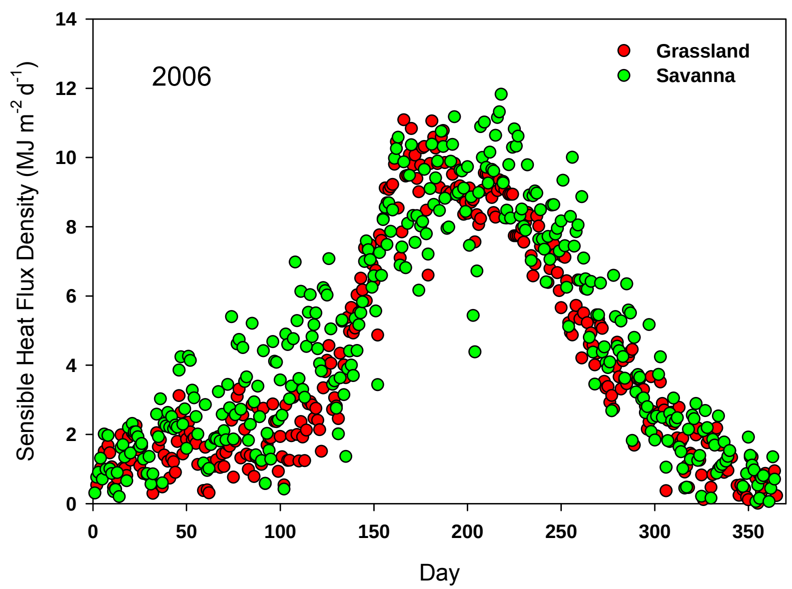


1. Savanna absorbs much more Radiation than grassland

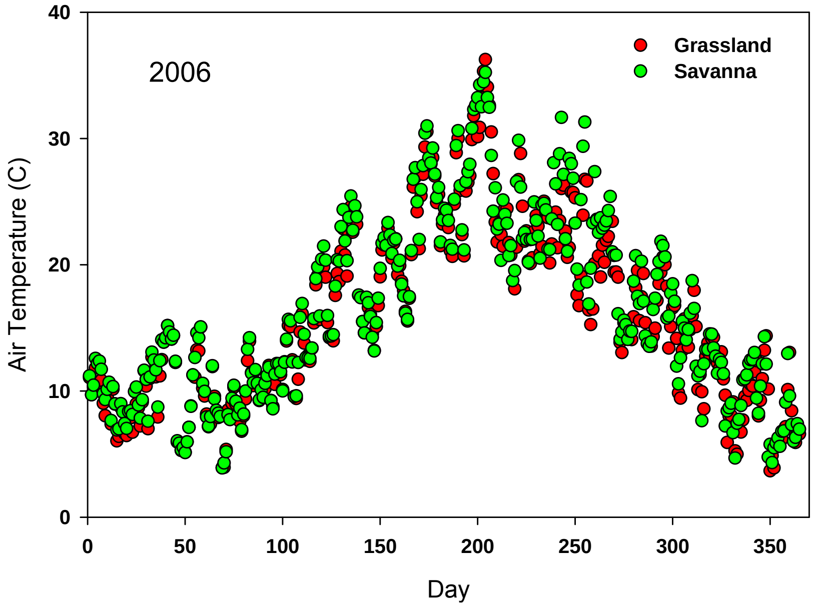


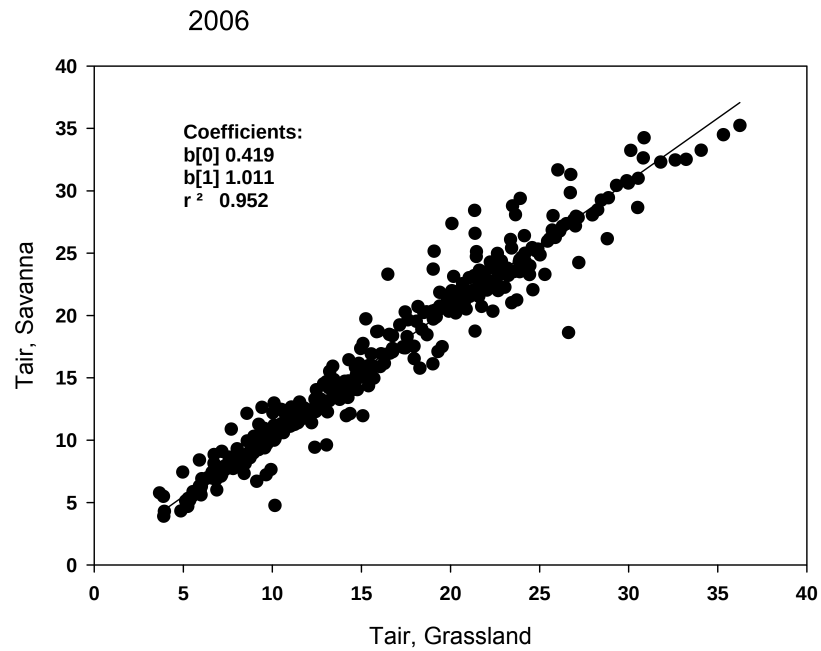
2. Grassland has much great albedo than savanna



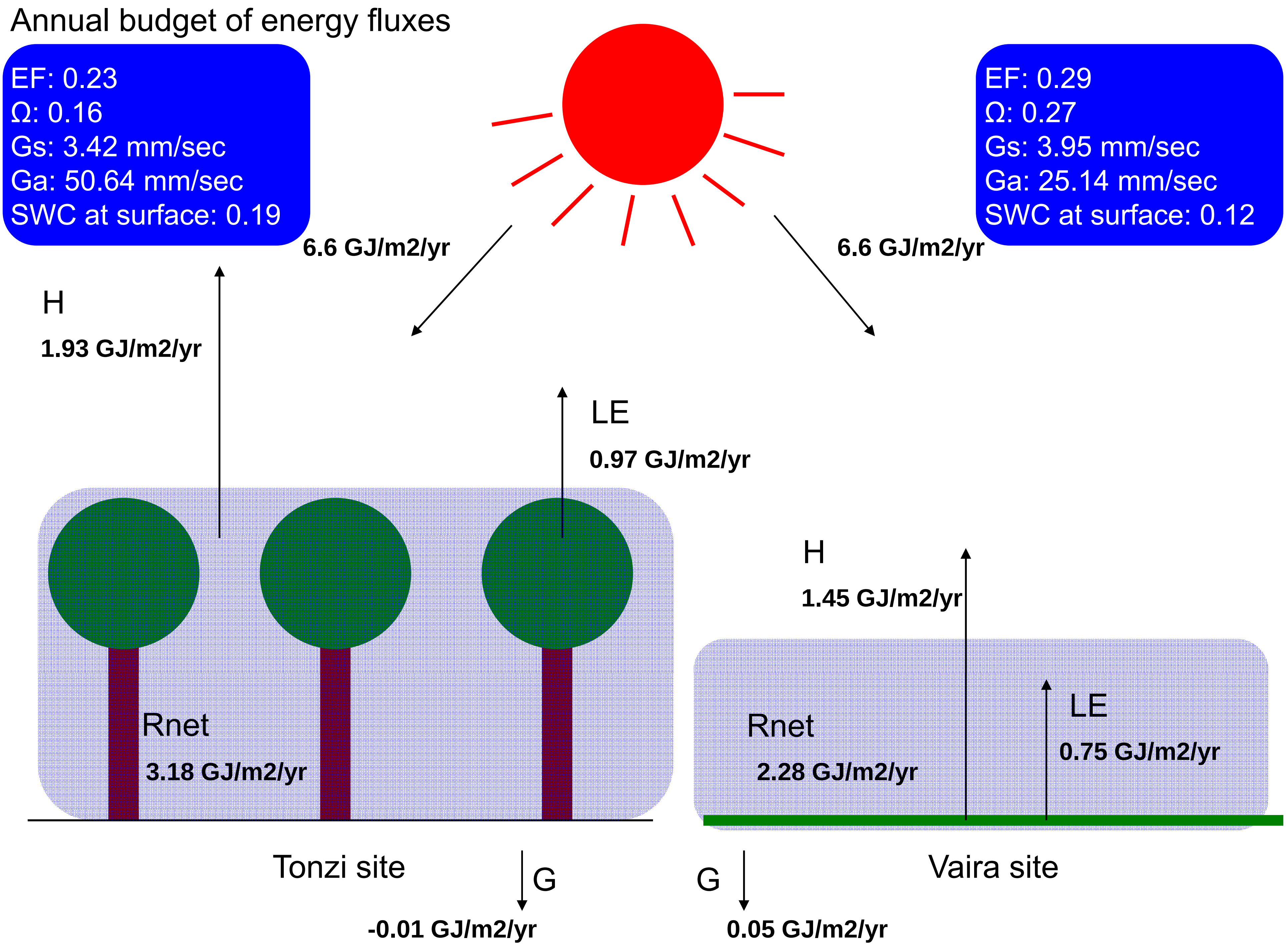


3. Savanna evaporates more, but it also injects more sensible heat into the atmosphere





4. But air temperature differences are small (15.7 vs 16.4 C) despite large differences in Energy Fluxes

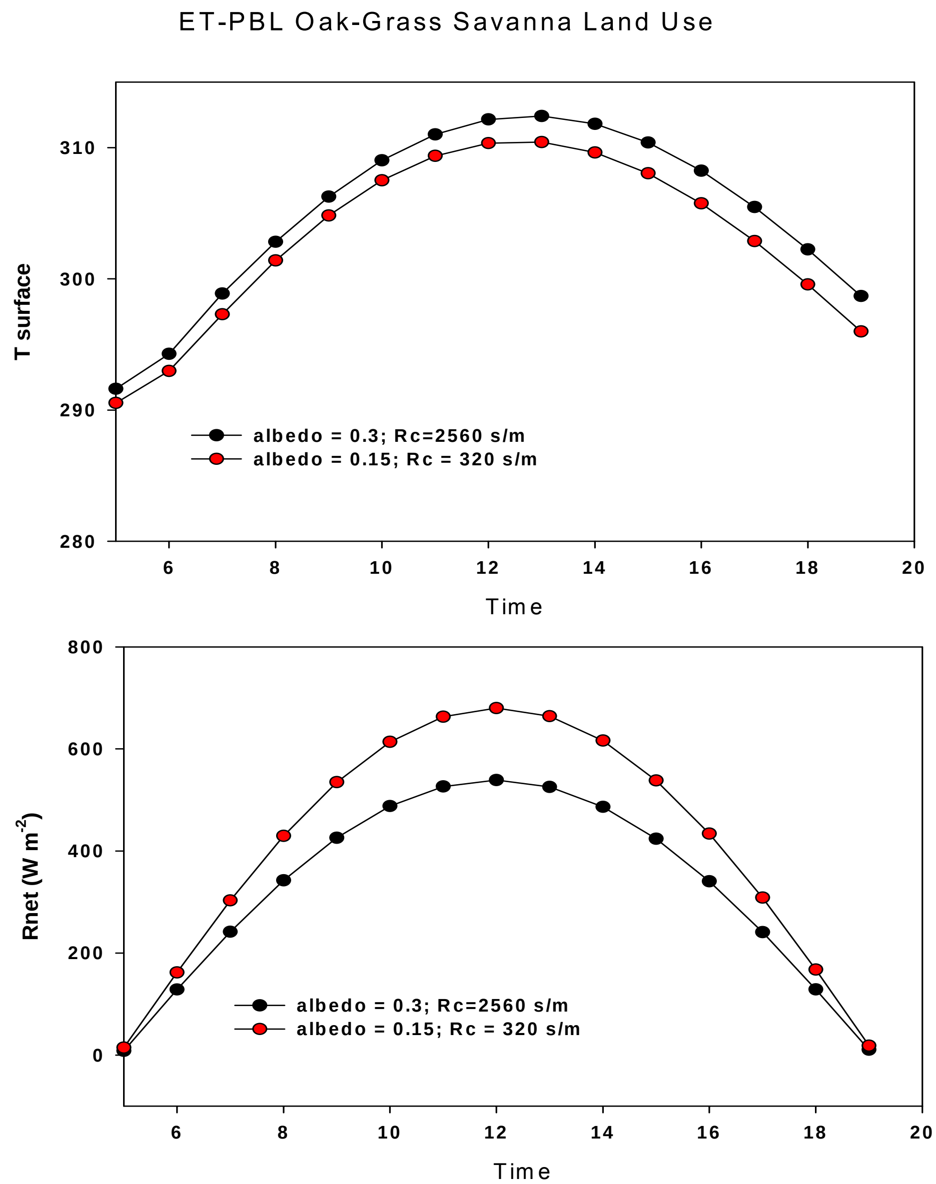


Annual budget of energy fluxes
EF: 0.23
Ω: 0.16
Gs: 3.42 mm/sec
Ga: 50.64 mm/sec
SWC at surface: 0.19
6.6 GJ/m2/yr
6.6 GJ/m2/yr
EF: 0.29
Ω: 0.27
Gs: 3.95 mm/sec
Ga: 25.14 mm/sec
SWC at surface: 0.12
H
1.93 GJ/m2/yr
LE
0.97 GJ/m2/yr
Rnet
3.18 GJ/m2/yr
H
1.45 GJ/m2/yr
LE
0.75 GJ/m2/yr
Rnet
2.28 GJ/m2/yr
Tonzi site
G
-0.01 GJ/m2/yr
G
0.05 GJ/m2/yr
Vaira site

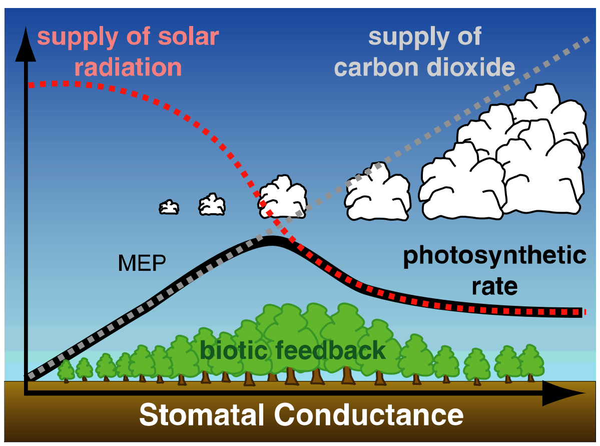
- The Energetics of afforestation/deforestation is complicated

- Forests have a low albedo, are darker and absorb more energy

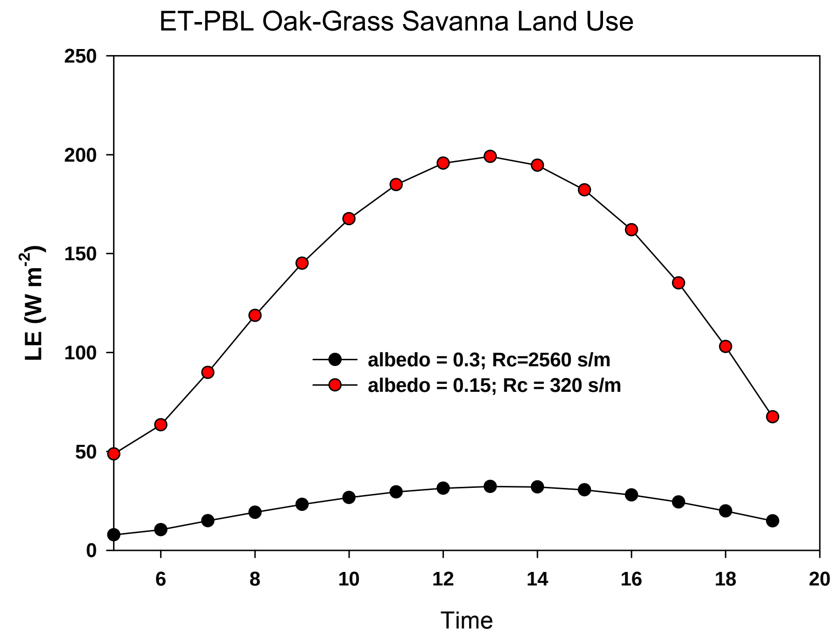
- But, Ironically the darker forest maybe cooler than a bright grassland due to evaporative cooling

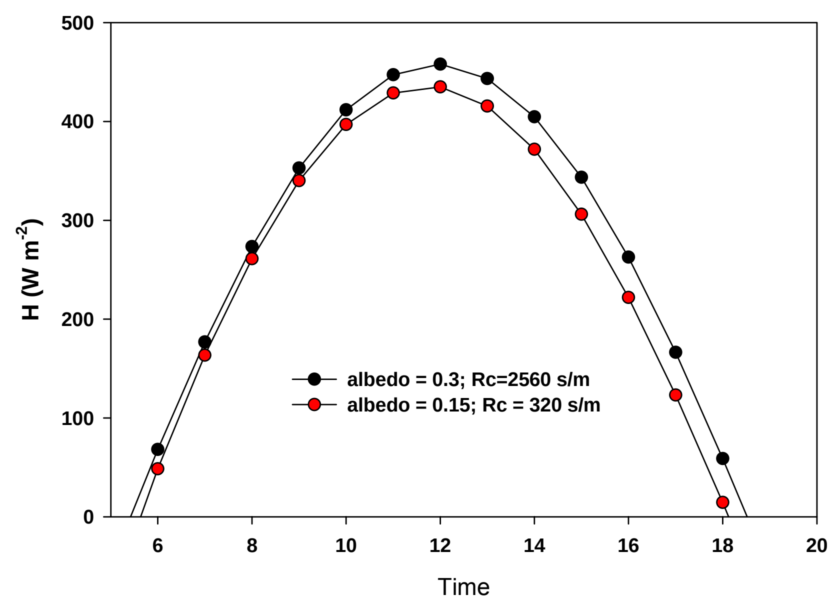


•Forests Transpire effectively, causing evaporative cooling, which in humid regions may form clouds and reduce planetary albedo



Axel Kleidon





PBL feedbacks affect Tair

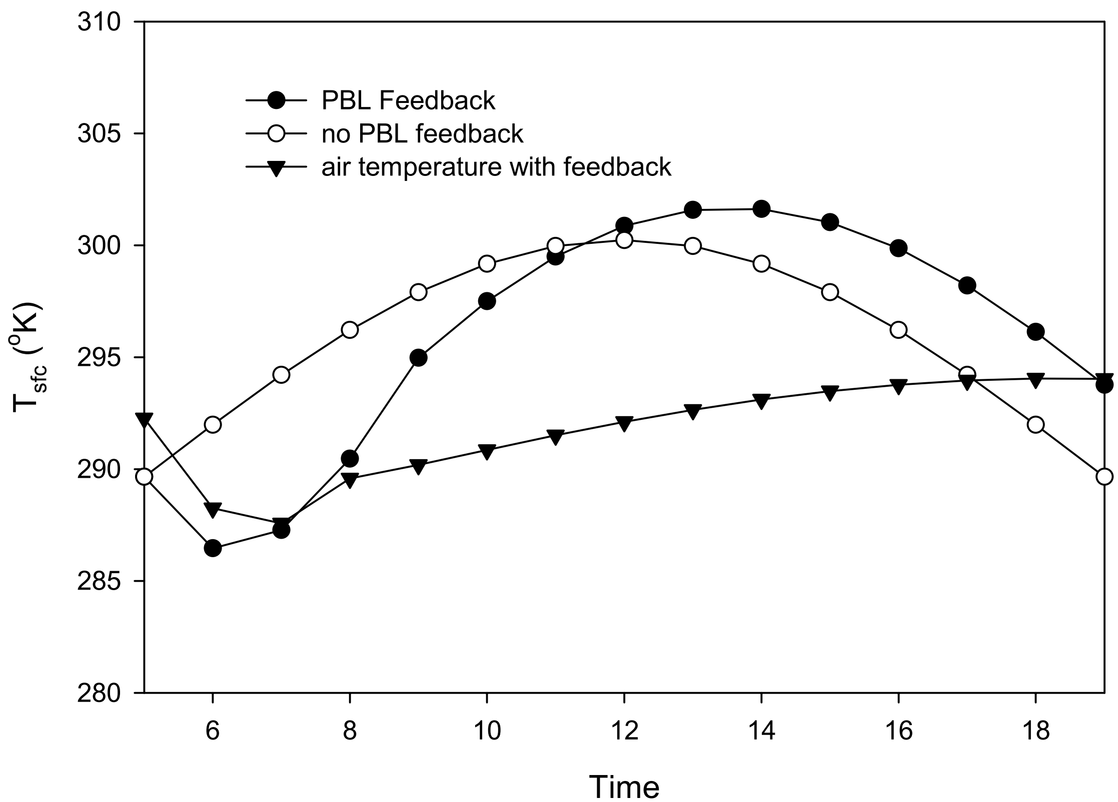
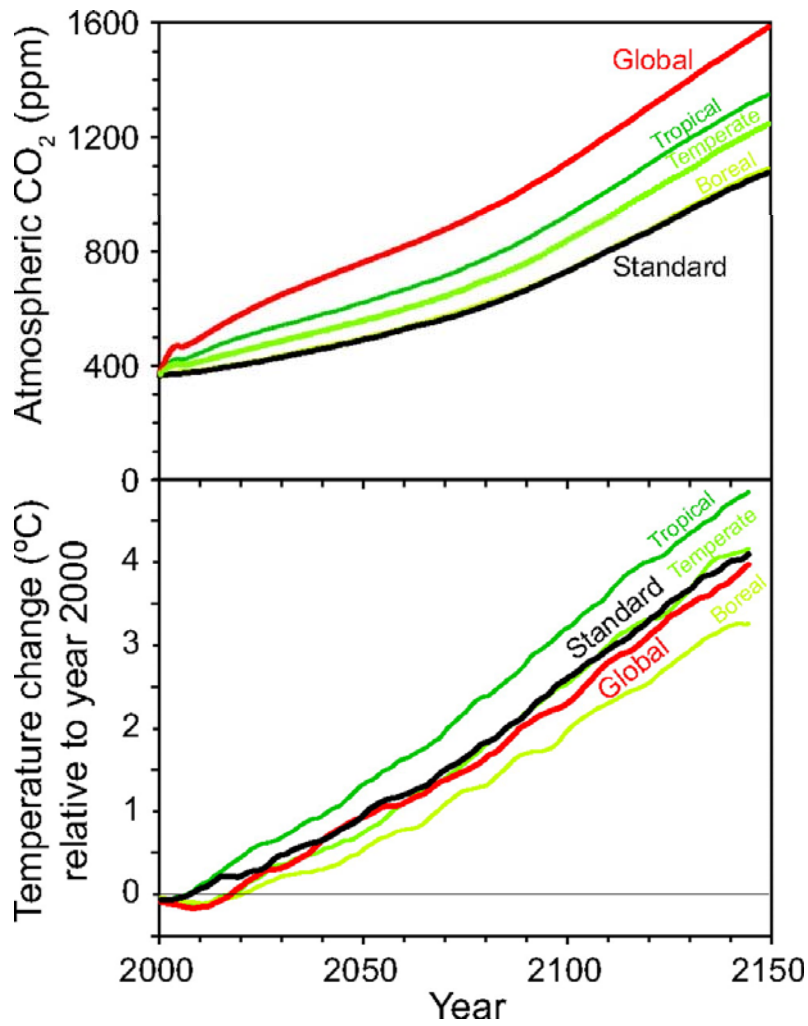
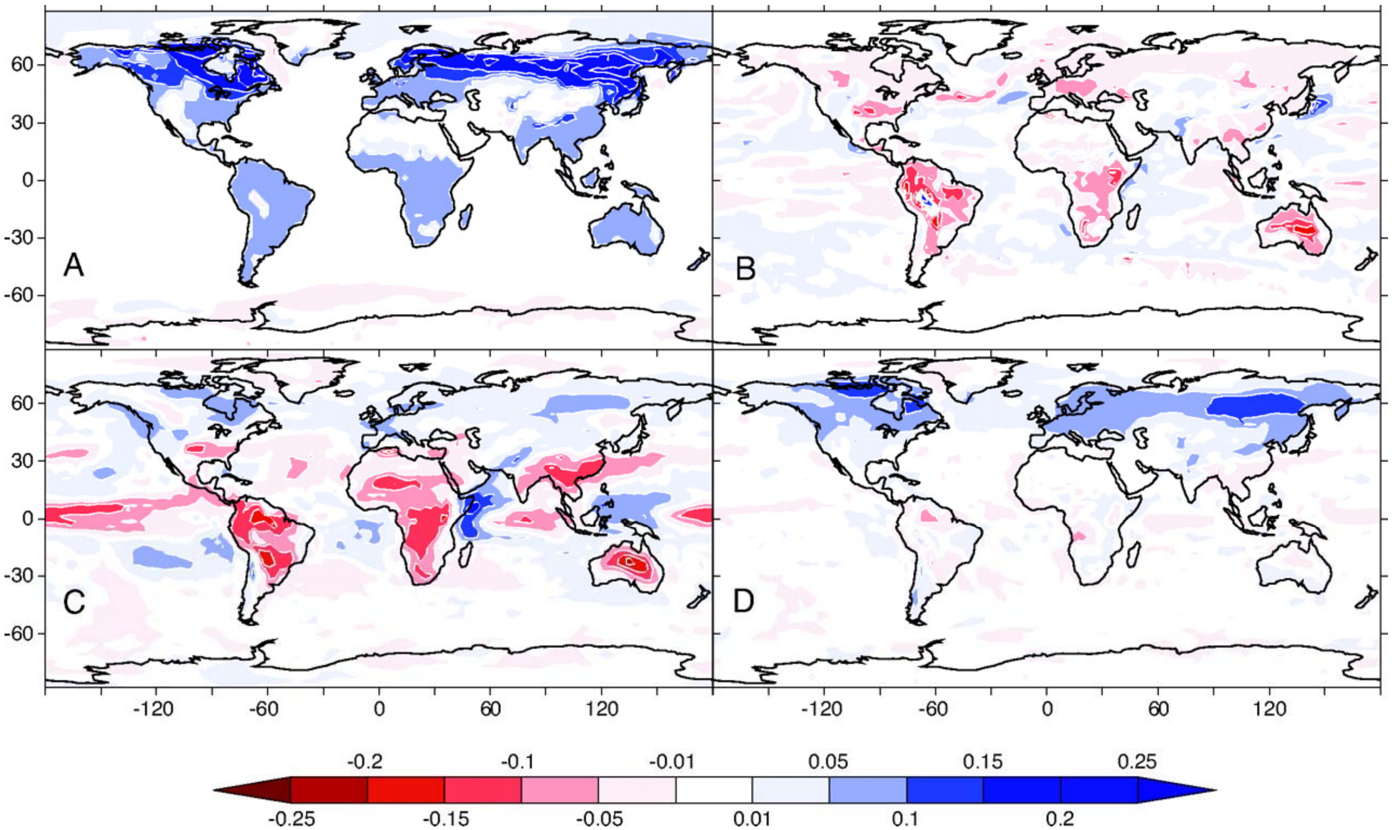


Fig. 1. Simulated temporal evolution of atmospheric CO2 (Upper) and 10-year running mean of surface temperature change (Lower) for the period 2000-2150 in the Standard and deforestation experiments



Bala, G. et al. (2007) Proc. Natl. Acad. Sci. USA 104, 6550-6555

Fig. 4. Simulated spatial pattern differences (Global minus Standard) in the decade centered on year 2100 for the surface albedo (fraction) (A), evapotranspiration rates (cm/day) (B), cloudiness (fraction) (C), and planetary albedo (fraction) (D) differences



Bala, G. et al. (2007) Proc. Natl. Acad. Sci. USA 104, 6550-6555

PNAS

- *“Finally, we must bear in mind that preservation of ecosystems is a primary goal of preventing global warming, and the destruction of ecosystems to prevent global warming would be a counterproductive and perverse strategy.*
- *Therefore, the cooling that could potentially arise from deforestation outside the tropics should not necessarily be viewed as a strategy for mitigating climate change because, apart from their potential climatic role, forests are valuable in many aspects.*
- *They provide natural habitat to plants and animals, preserve the biodiversity of natural ecosystems, produce economically valuable timber and firewood, protect watersheds through prevention of soil erosion, and indirectly prevent ocean acidification by reducing atmospheric CO2.*
- *In planning responses to global challenges, therefore, it is important to pursue broad goals and to avoid narrow criteria that may lead to environmentally harmful consequences”.*
- *Bala et al 2007 PNAS*

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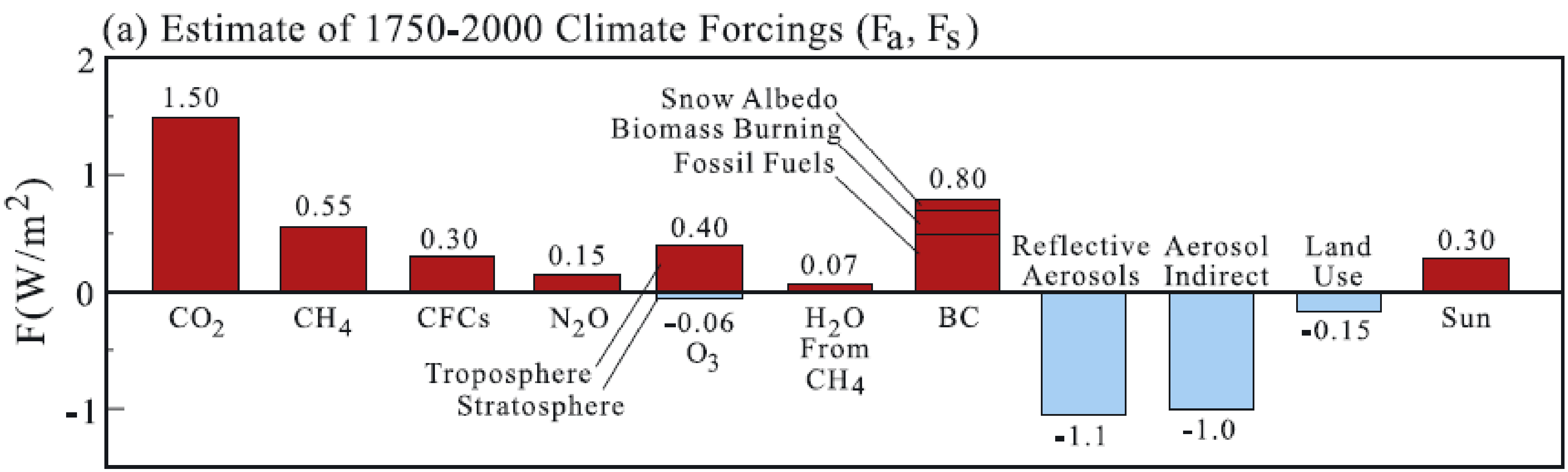
  - Food for Carbon and Energy
  - Energy is needed to produce, transport and transform biomass into energy
  - Role of forests for habitat and resources

Contemporary Radiative Forcing



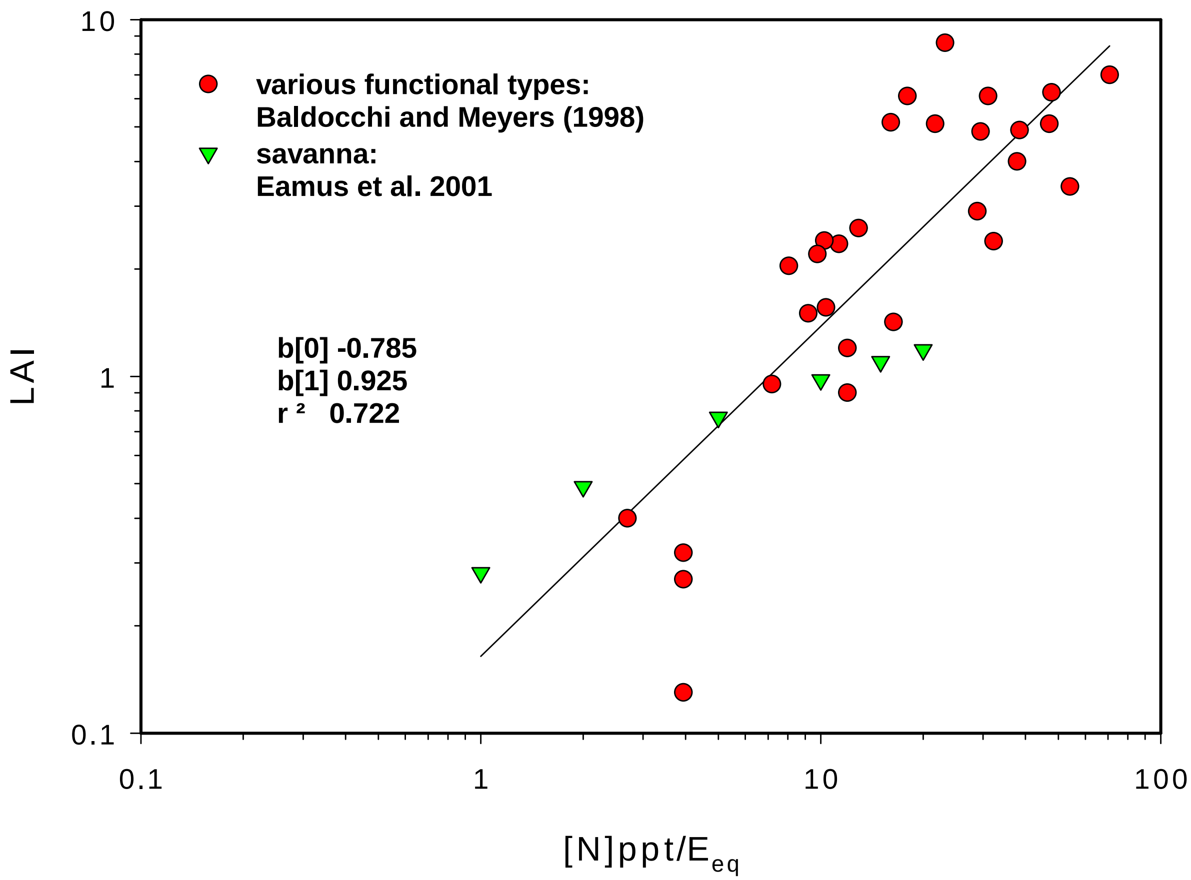
Hansen et al 2005 JGR

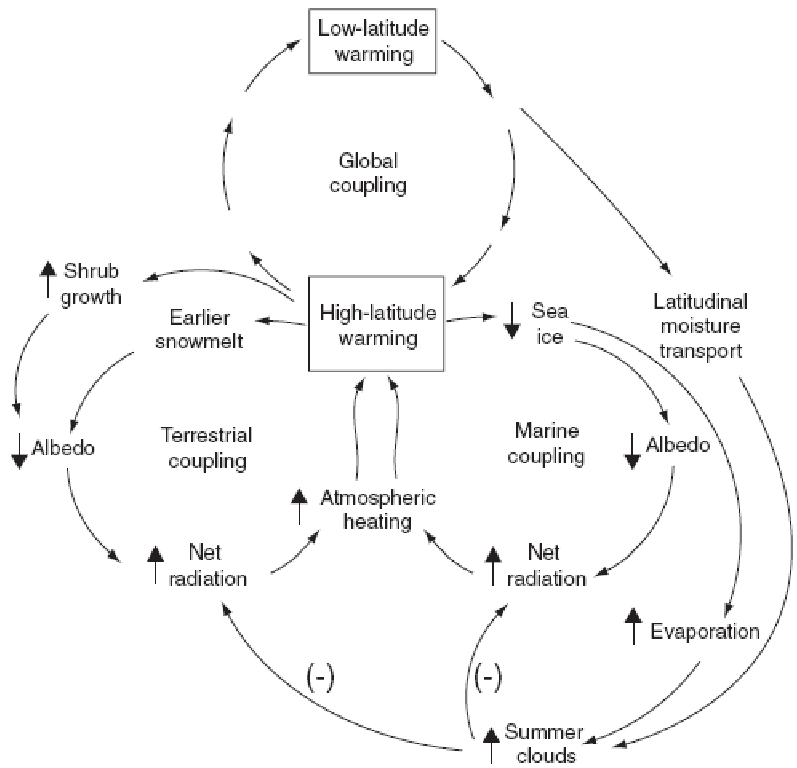
Energy fluxes

- Potential Energy Production by Energy Crops, 2025
  - 2-22 EJ yr^{-1}
  - Offsets 100-2070 Mt CO_2
  - 0.564 Gt C/yr^{-1}

Sims et al 2006 Global Change Biology

You Need Water to Grow Trees!





Chapin et al 2005 Science