Greenhouse gas emissions: present trends and future requirements

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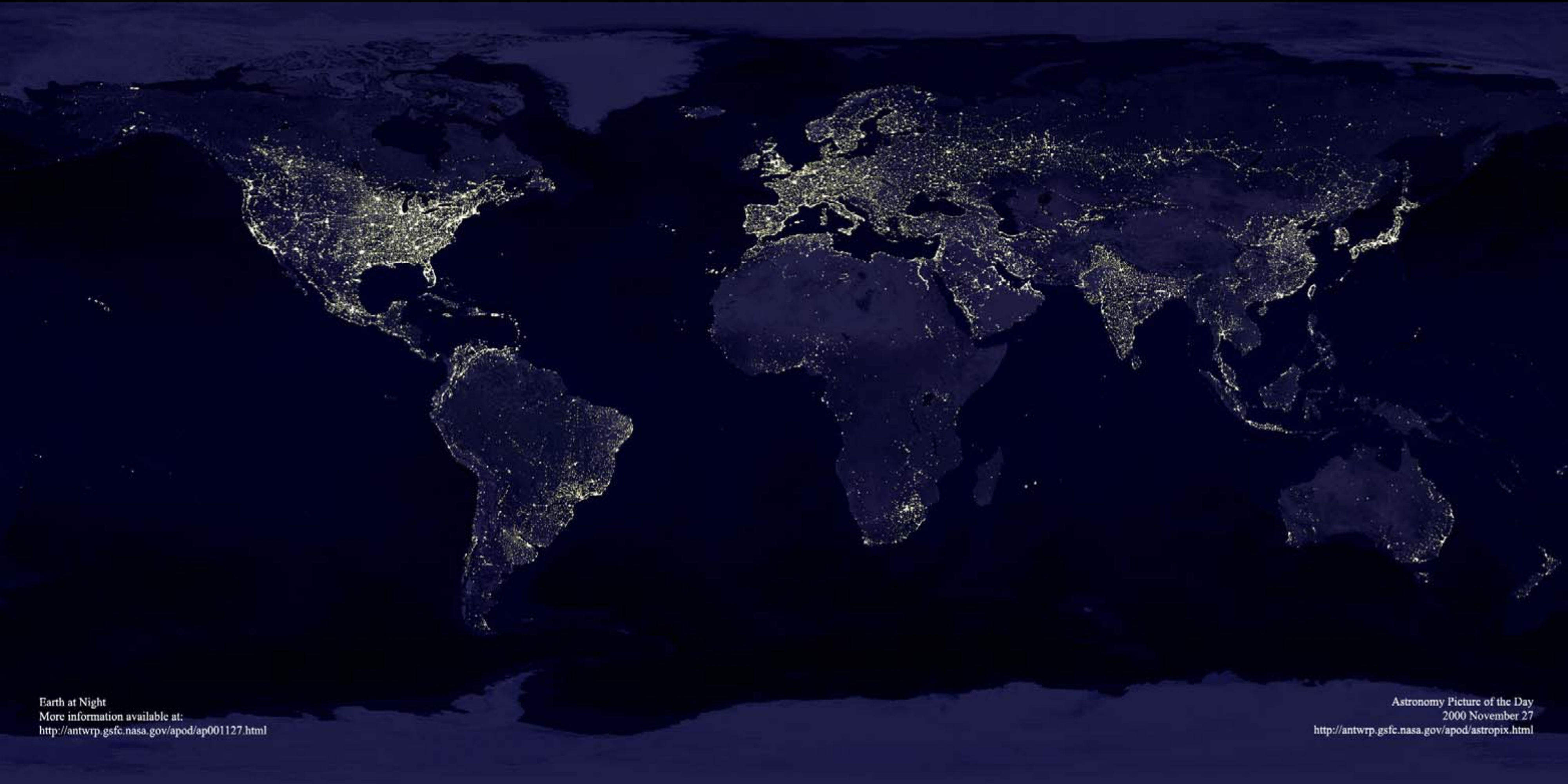
Thanks: GCP colleagues (especially Pep Canadell)
LSCE colleagues (especially Philippe Ciais, Peter Rayner)

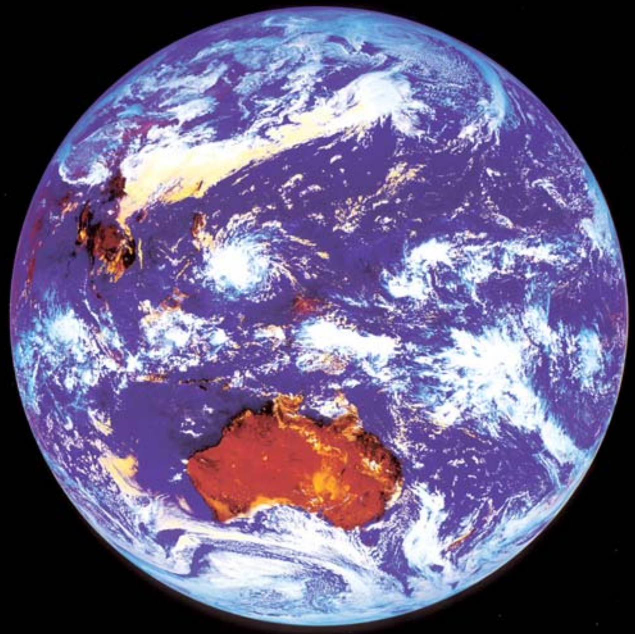
CSIRO

Global Carbon Project

Rapid change on Planet Earth



Two ecologies

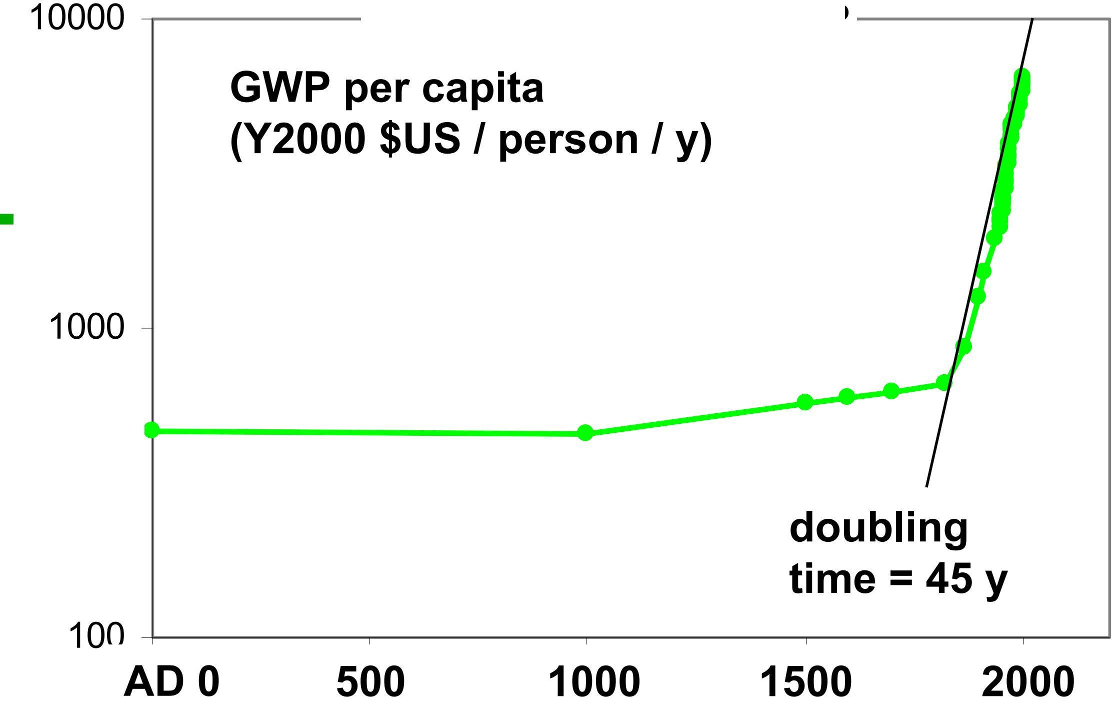


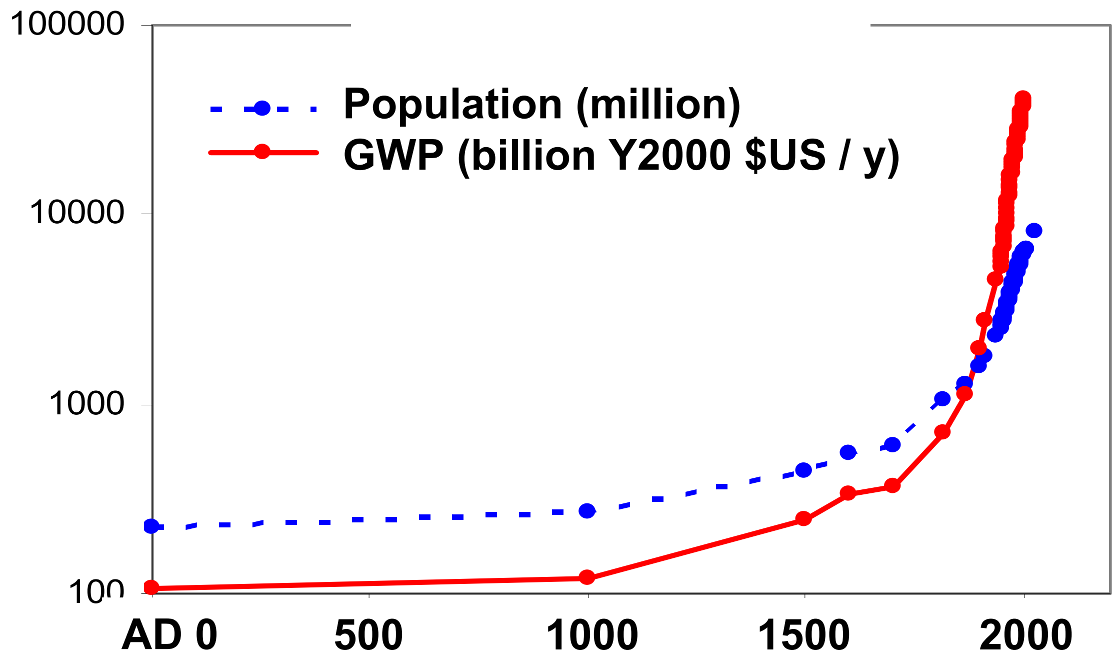
- The biopshere
  - A complex adaptive system based on carbon
  - Evolving for 3.5 billion years
- The anthroposphere
  - One species finds a new evolutionary trick: use of external energy
  - Evolving for thousands of years
  - Biologically based, with extra technological, social, cultural levels

A phase transition in human ecology

- Since 1800, global wealth and per-person resource use have doubled every 45 years

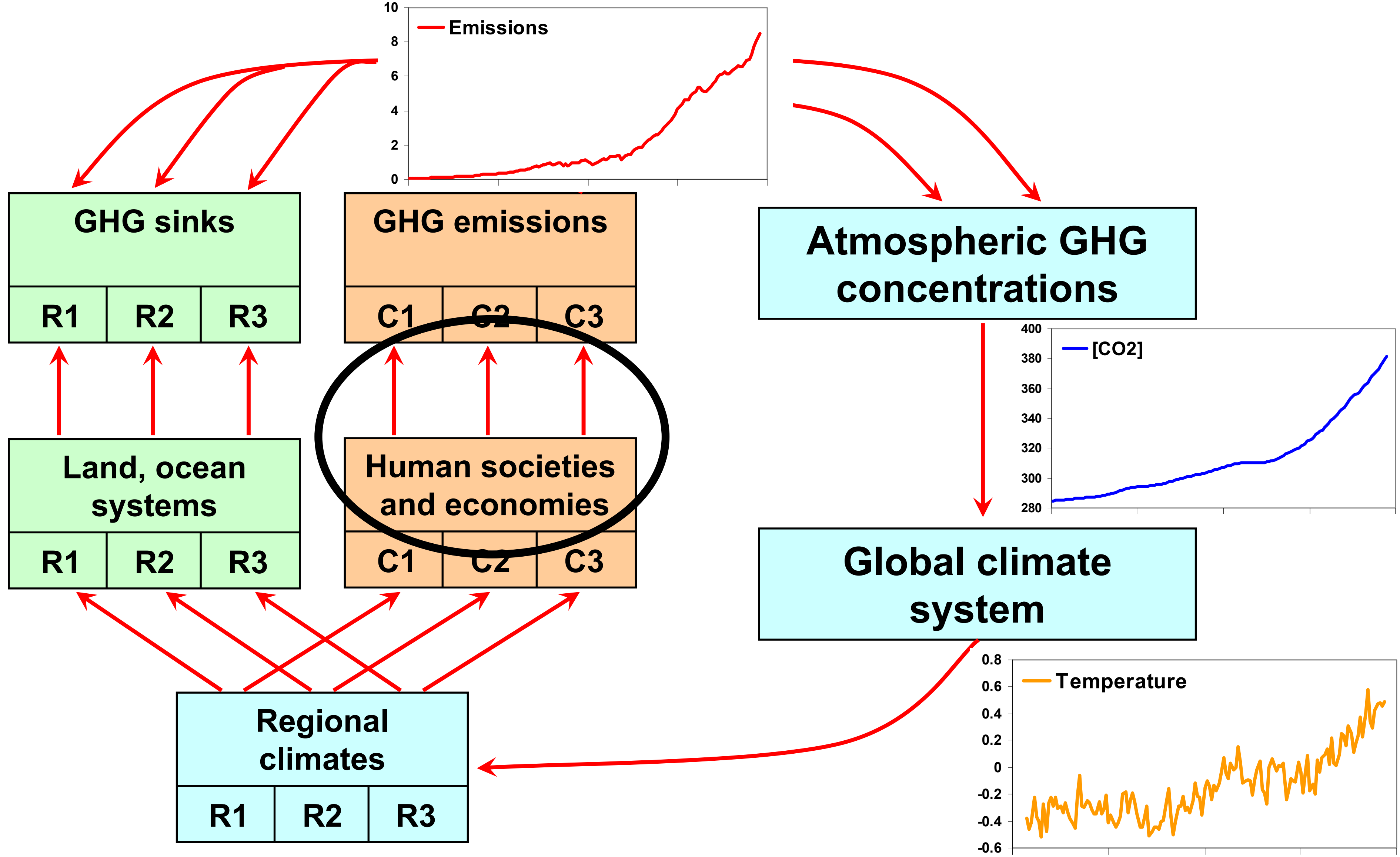
- Growth in consumption:
  - essential before 1900
  - disaster after 2050





Angus Maddison (http://www.ggdc.net/maddison/)

Feedbacks in the carbon-climate-human system



Outline

- Introduction: the carbon-climate-human system

- Trends in CO_2 emissions from fossil fuels
  - Update to 2007
  - Development trajectories and implications

- The full carbon budget and the airborne fraction (AF)
  - The AF is increasing
  - BUT the AF is remarkably steady
  - The AF is the gateway from forcing to response

- Responses: defining and sharing the burden

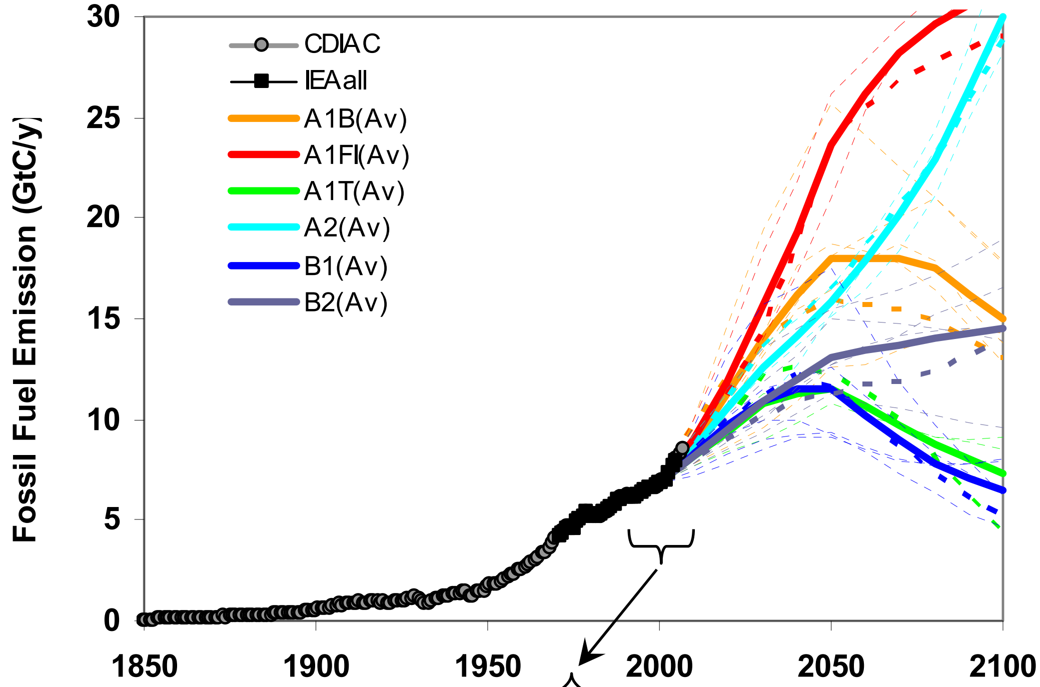
Global CO_2 emissions from fossil fuels to 2007

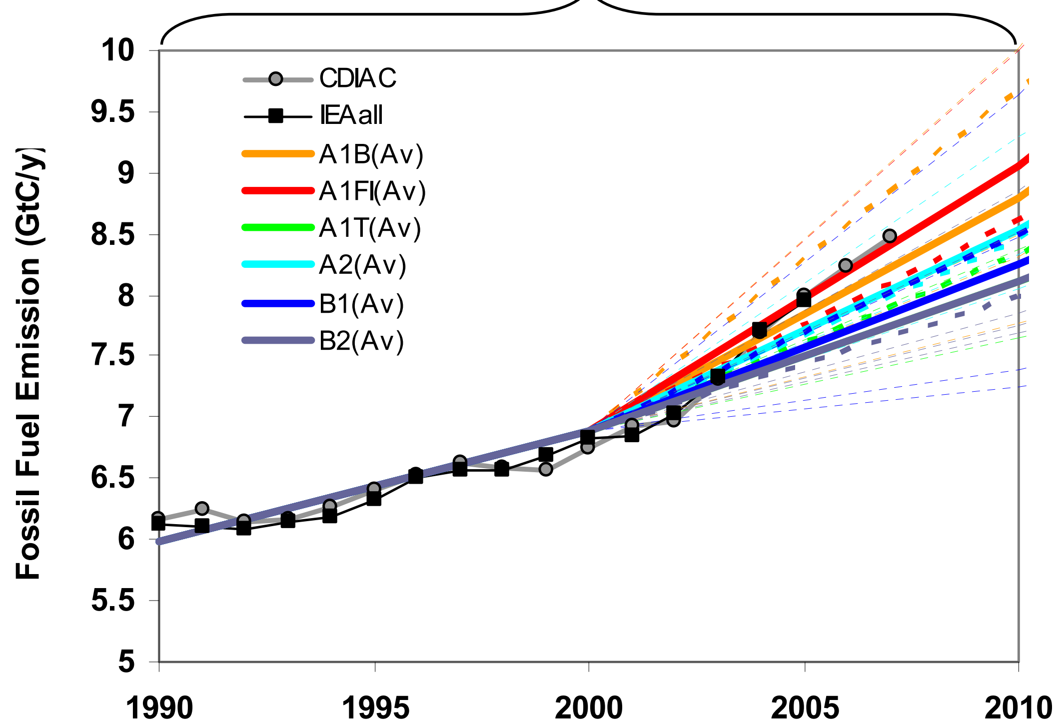
- Emissions from fossil fuels and industry (CDIAC data)

Year	Emissions (GtC/y)
2004	7.69
2005	7.99
2006	8.23
2007	**8.47**

- Growth rates (CDIAC data)

Decade	Growth rate
1980-89	1.90 % y^{-1}
1990-99	0.93 % y^{-1}
2000-07	**3.47 % y^{-1}**



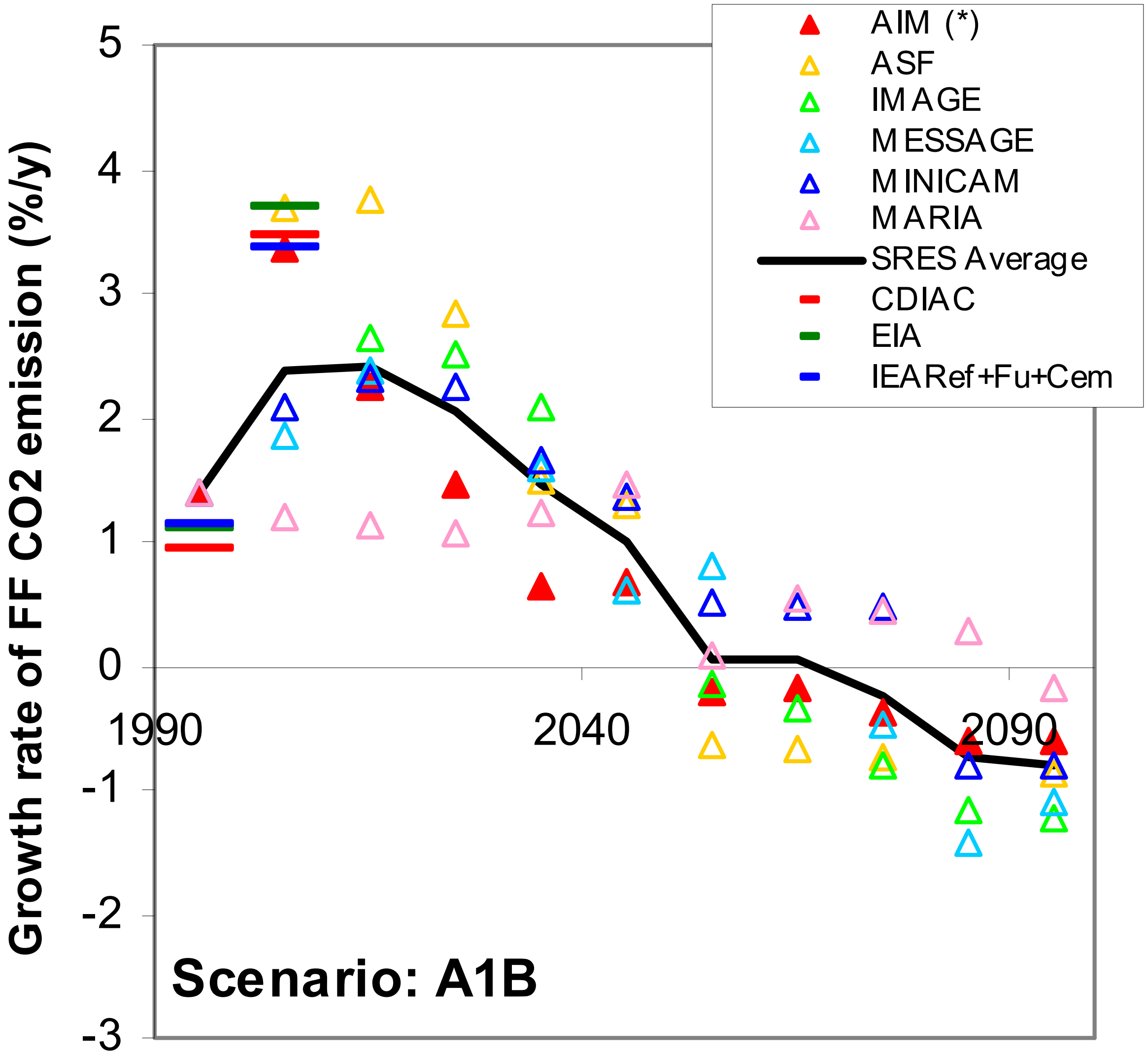


Graphs: Raupach et al. (2007) PNAS, with updated data: CDIAC to 2007, IEA to 2005

Growth rates of fossil-fuel CO_2 emissions: SRES scenarios and observations 2000-2005

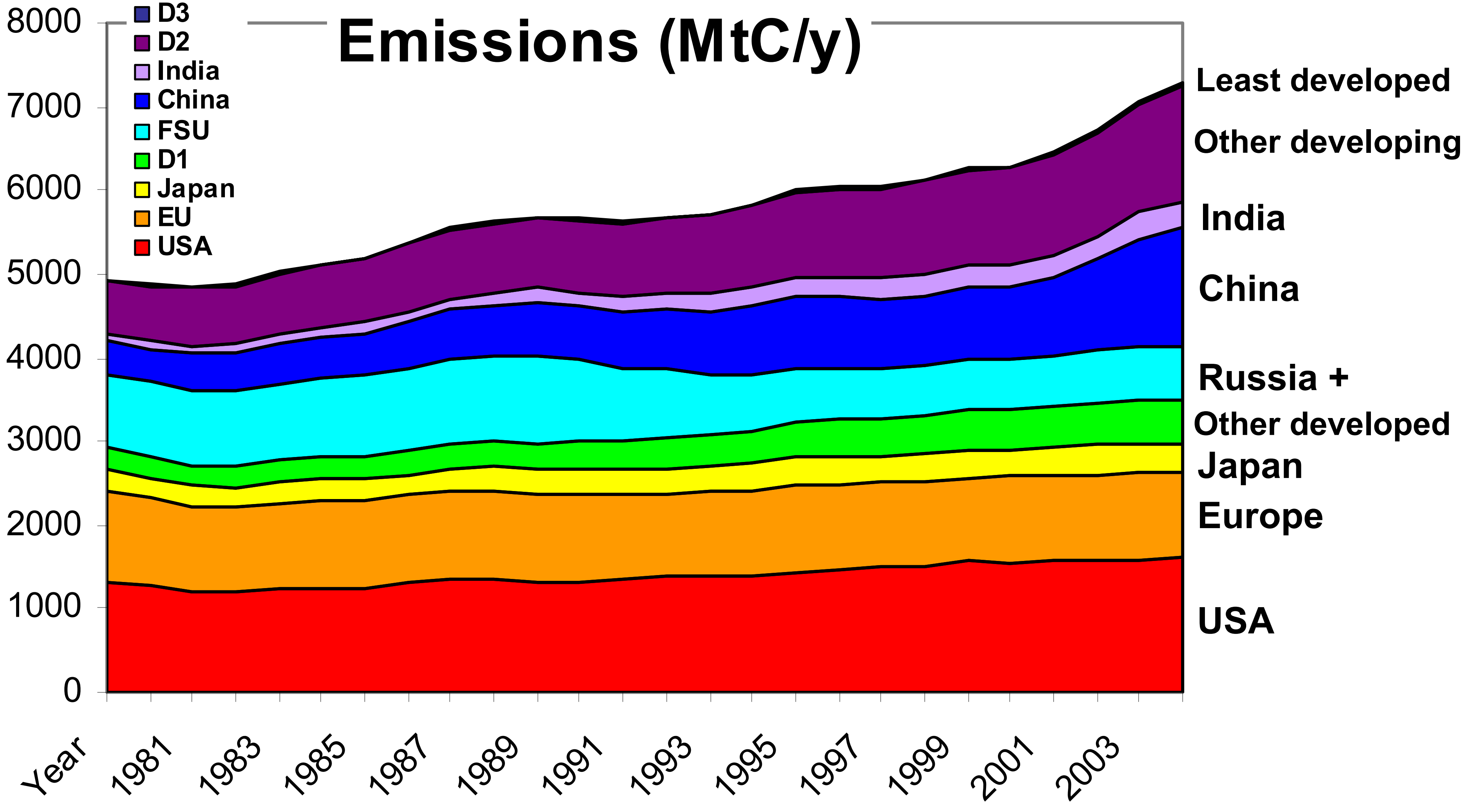
- Emissions growth (%/y)

- Bars: Observations
- Solid points: Marker scenario
- Open points: Other scenarios
- Black line: Scenario average

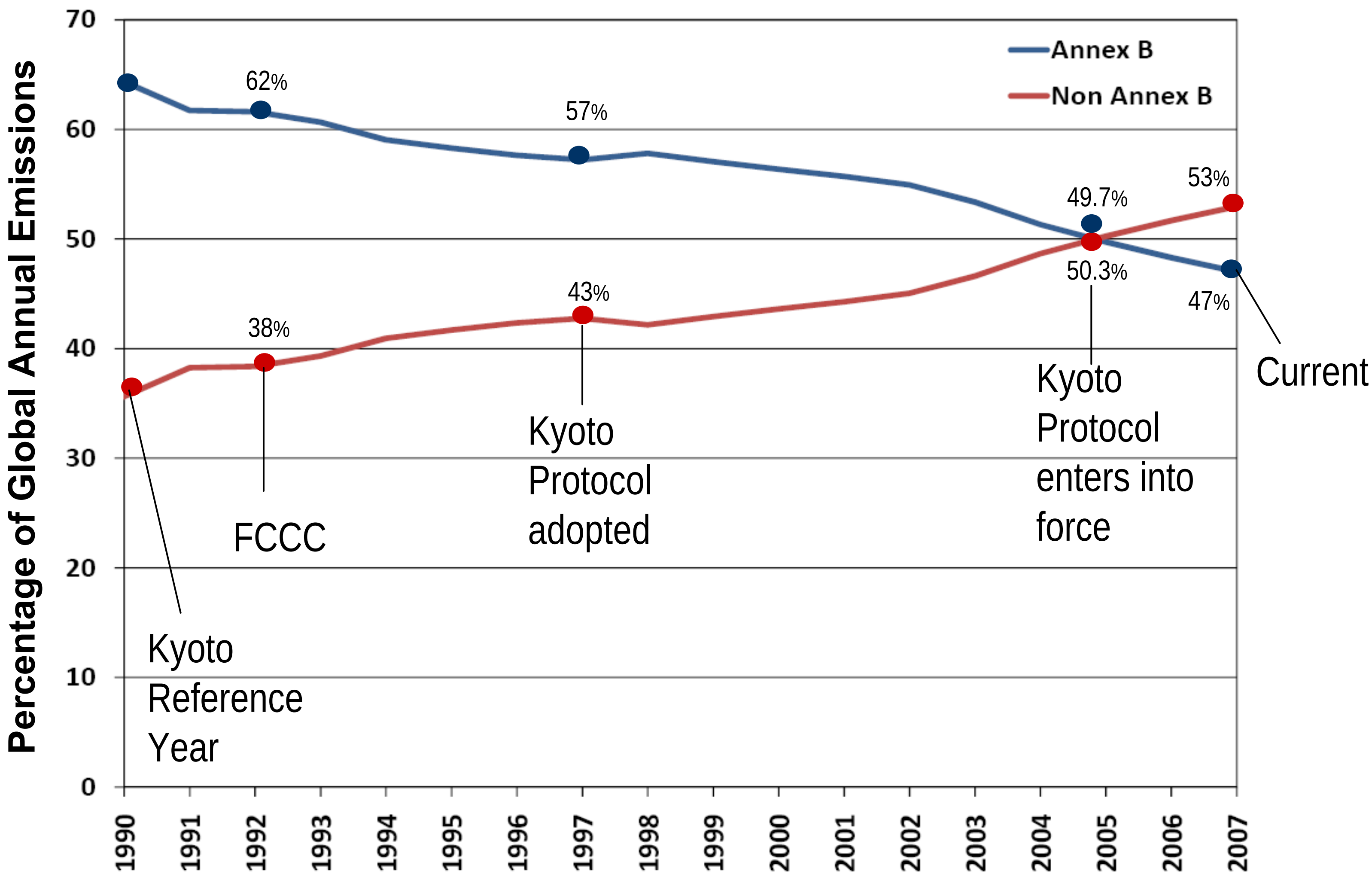


Raupach et al. (2007) PNAS
Updated to 2005 with IEA data

CO_2 from fossil fuels

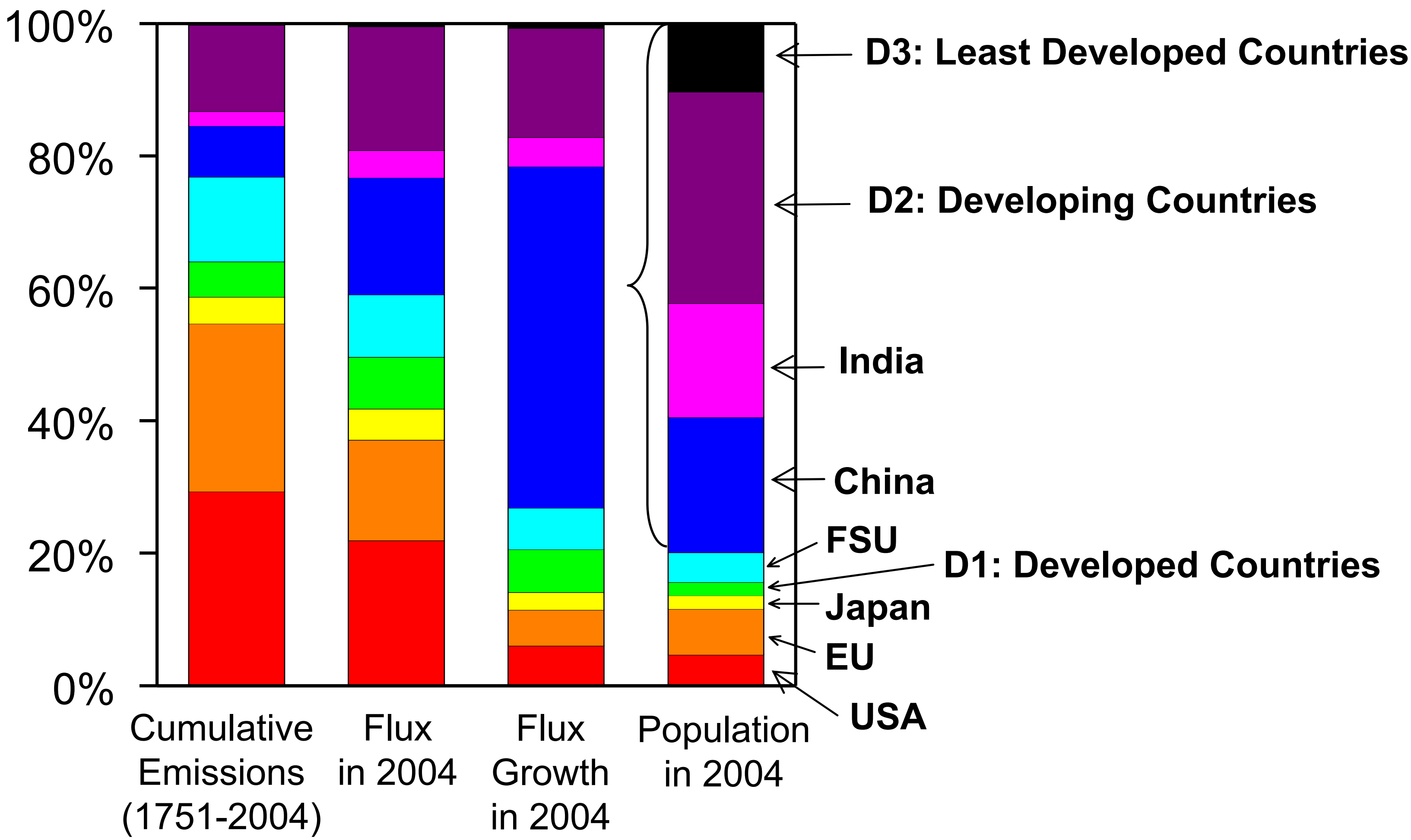


Emissions from developing countries are growing fast



J. Gregg and G. Marland, 2008, personal communication

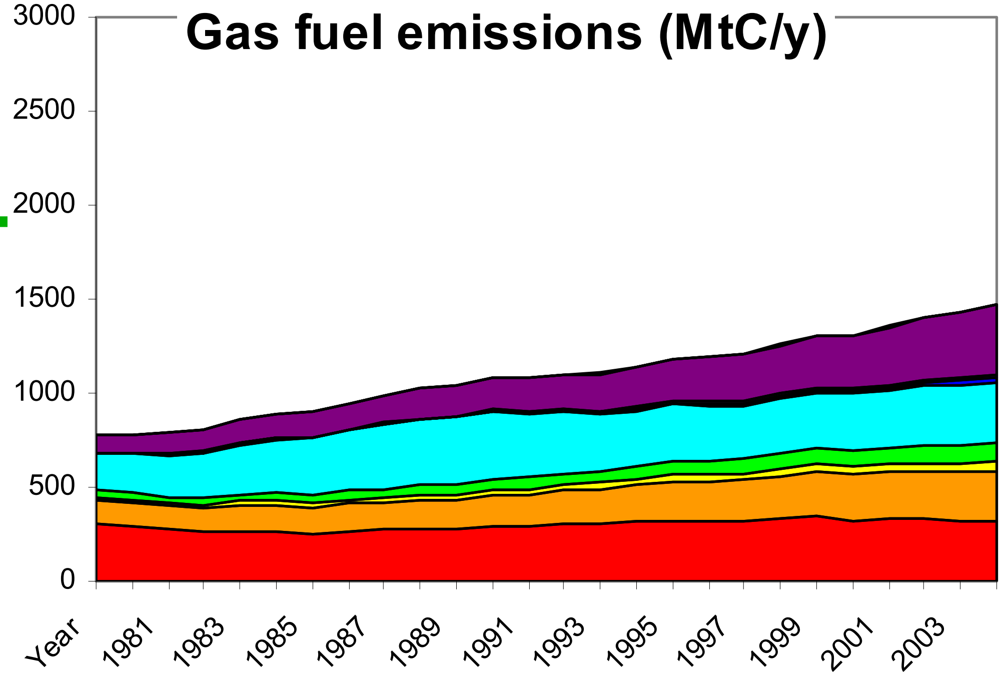
Unequal distribution of cumulative emissions

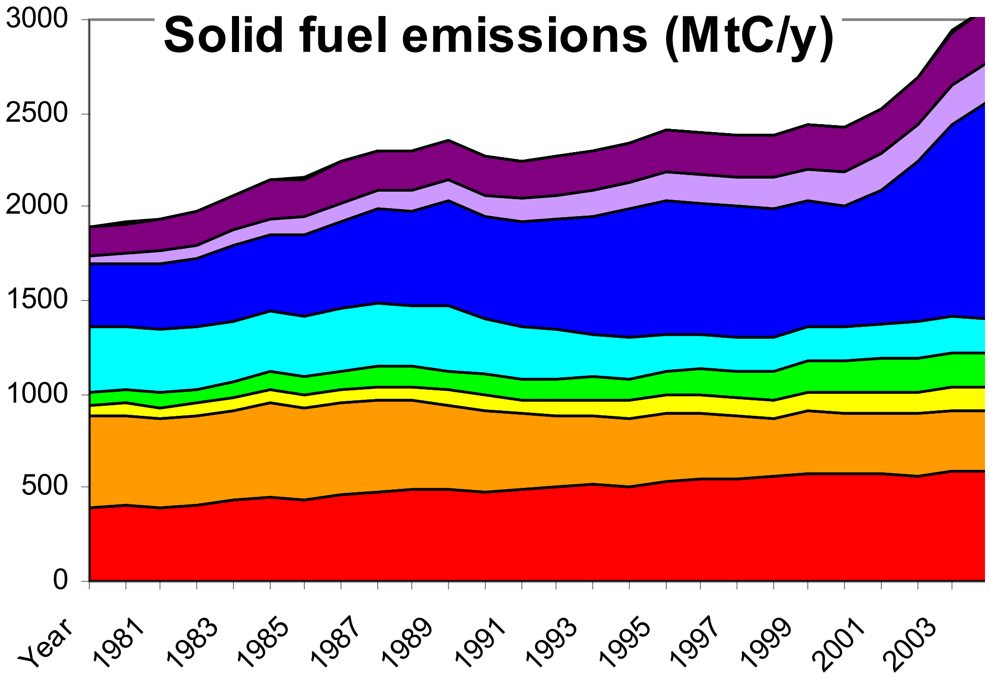


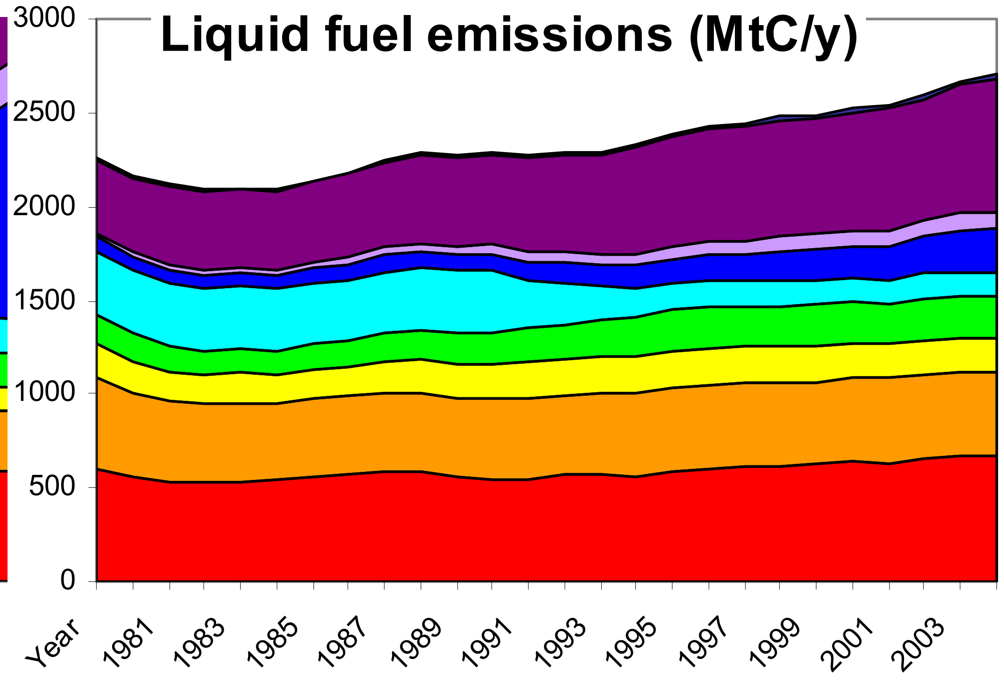
Raupach et al. (2007) PNAS

Emissions from solid, liquid, gas fuels

- Global : (S, F, G) = (43, 37, 20)
- China: solid fuels dominate
- D2: liquid fuels dominate
- FSU: gas fuels dominate







Raupach et al. (2007) PNAS
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Drivers of global emissions

- Kaya Identity

$$F = P \times \frac{G}{P} \times \frac{E}{G} \times \frac{F}{E}$$

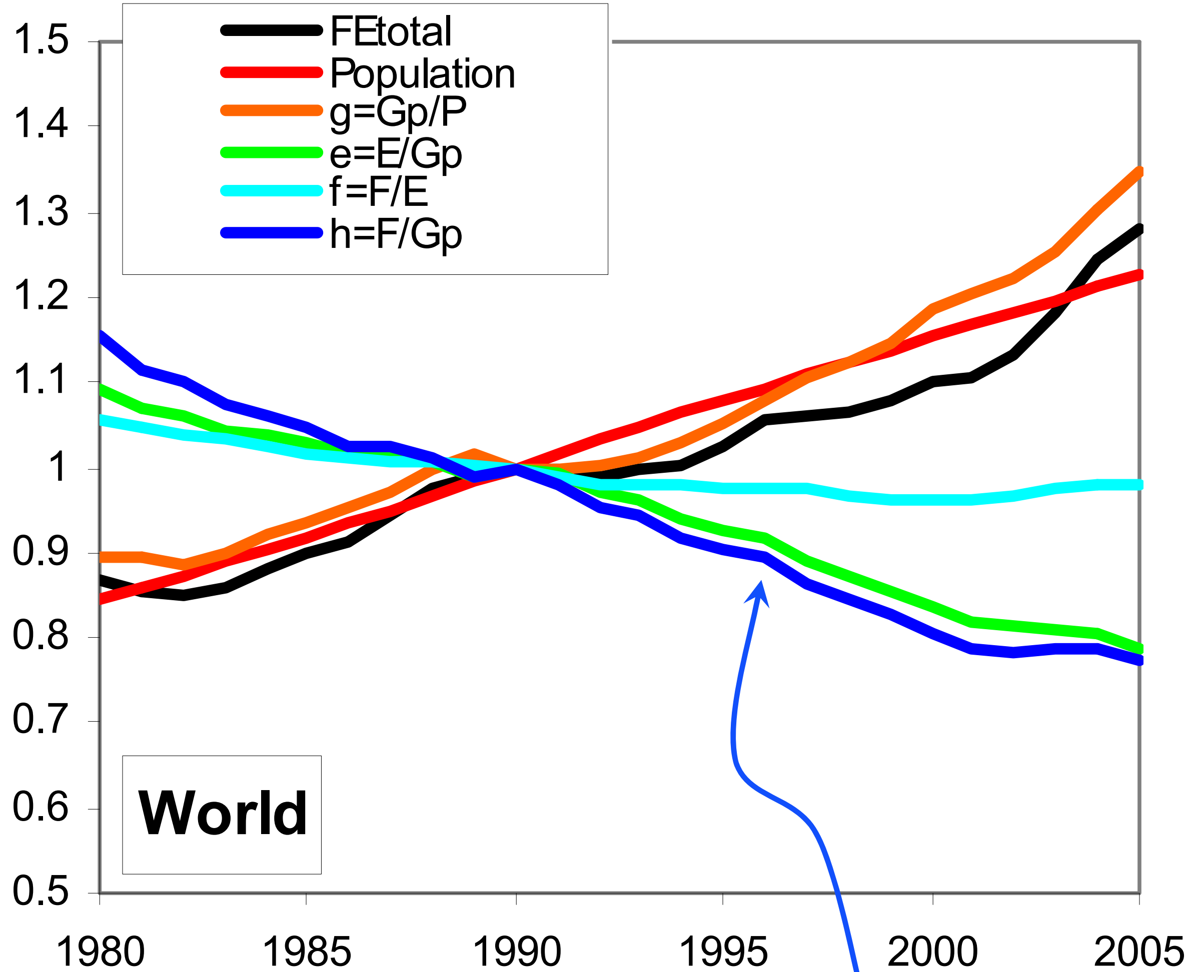
Fossil-fuel CO_2 emission

Population

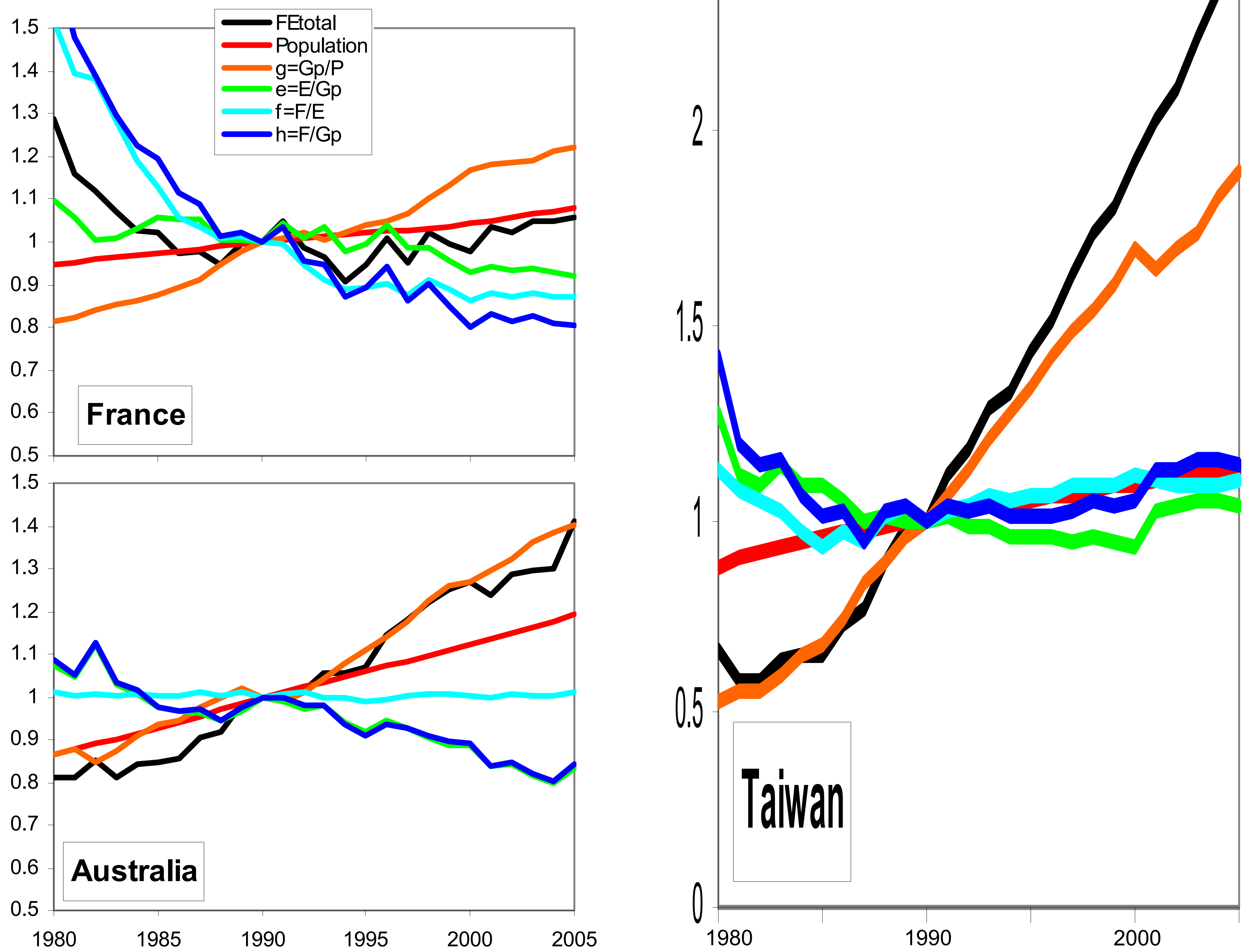
Per-capita GDP

Energy intensity of GDP

Carbon intensity of energy



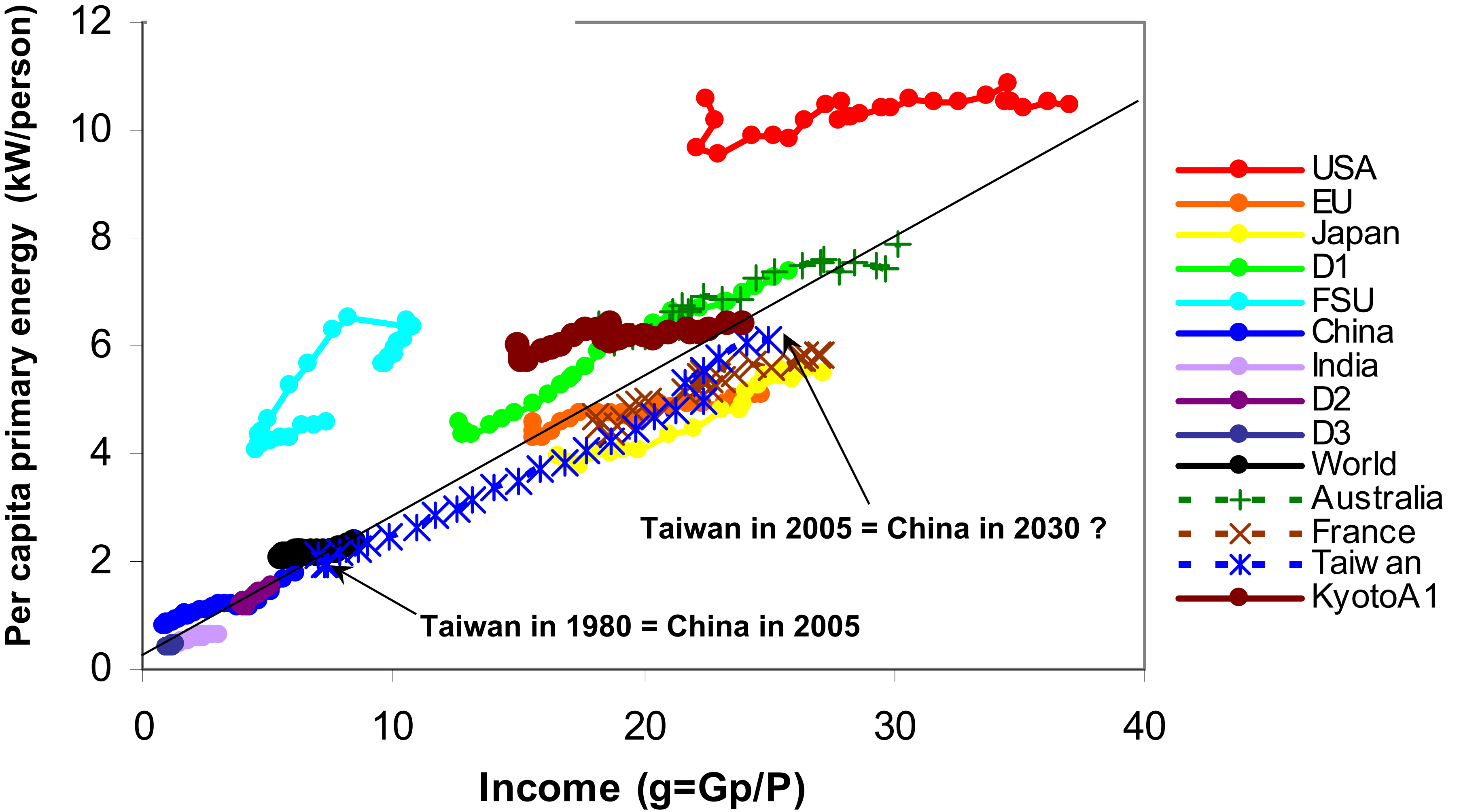
Carbon intensity of GDP
= F/G = (E/G) x (F/E)



FEtotal
Population
g=Gp/P
e=E/Gp
f=F/E
h=F/Gp
France
Australia
Taiwan
1980
1985
1990
1995
2000
2005

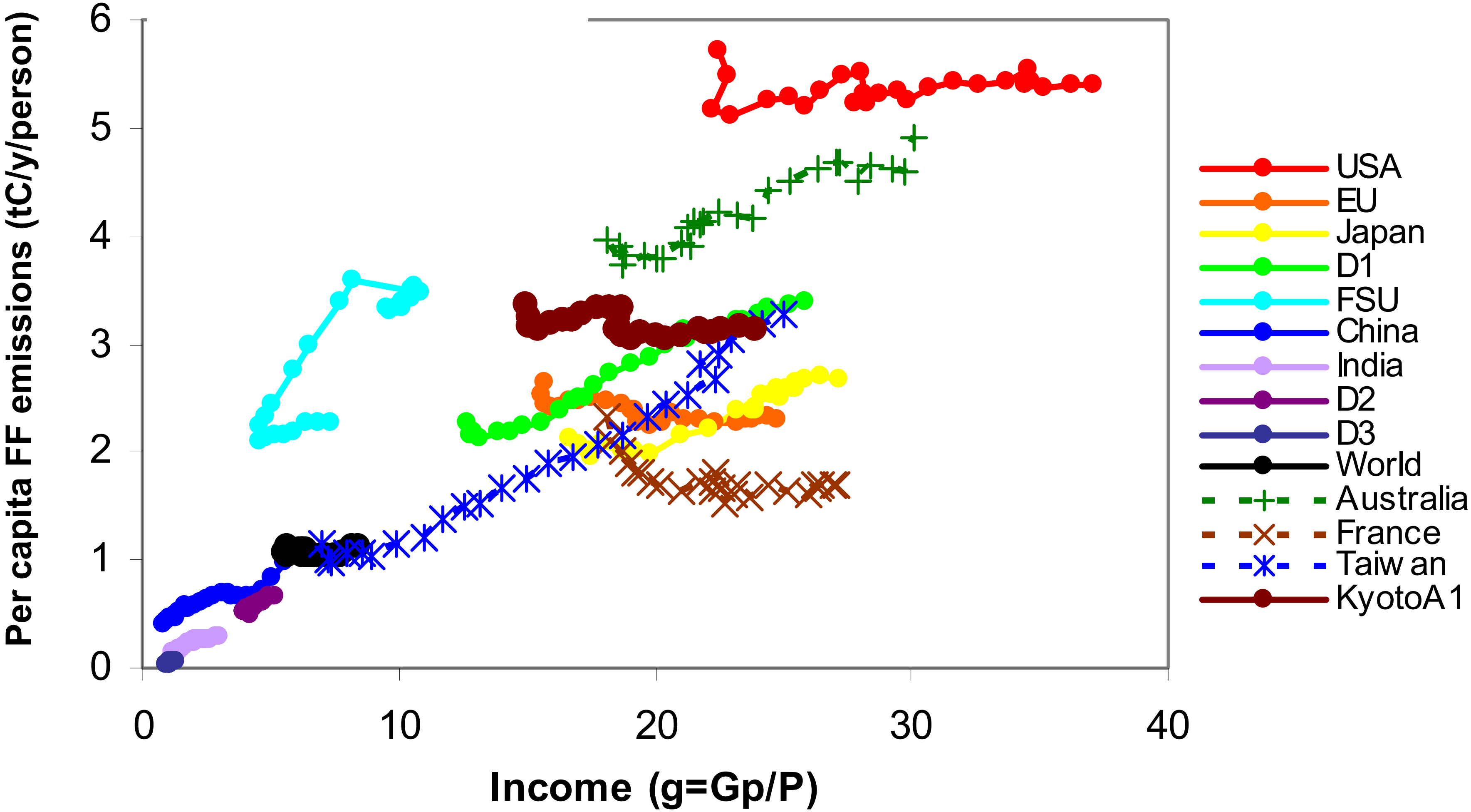
Development trajectories: energy

- Plot per capita primary energy against income, from 1980 to 2005



Development trajectories: CO_2 emissions

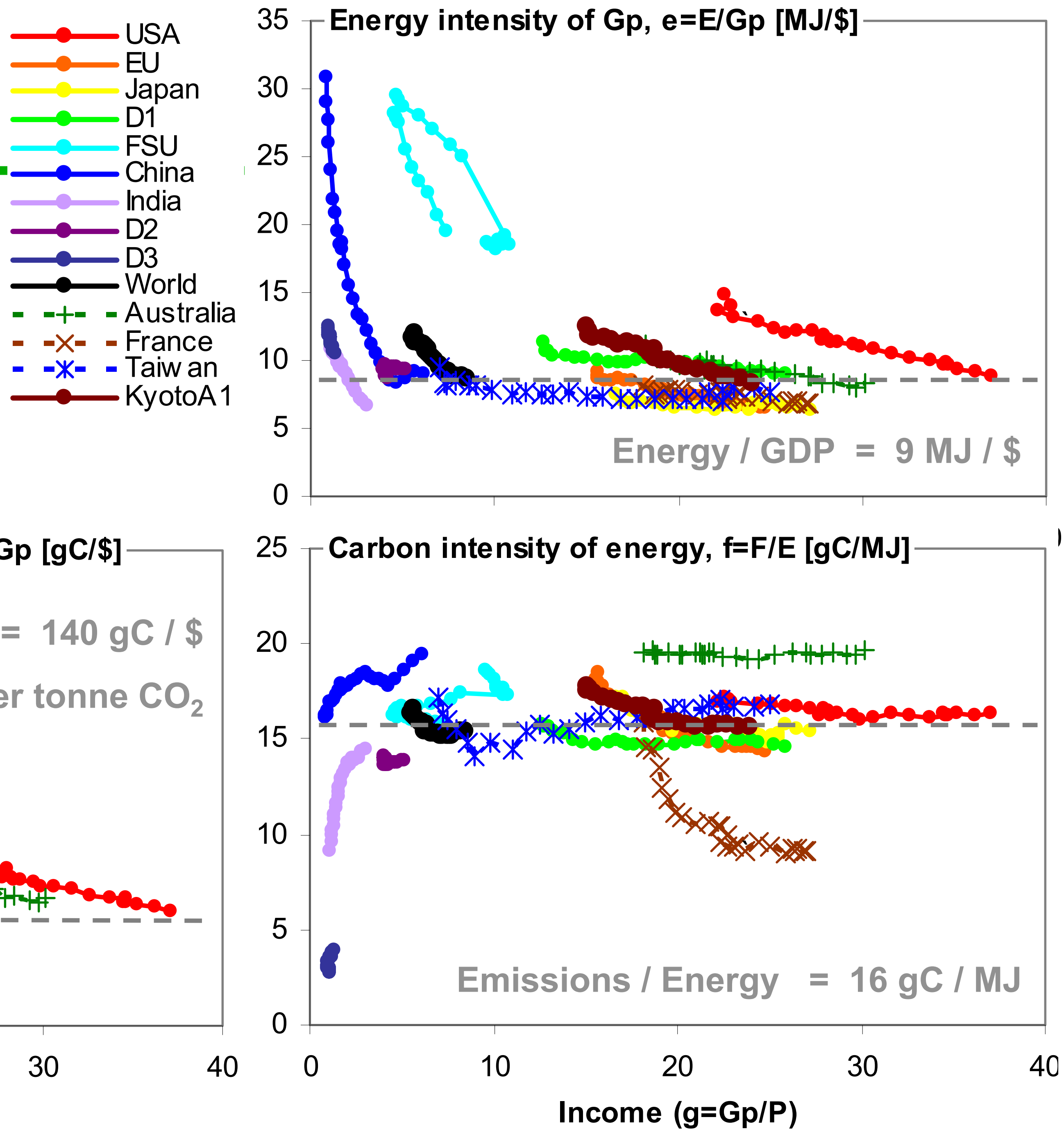
- Plot per capita FF emissions against income, from 1980 to 2005



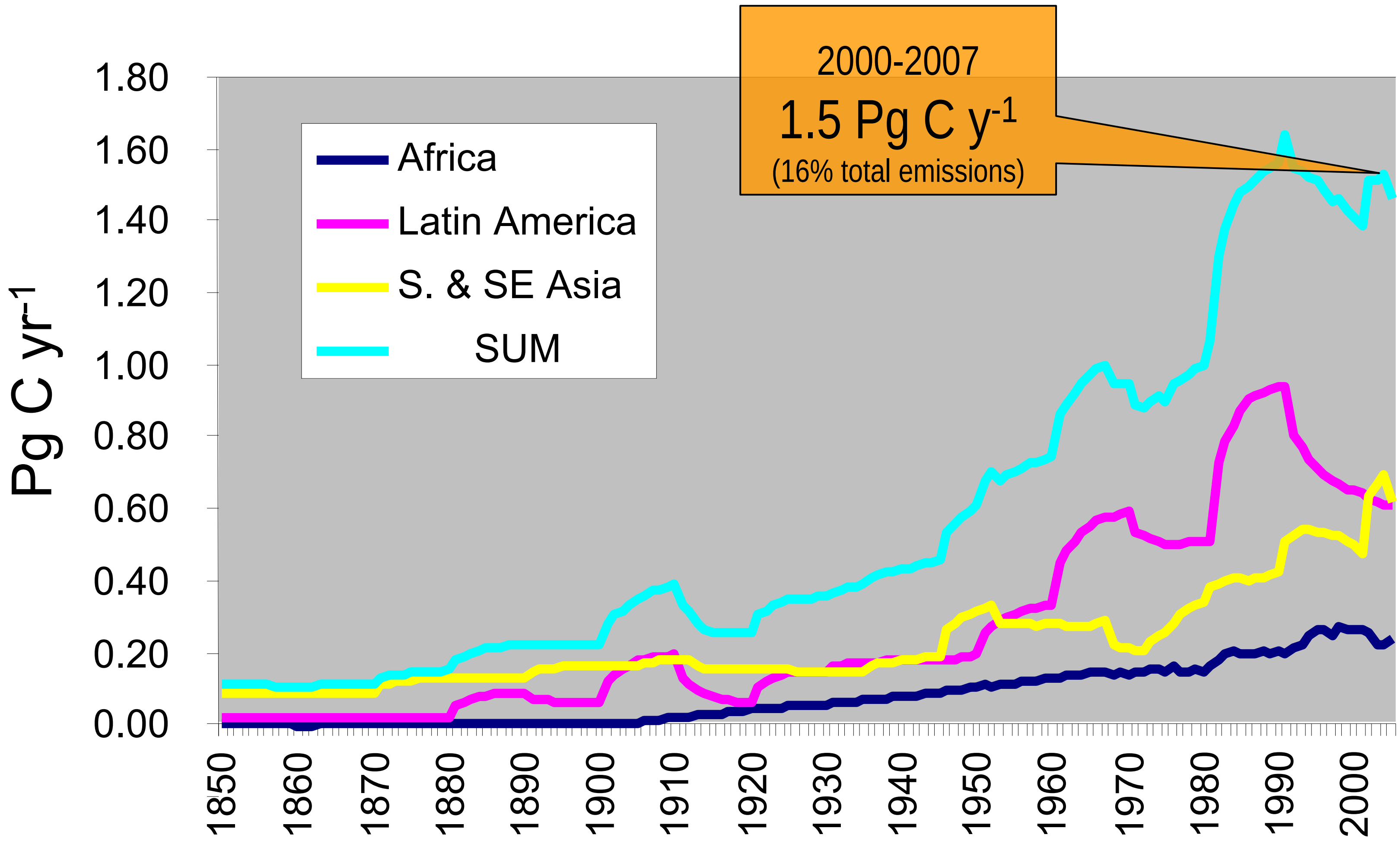
Raupach (2008) unpublished

Intensities

- Energy / GDP
  x Emissions / Energy
  = Emissions / GDP

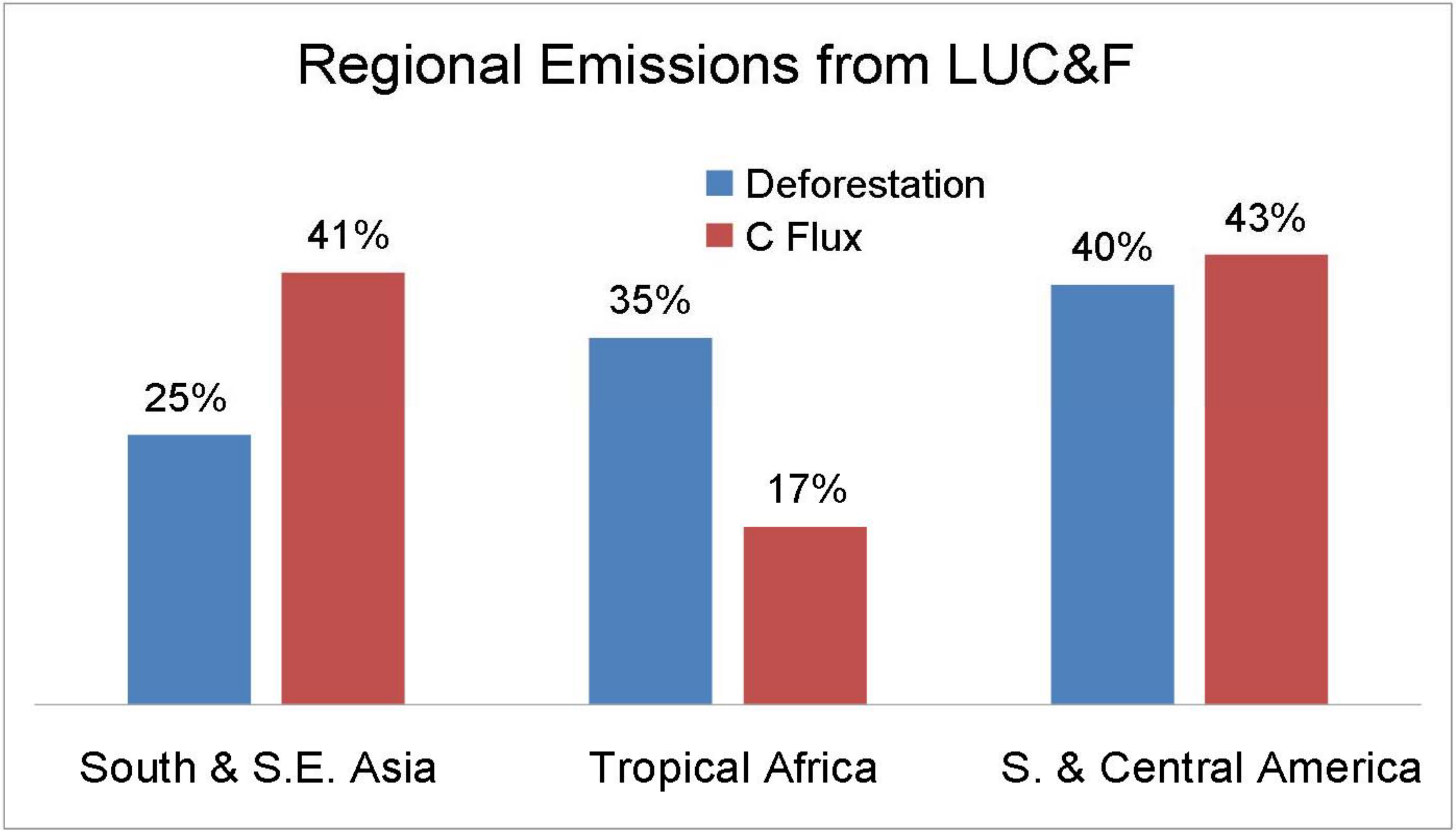


CO_2 emissions from land use change
Net emissions from tropical deforestation



R.A. Houghton (unpublished)

CO_2 emissions from land use change
The effect of differing biomass densities



Canadell, Raupach and Houghton (Biogeosciences, submitted)

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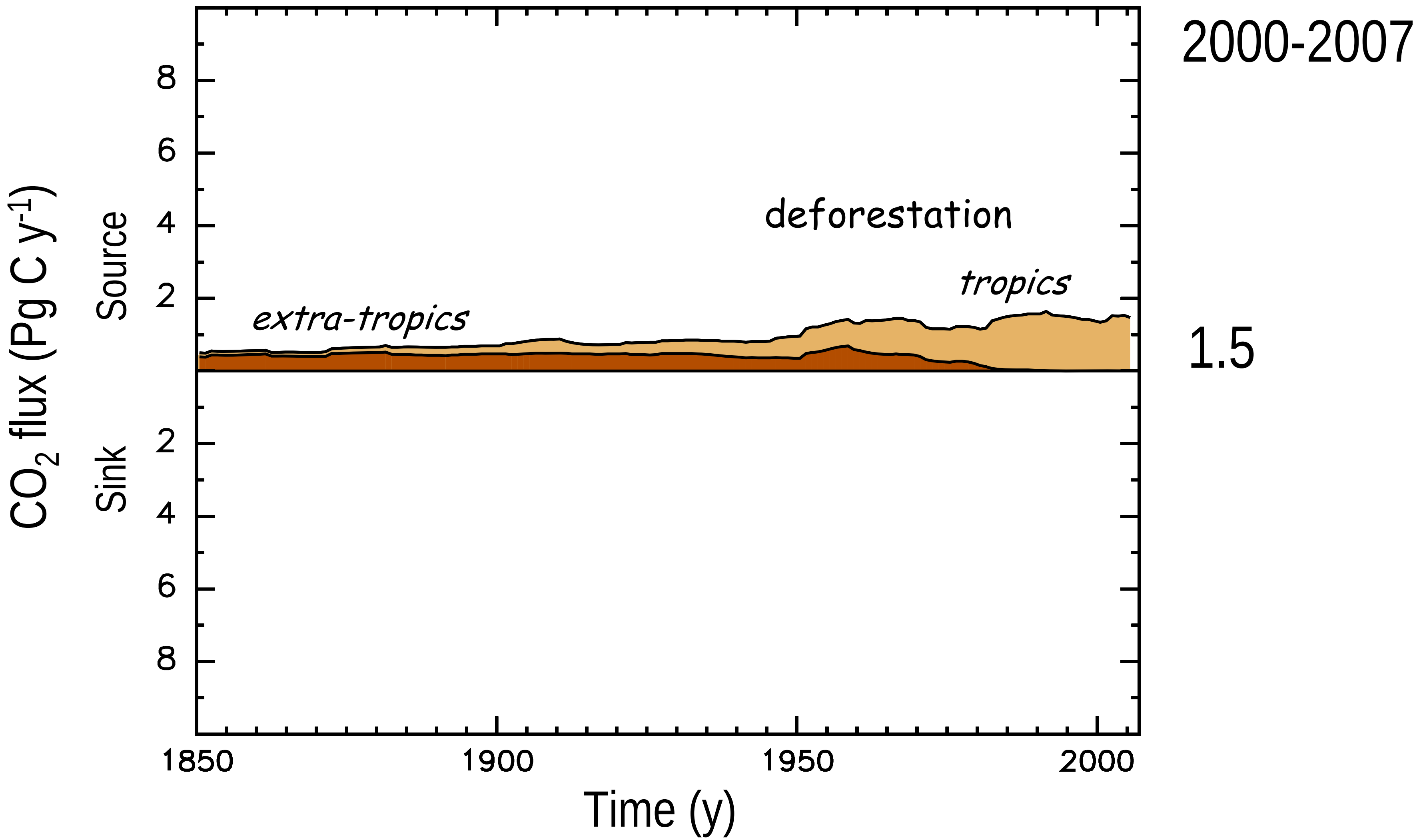
Growth in atmospheric CO_2

- Atmospheric CO_2 concentration in 2007 = **382.7 ppm**

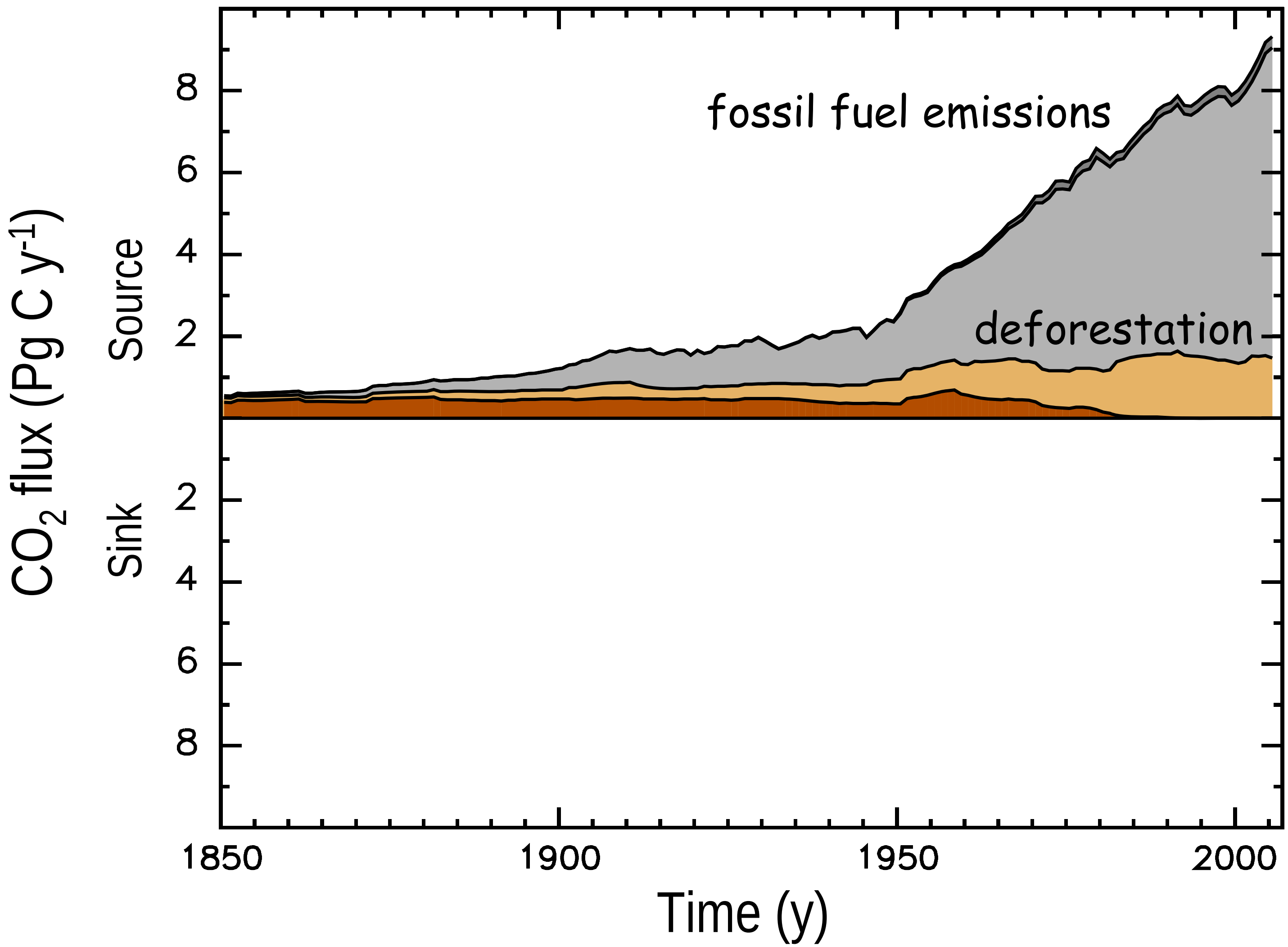
- Growth rates:
  - 1970-79: 1.3 ppm y^{-1}
  - 1980-89: 1.6 ppm y^{-1}
  - 1990-99: 1.5 ppm y^{-1}
  - **2000-07: 2.0 ppm y^{-1}**

Global CO_2 budget 1850-2007



Global Carbon Project (2008)

Global CO_2 budget 1850-2007



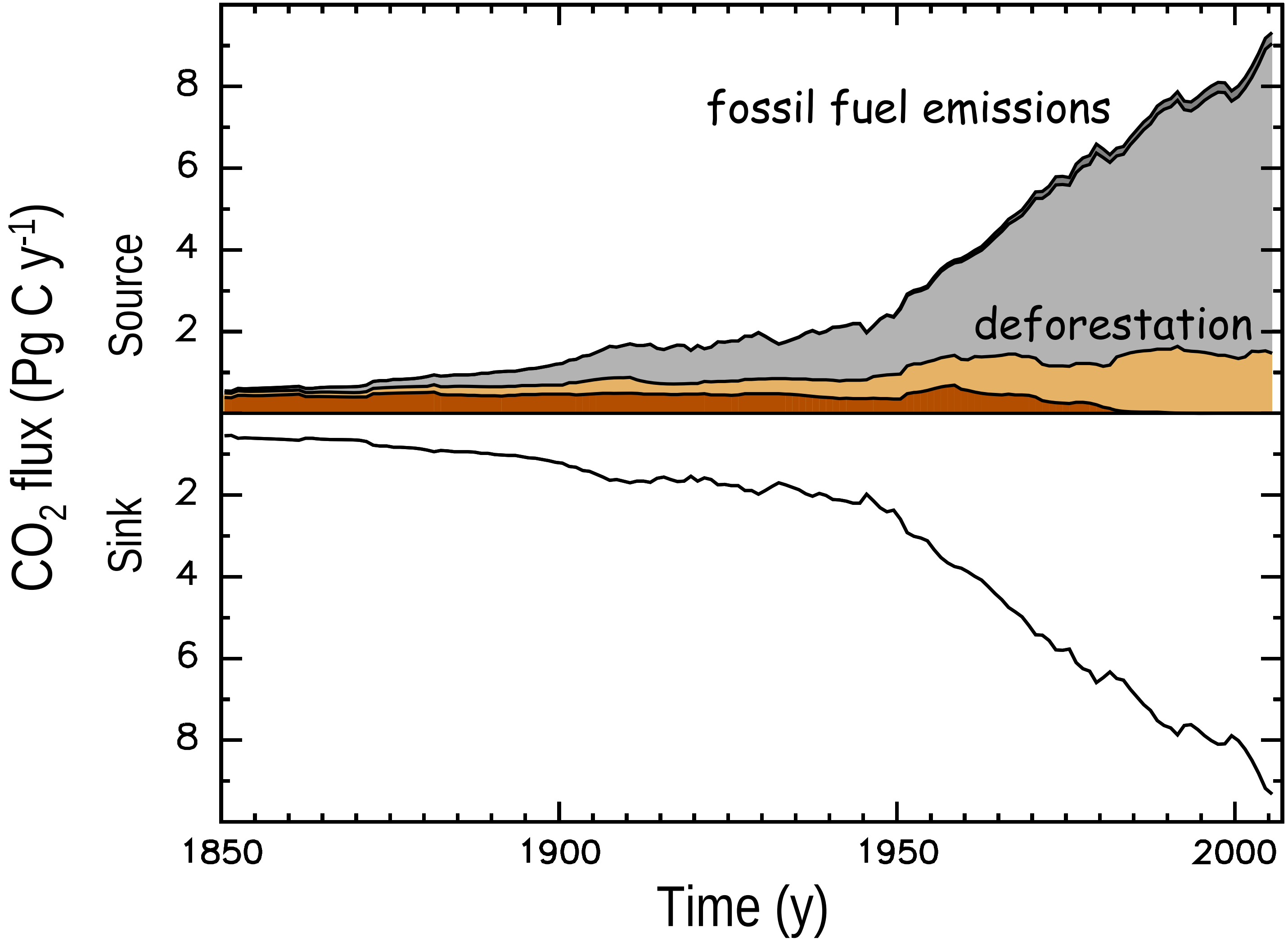
2000-2007

7.5

1.5

Global Carbon Project (2008)

Global CO_2 budget 1850-2007



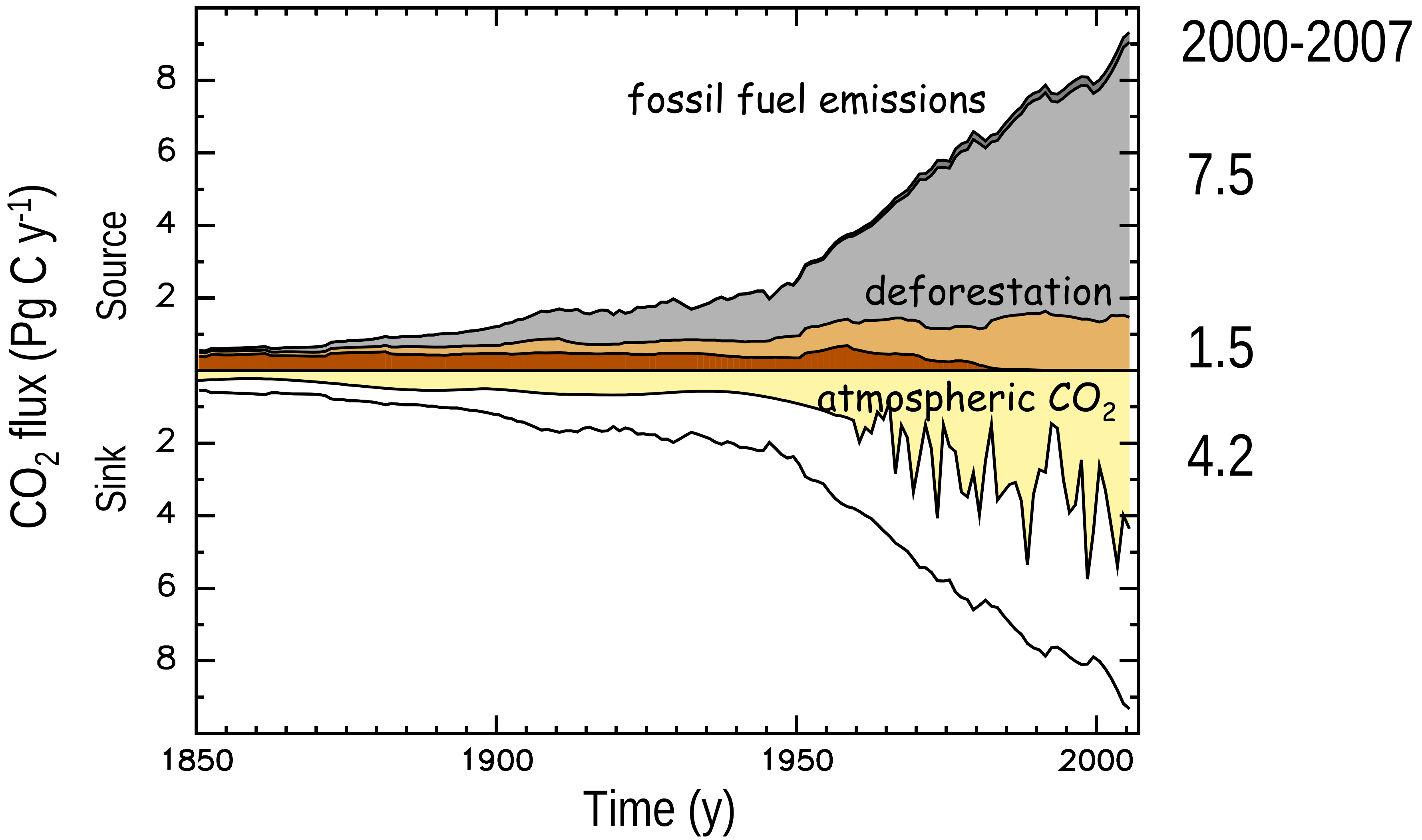
2000-2007

7.5

1.5

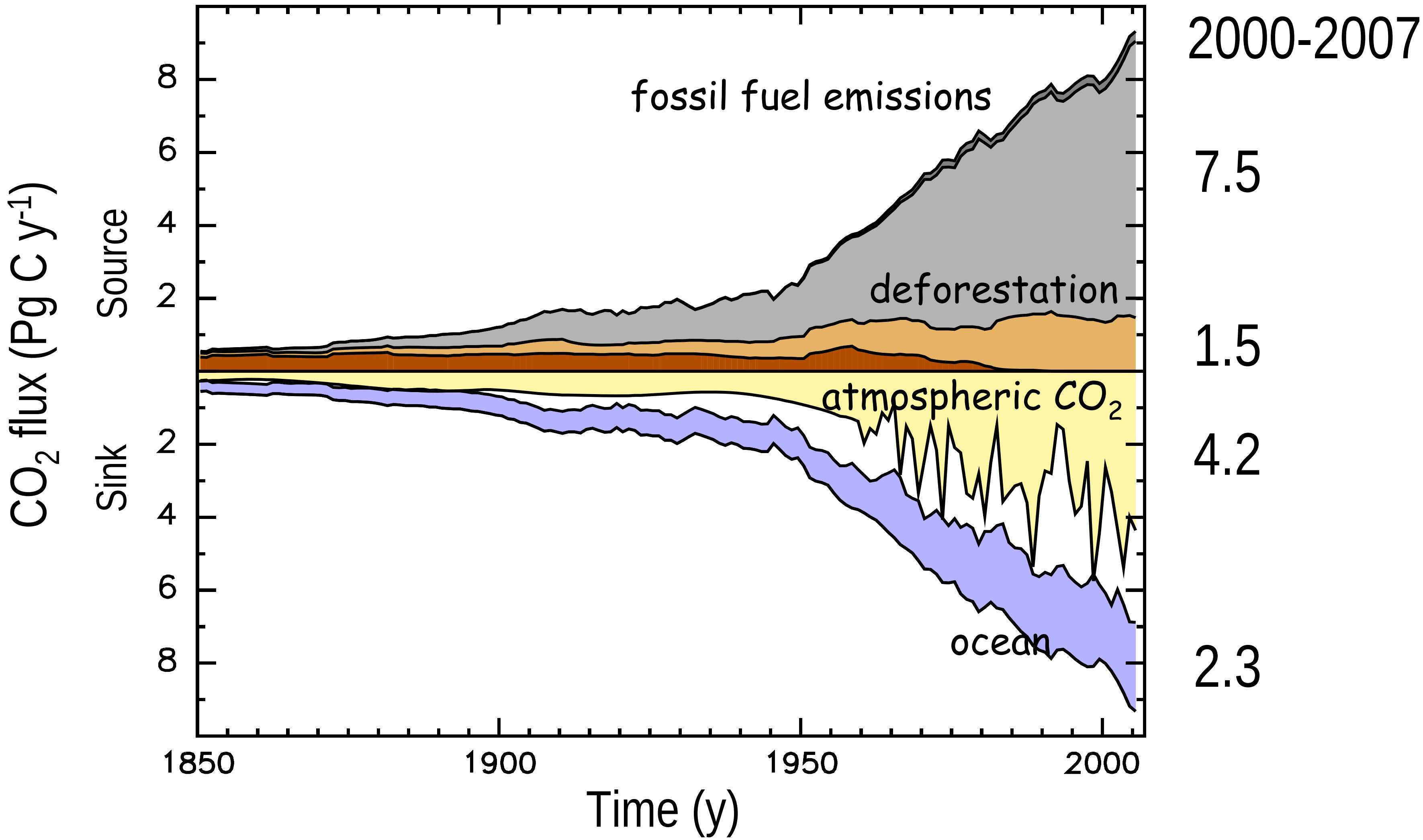
Global Carbon Project (2008)

Global CO_2 budget 1850-2007



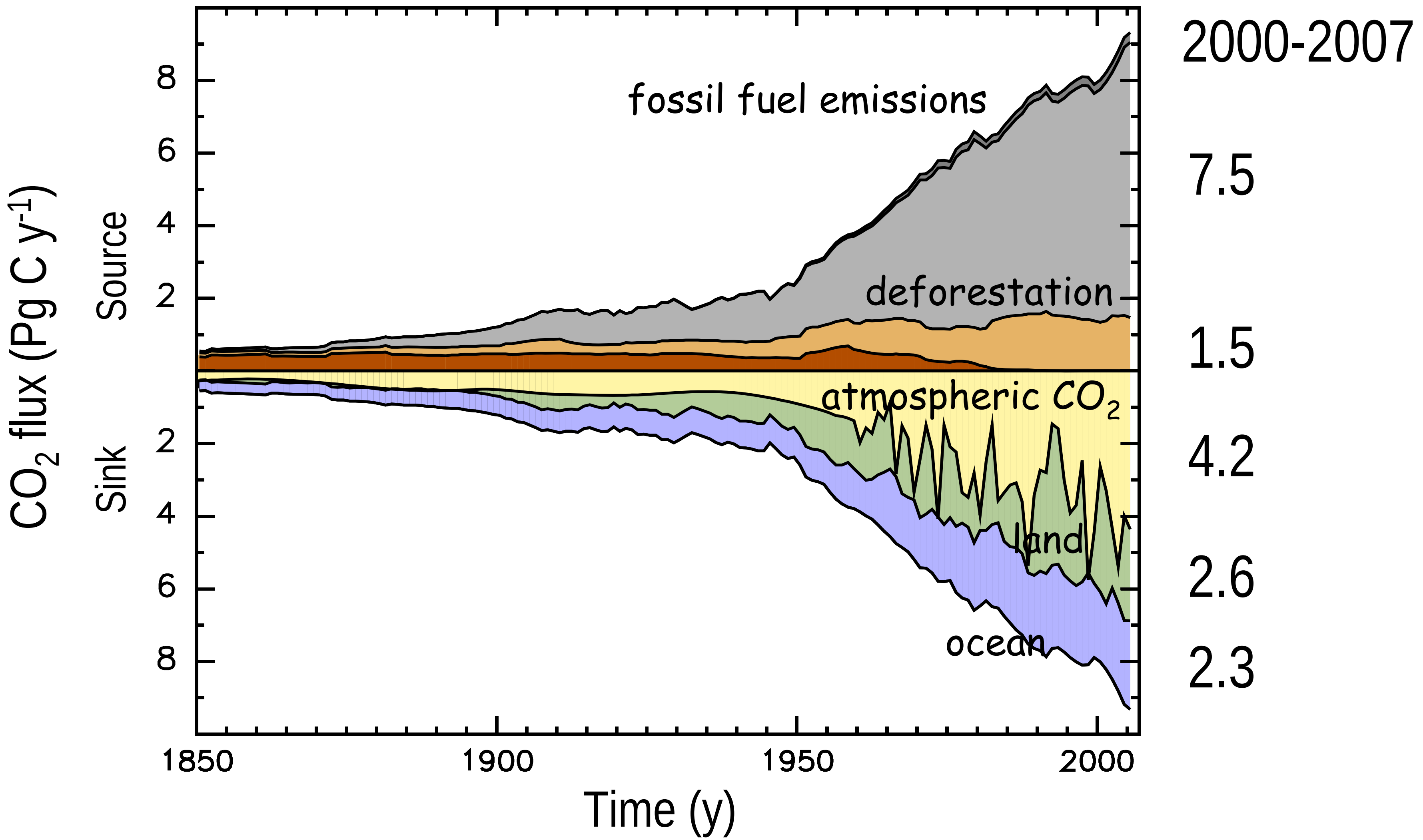
Global Carbon Project (2008)

Global CO_2 budget 1850-2007



Global Carbon Project (2008)

Global CO_2 budget 1850-2007

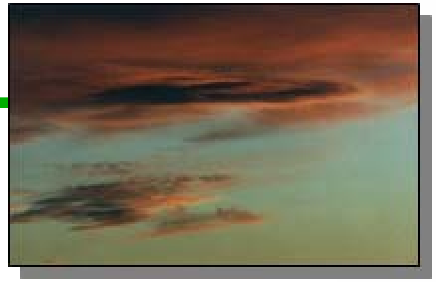


Global Carbon Project (2008)

Climate change at 55% discount

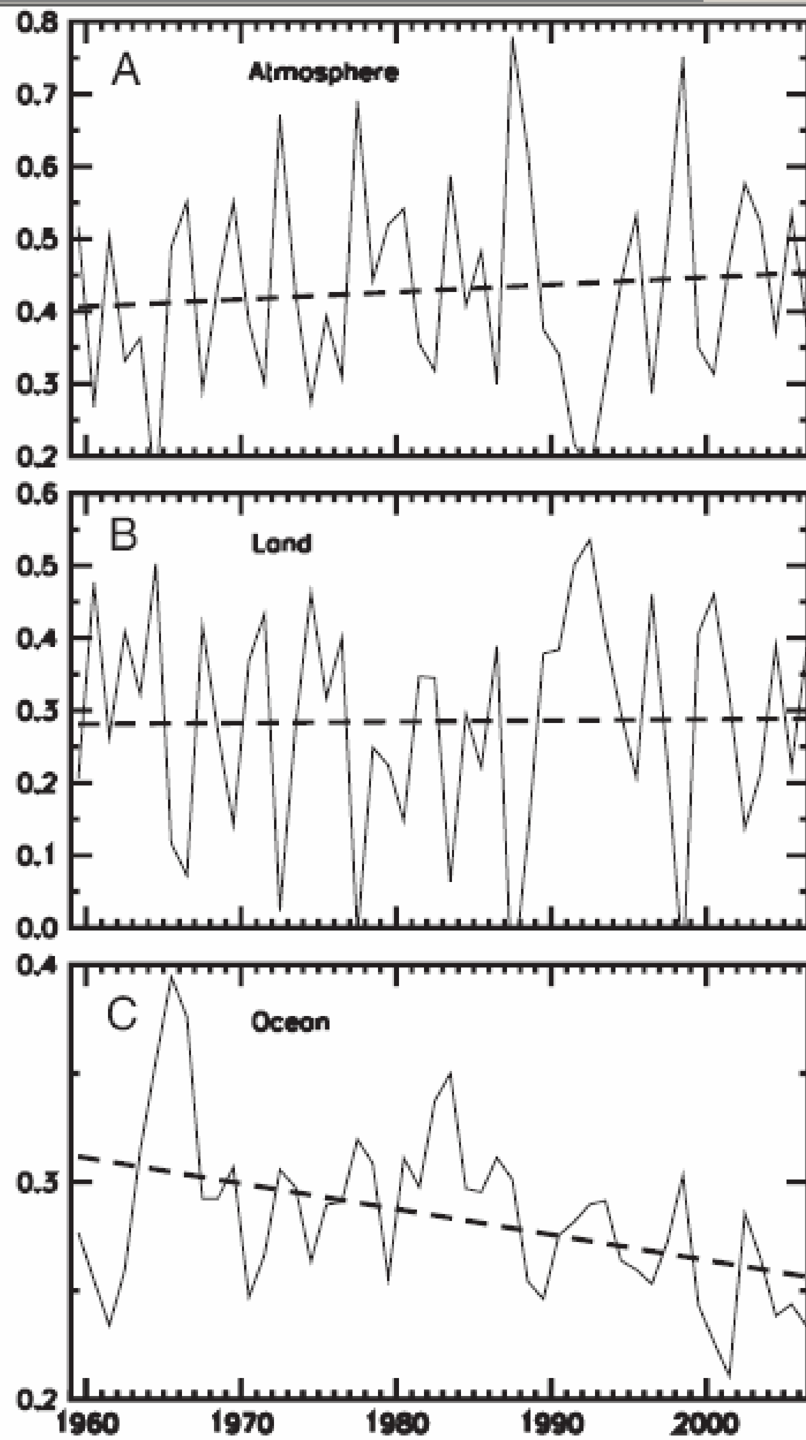
Where CO_2 goes:

- 45% to atmosphere
  - increasing



- 30% to land
  - steady

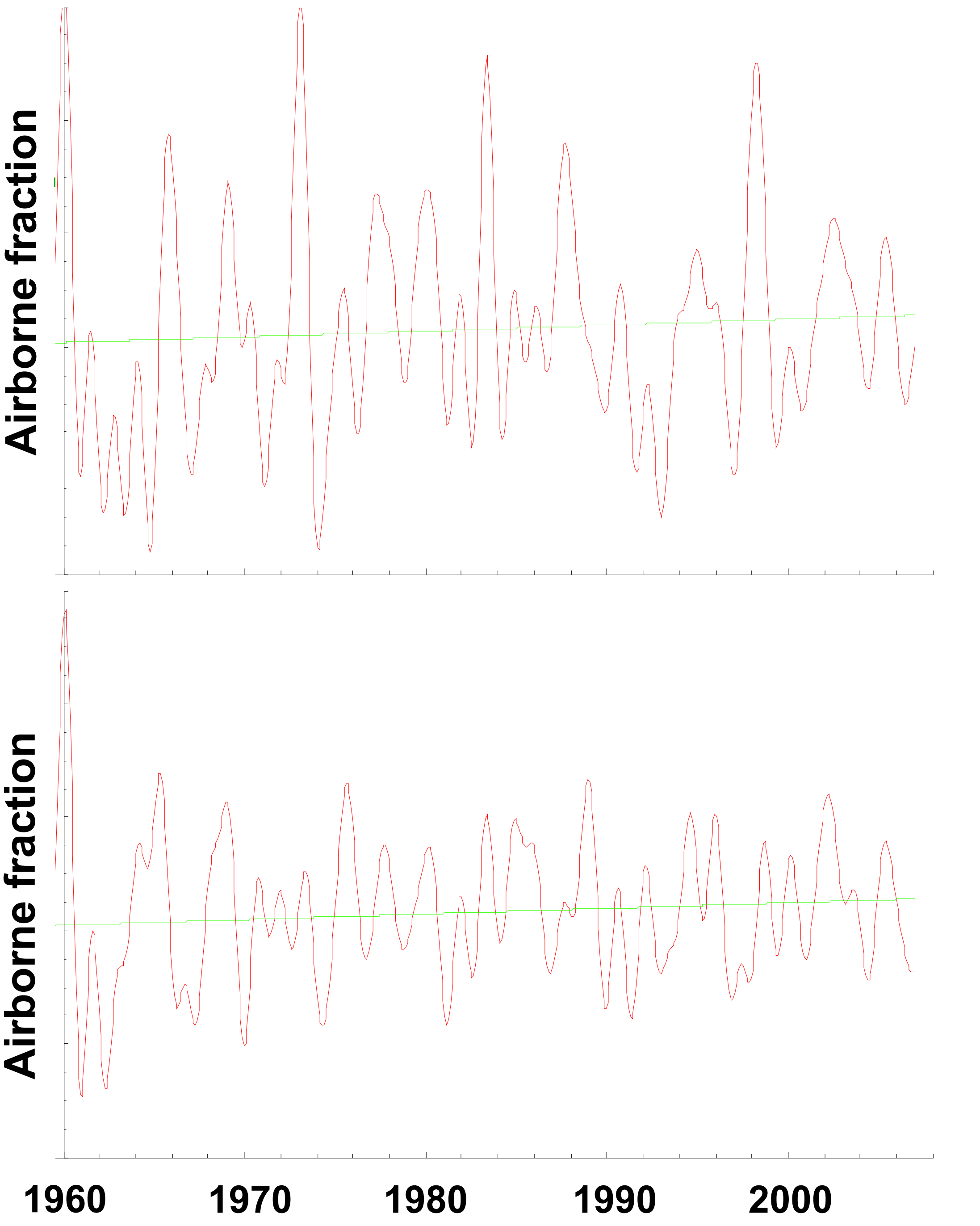
- 25% to ocean
  - decreasing



Canadell et al. (2007) PNAS

Increasing trend in airborne fraction

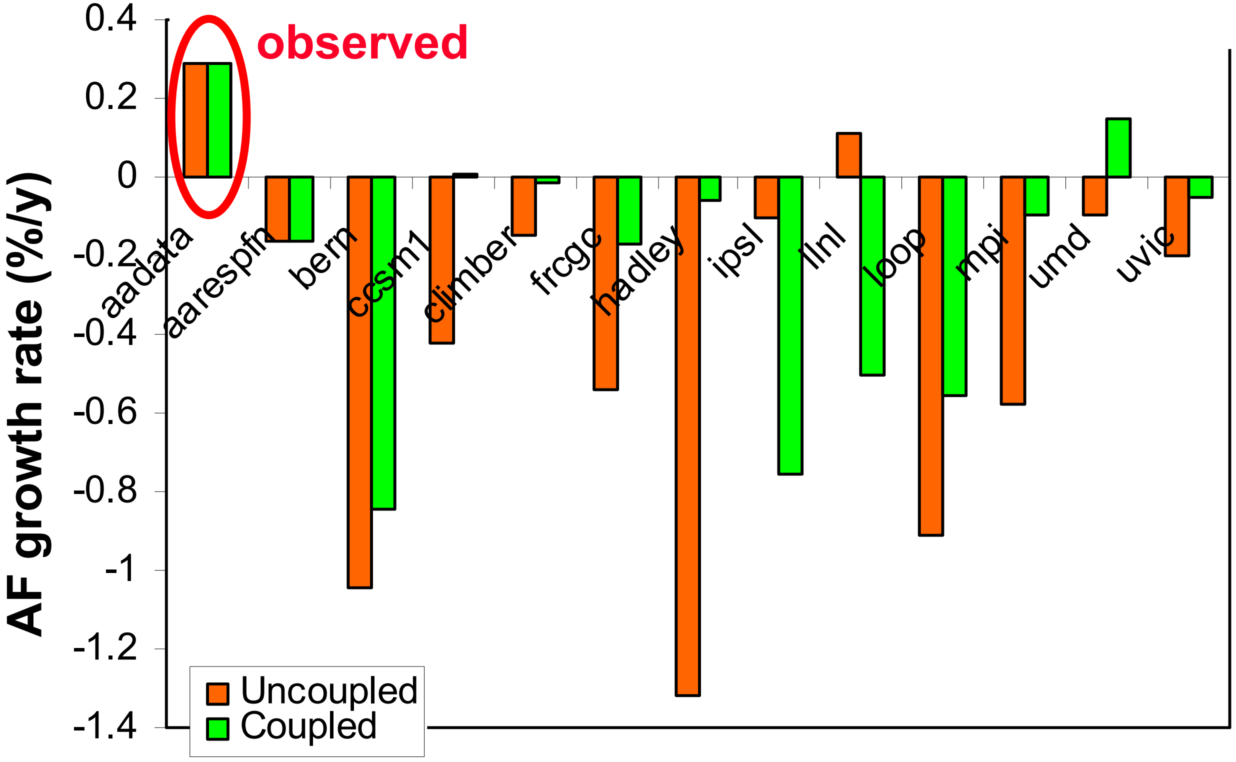
- Airborne fraction (AF) = $(dC_a/dt) / (F_{Foss} + F_{LUC})$
- Without noise reduction:
  - AF trend = **0.24 %/y**
  - Prob (trend > 0) = 0.8
- With noise reduction:
  - AF trend = **0.24 %/y**
  - Prob (trend > 0) = 0.9



Canadell et al. (2007) PNAS
Raupach et al. 2008, Biogeosciences (submitted)

Implications of AF trend

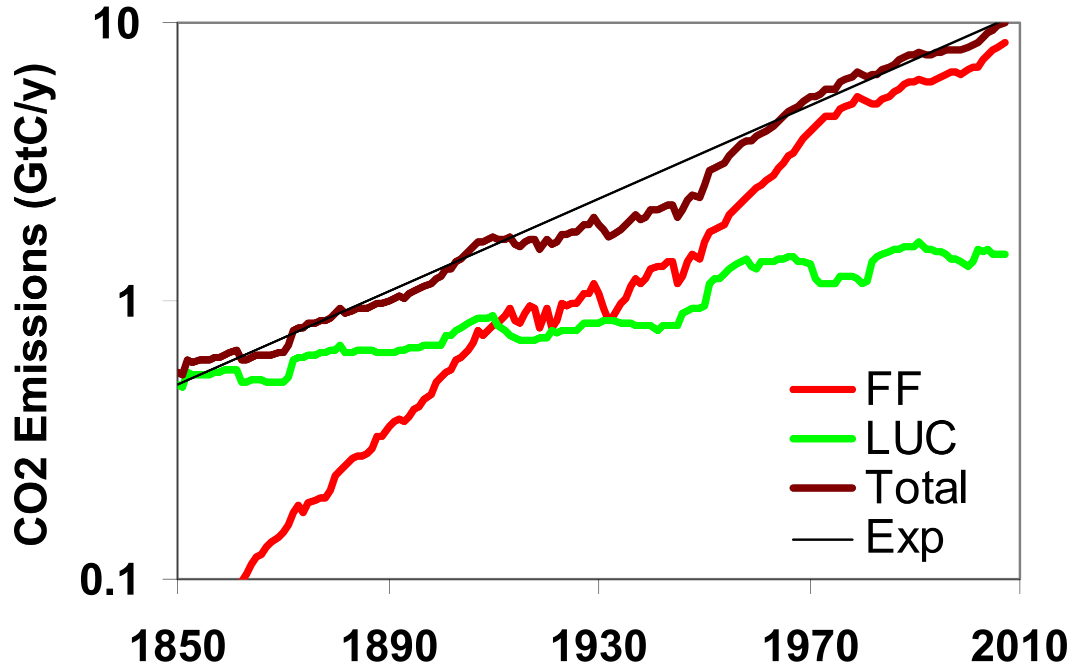
- Total (land + ocean) CO_2 sinks are not keeping pace with total emissions
  - (even though sinks are increasing overall)
- Most current carbon-climate models (C^4MIP) do not see an increasing AF
  - This is a severe model test

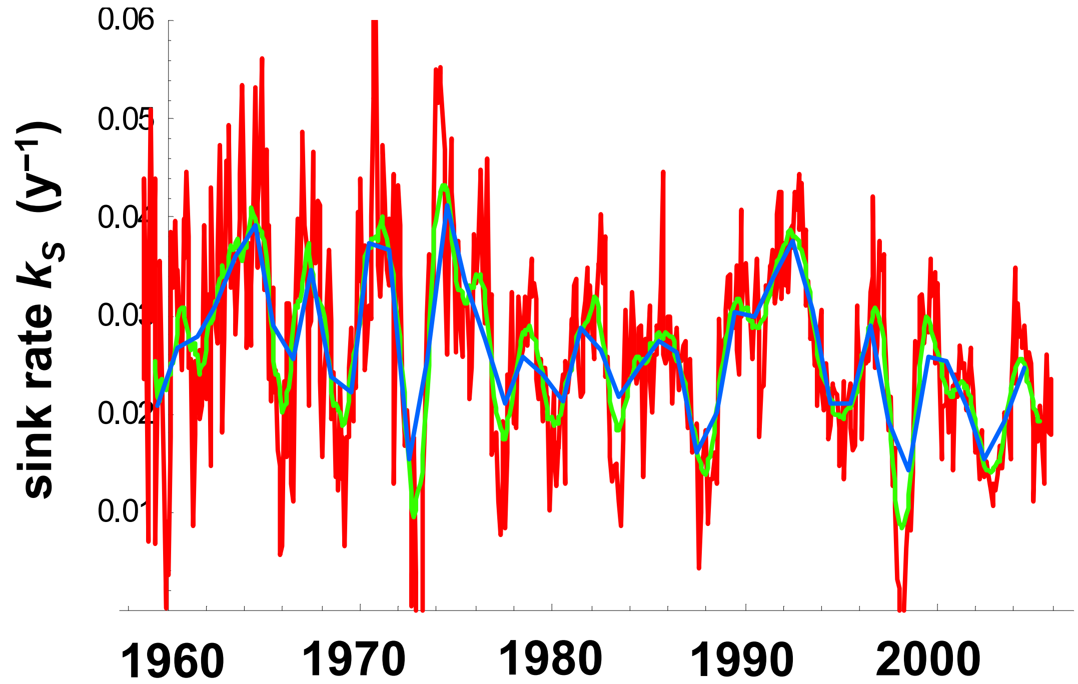


Why is AF so steady? Two remarkable facts

- Emissions have grown exponentially since 1850
  - growth rate = 0.02 y^{-1}
  - doubling time = 36 y

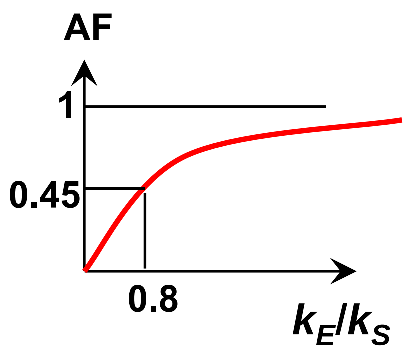
- Land and ocean sinks are nearly first-order-kinetic:
  - total sink = $k_S(CO_2 - 280)$
  - sink rate k_S = 0.025 y^{-1}
  - halving time = 28 y
  - but not exact: k_S is decreasing slowly





Consequence: AF varies little as sinks weaken

- Assume (1) sinks obey first-order kinetics, (2) emissions grow exponentially
- Equation for CO_2: $$\boxed{C_a'(t) = F_{E0}\exp(k_E t) - k_S(C_a - C_q)}$$
- Analytic solution: $$\boxed{C_a(t) = C_q + \frac{F_{E0}\left(e^{k_E t} - e^{-k_S t}\right)}{k_E + k_S}}$$
- Airborne fraction: $$\boxed{\mathrm{AF}(t) = \frac{k_E}{k_E + k_S} + \cancel{\frac{k_S\, e^{-(k_E + k_S)t}}{k_E + k_S}}}$$



- Implications:
  - Predicted present AF = 0.45
  - Fractional sensitivity of AF to k_S = −(1−AF) ≈ −0.5 (now)
  - AF varies little as sinks weaken because: sinks are weakening slowly
    sensitivity of AF is low

Drivers of CO_2 emissions and CO_2 growth rate

- Total CO_2 emissions (Kaya)

$$\left[\text{Emission}\right] = \left[\text{Pop}\right]\left[\begin{matrix}\text{Per-cap}\\ \text{GDP}\end{matrix}\right]\left[\begin{matrix}\text{C intensity}\\ \text{of GDP}\end{matrix}\right]$$

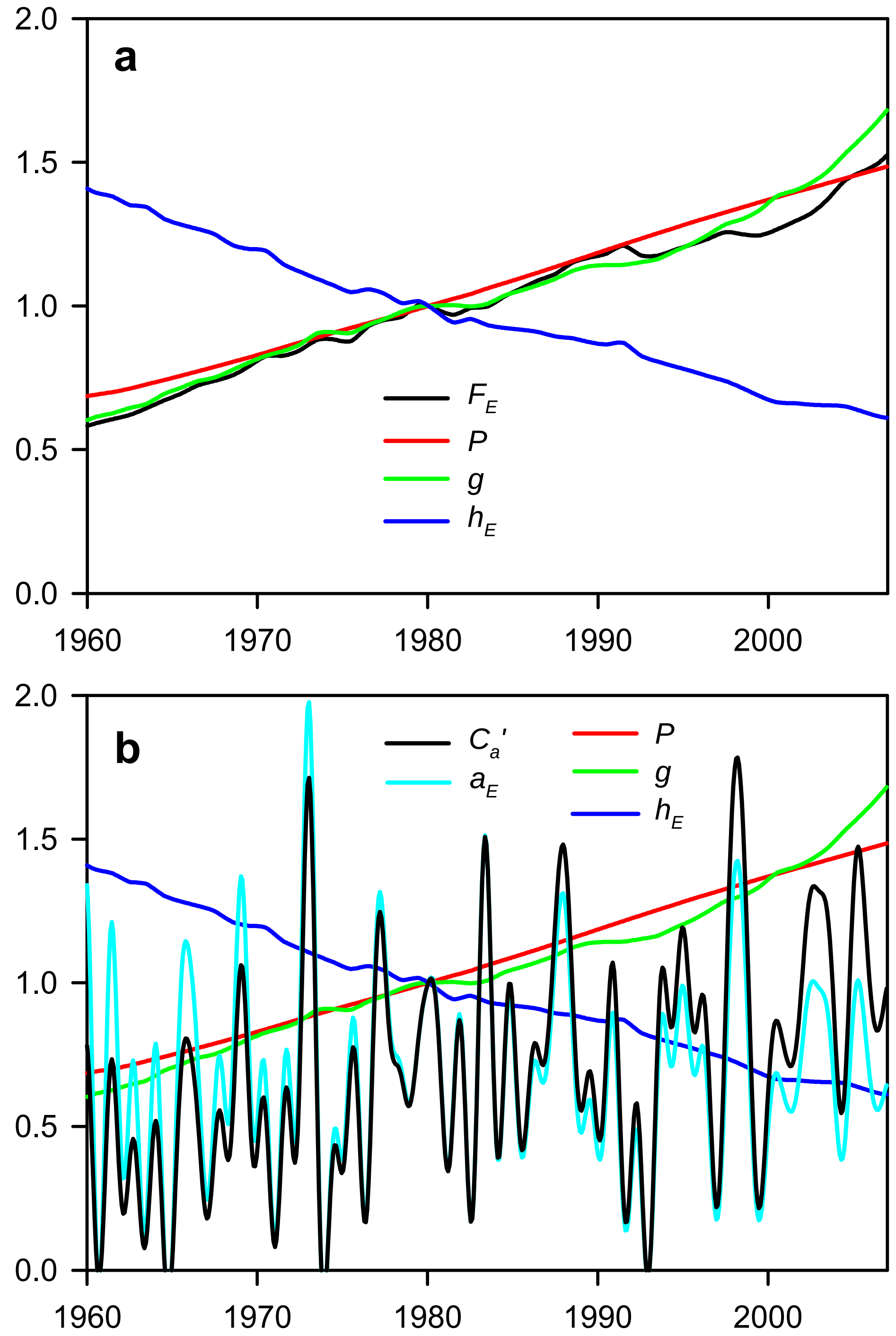
+ 1.8 = + 1.7 + 1.8 − 1.7

(growth rates in % y^{-1})

- CO_2 growth rate (extended Kaya)

$$\left[\begin{matrix}CO_2\\ \text{growth}\end{matrix}\right] = \left[\text{AF}\right]\left[\text{Pop}\right]\left[\begin{matrix}\text{Per-cap}\\ \text{GDP}\end{matrix}\right]\left[\begin{matrix}\text{C intensity}\\ \text{of GDP}\end{matrix}\right]$$

+ 2.0 = + 0.2 + 1.7 + 1.8 − 1.7



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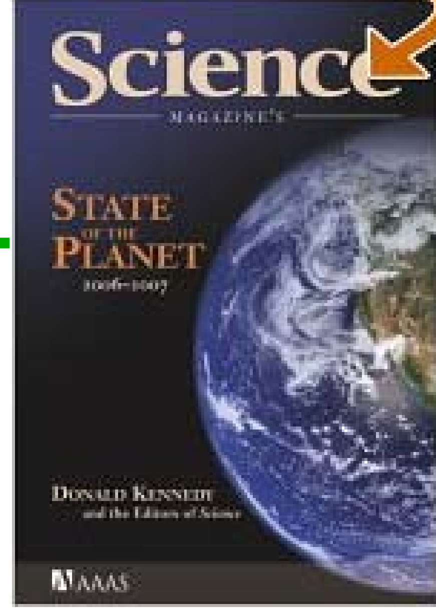
The tragedy of the commons – and beyond

- Hardin (1968) - model of herders on a common pasture
  - problem has no purely technical fix

- Tragedy-of-commons problems can be solved!
  - ***Adaptive governance in complex systems***
  - Requires:
    - Information
    - Conflict resolution
    - Rule compliance
    - Infrastructure
    - Readiness for change

- A broader appreciation of wealth:
  Natural, physical, financial, human, <u>**social**</u> capital



Hardin G (1968) The tragedy of the commons. Science **162**, 1243.

Dietz T, Ostrom E, Stern PC (2003) The struggle to govern the commons. Science **302**.

Pretty J (2003) Social capital and the collective mangement of resources. Science **302**.

Reprinted in Kennedy D et al. (2006) Science Magazine's State of the Planet 2006-2007. Island Press, Washington DC.

Mitigation challenge as a cap on cumulative emissions

- Target to avoid dangerous climate change:
  - Stabilise at CO_2e(Kyoto GHGs) < 450 to 500 ppm

- This requires a cap *Q* on cumulative global CO_2 emissions (for all time)
  - CO_2 emission is a finite, non-renewable resource!
  - **CO_2 emissions cap is less than *Q* = 500 PgC from 2000-2100**
  - Compare: 500 PgC from 1800 to 2000
  - **Robust rule: 1 PgC = 0.25 ppm CO_2 in atmosphere at current CO_2 airborne fraction**

- Influences on CO_2 cap:

Future emissions of other GHGs:	moderate	(< 100 PgC)
Future of CO_2 airborne fraction:	large	(> 100 PgC)
Future of climate sensitivity:	very large	(~ 200 PgC)

Sharing future emissions

- Separate (1) cap, (2) sharing, (3) timing, (4) compliance
- **Sharing:** cumulative emissions *Q* can be shared in 2 basic ways:
  - – by population (P_i for nation *i*)
  - – by wealth-based measures, eg present emissions (F_i)

- Shares must lie between these limits, so quota (Q_i) for country *i* is:

$$\boxed{Q_i = Q\left((1-w)\frac{F_i}{F} + w\frac{P_i}{P}\right)} \qquad \left(\text{with } F = \sum F_i,\ P = \sum P_i\right)$$

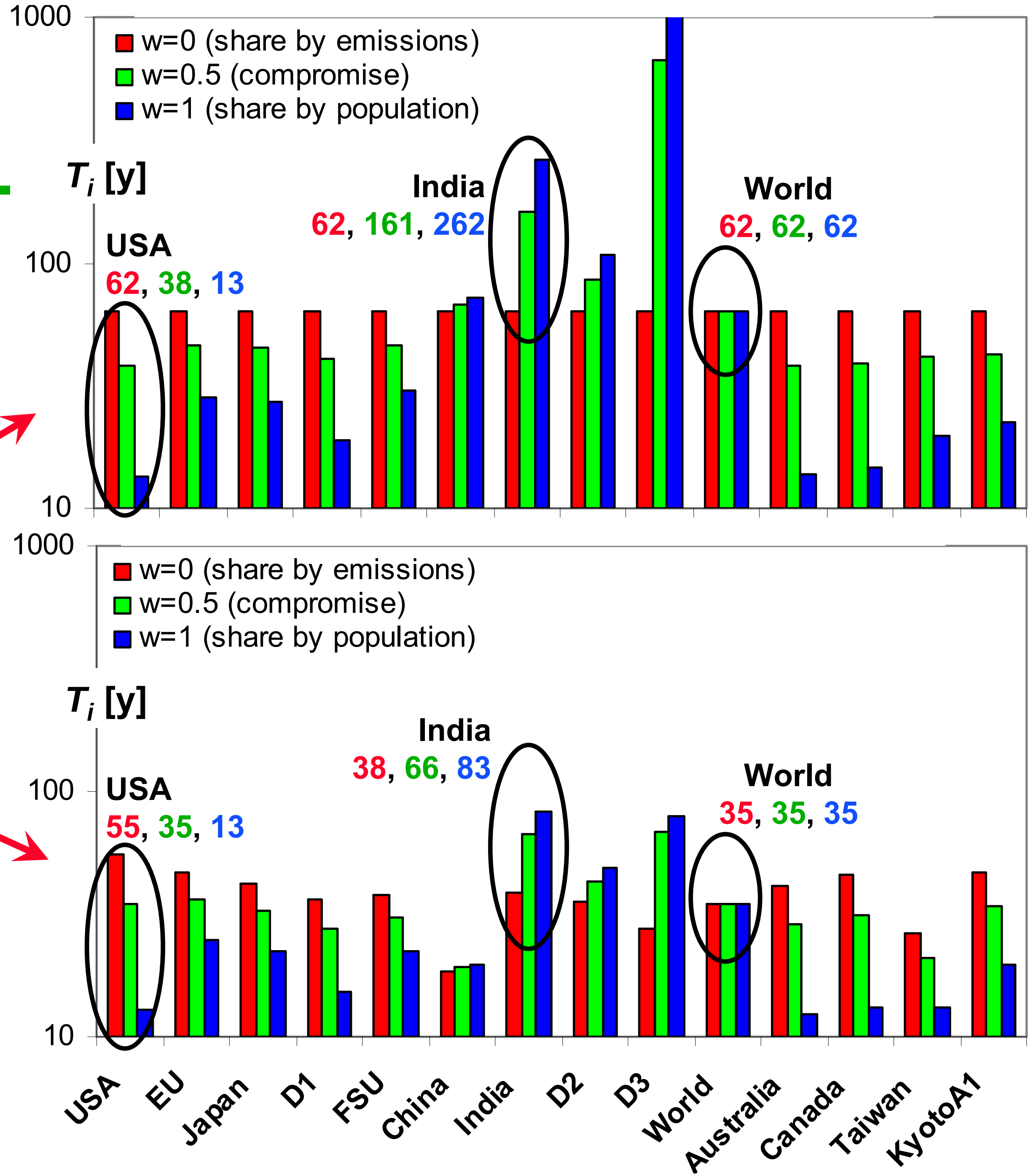
- Time to exhaust quota at current emission:

$$\boxed{T_i = T\left((1-w) + w\frac{F/P}{F_i/P_i}\right)} \qquad \left(\text{with } T_i = \frac{F_i}{Q_i},\ T = \frac{F}{Q}\right)$$

- Weight w (between 0 and 1) is a "global equity number"

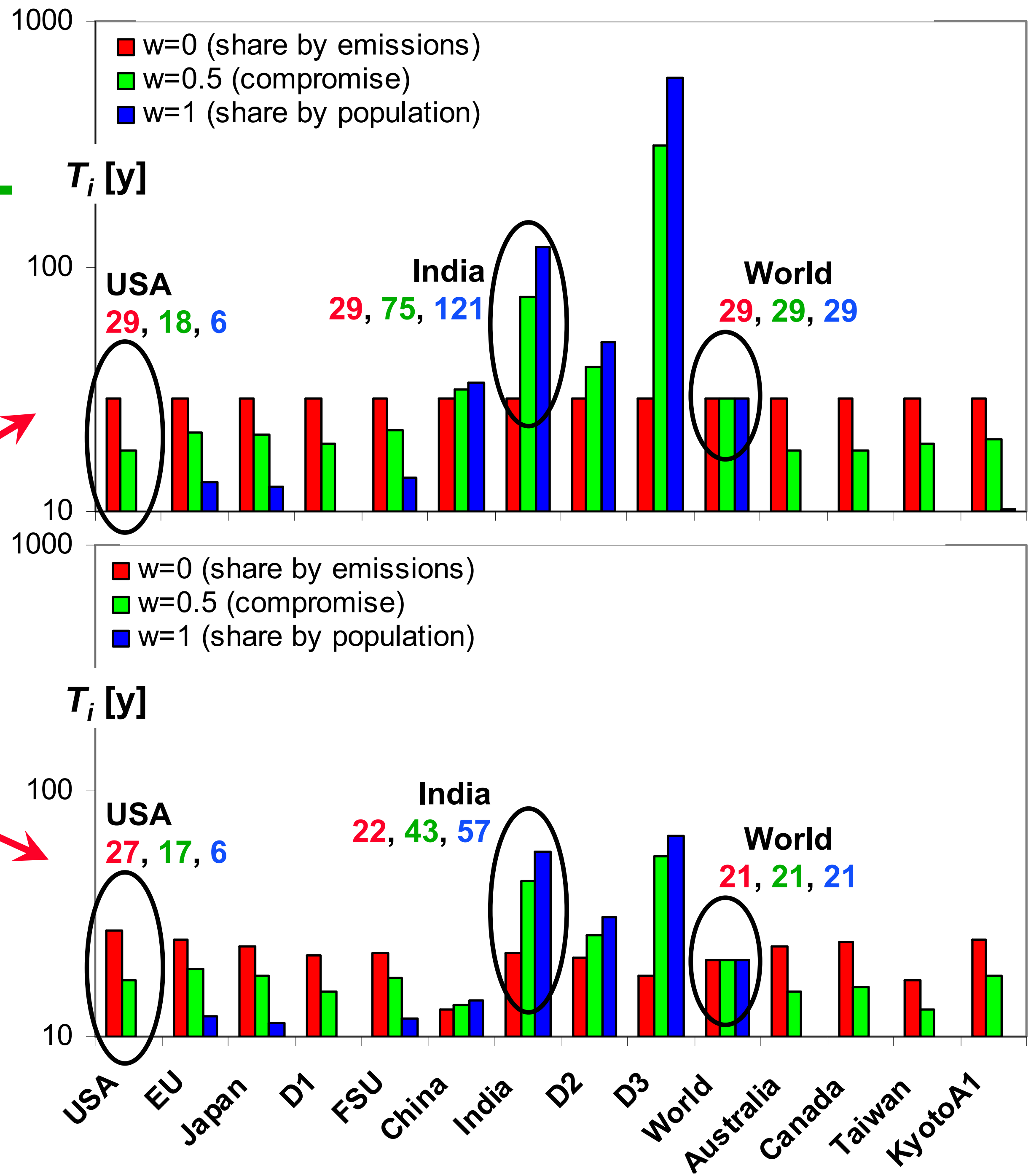
Sharing emissions: Quota Q = 500 PgC

- T_i = time to exhaust quota for region i (start in 2004)
  - steady emissions (at 2004 levels)
  - growing emissions (at 2004 rates)
- Q = 500 PgC =>
  - $\Delta[CO_2] \approx 125$ ppm
  - $[CO_2] \approx 500$ ppm



Sharing emissions: Quota Q = 250 PgC

- T_i = time to exhaust quota for region *i* (start in 2004)
  - steady emissions (at 2004 levels)
  - growing emissions (at 2004 rates)
- Q = 250 PgC =>
  - Δ[CO2] ≈ 60 ppm
  - [CO2] ≈ 440 ppm



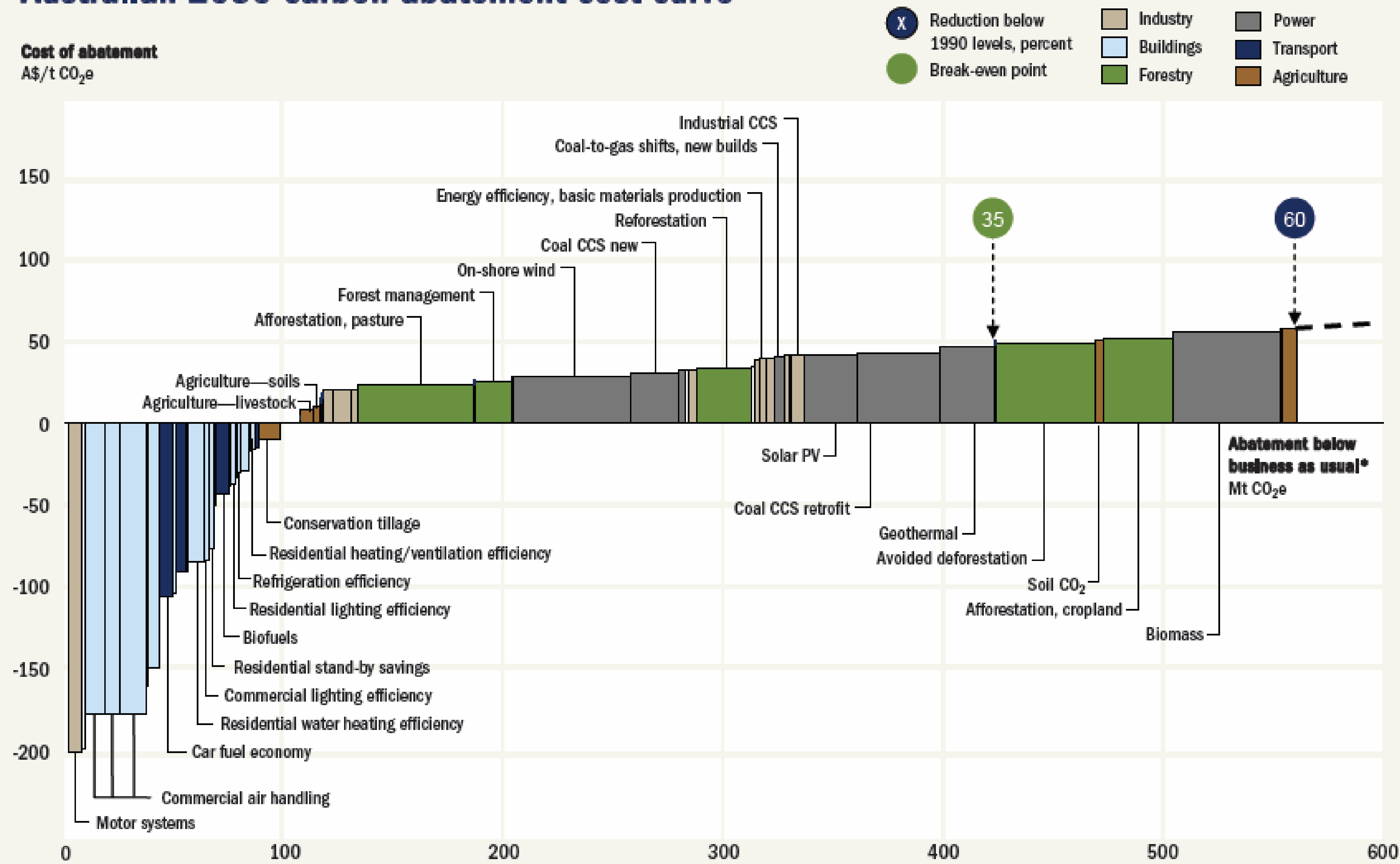
What do we do?

- **Next steps**
  - Efficient appliances, insulation, ...
  - Passive heating, cooling
  - Efficient vehicles
  - Reduced travel (offsets to renewables)
  - Forestry (plant, manage, store, avoid deforestation)

- **Transformations**
  - Non-fossil energy infrastructure
  - Renewable energy storage (GW-days)
  - Distributed urban energy (use "waste")
  - Redesigning urban energy, transport, water, lifestyles, ...

- **Europe's first commercial solar thermal power plant at la Mayor, near Seville, Spain**
- **11 MW, expanding to 300 MW**
- **Molten salt heat storage**

Australian 2030 carbon abatement cost curve



Note: Abatement opportunities are not additive to those of previous years

Source: McKinsey Australia Climate Change Initiative

What more? Four essential response components

- **Technical**
  - Broad portfolio: conservation, renewables, cleaner fossil fuels, ...
  - A workable transition pathway
- **Economic**
  - Market drivers: greenhouse accounting and trading mechanisms
- **Policy**
  - Agreed cap on cumulative emissions
  - Agreed rules to govern national emission flux trajectories
  - Policies to make greenhouse costs visible (carbon price signal)
  - Support for innovation
- **Cultural and social: building social capital across connected scales**
  - Global: protection of the shared earth system as a global imperative
  - Local: decoupling quality of life from consumption

Summary

- Trends in CO_2 emissions from fossil fuels
  - Growth: 3.47 % y^{-1} for 2000-07 (up from 1% y^{-1} for 1990-99)
  - Increasing emissions share from developing countries
  - Tight connections: energy <> wealth, and carbon <> energy
  - Our future wellbeing depends on breaking these connections
- The full carbon budget and the airborne fraction (AF)
  - The AF is increasing
  - BUT the AF is remarkably steady - sinks are nearly first order
  - The AF is the gateway from emissions forcing to climate response
- Responses: defining and sharing the burden
  - Cap on cumulative emissions: 500 GtC (world has 35 y supply)
250 GtC (world has 21 y supply)
  - "Global equity weight" provides a simple means of sharing
  - Response components: technical, economic, policy, socio-cultural

We are starstuff

billion-year-old carbon

We are golden

caught in the devil's bargain

(Joni Mitchell, Woodstock)