The Global Environmental Change:
Carbon Sequestration

Sources of Anthropogenic Greenhouse Gas Emissions

Carbon Sequestration

The global C politics

Summary

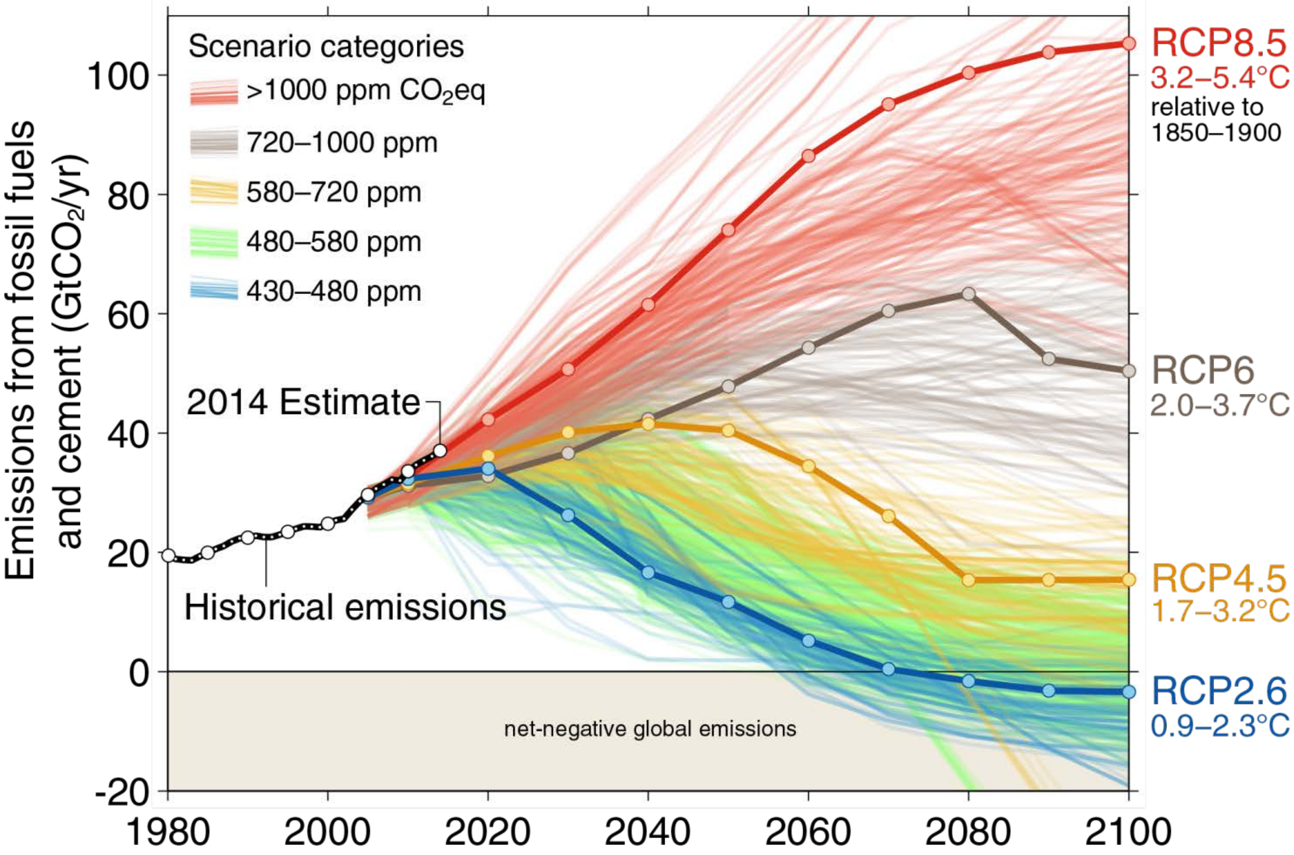
Sources of Anthropogenic Greenhouse Gas Emissions

Fossil fuel combustion
Deforestation
Plowing soils
Rice paddies
Domesticated animals

Observed Emissions and Emissions Scenarios

Emissions are on track for 3.2–5.4ºC “likely” increase in temperature above pre-industrial
Large and sustained mitigation is required to keep below 2ºC

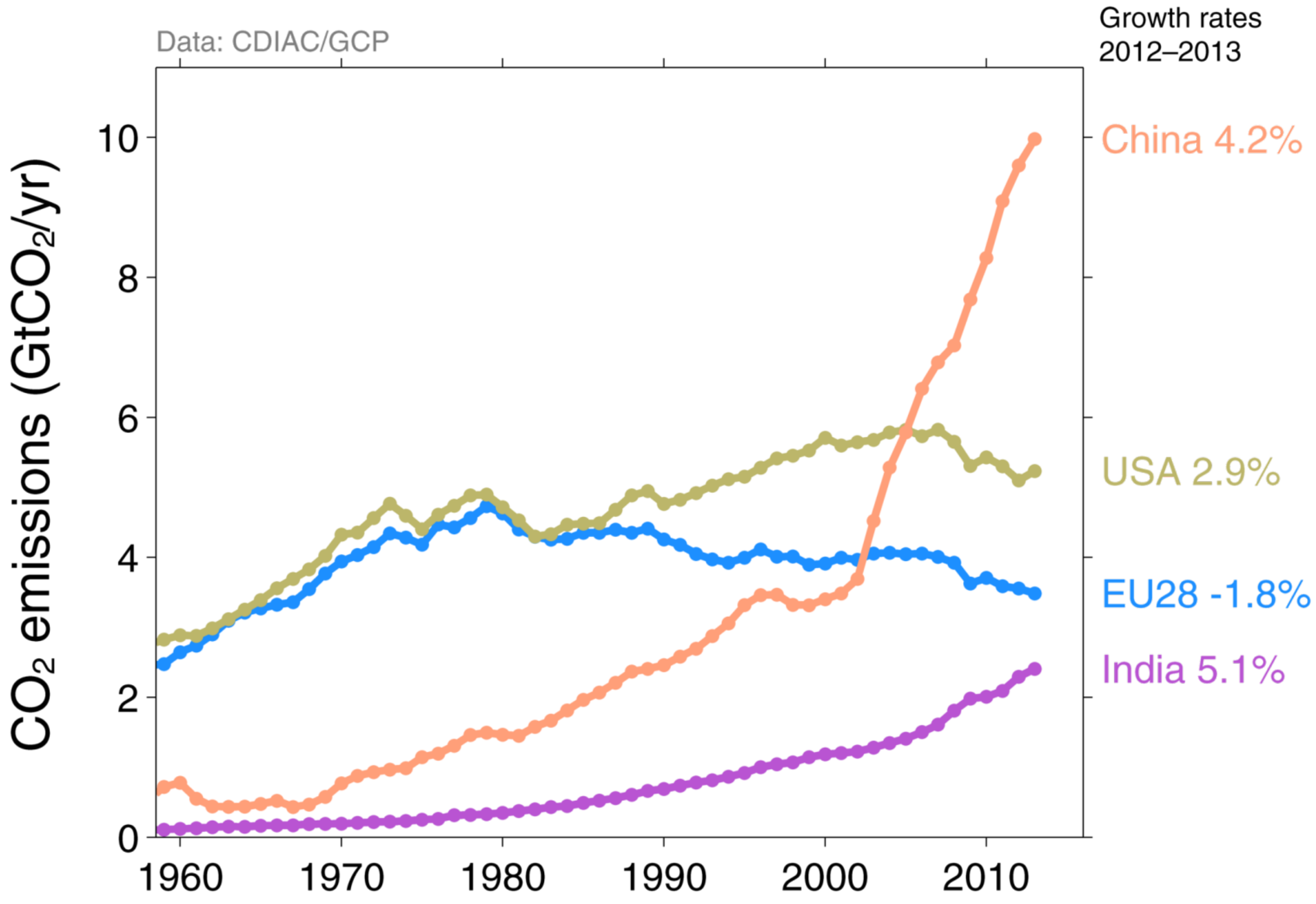
Data: CDIAC/GCP/IPCC/Fuss et al 2014



Over 1000 scenarios from the IPCC Fifth Assessment Report are shown
Source: Fuss et al 2014; CDIAC; Global Carbon Budget 2014

Top Fossil Fuel Emitters (Absolute)

The top four emitters in 2013 covered 58% of global emissions
China (28%), United States (14%), EU28 (10%), India (7%)

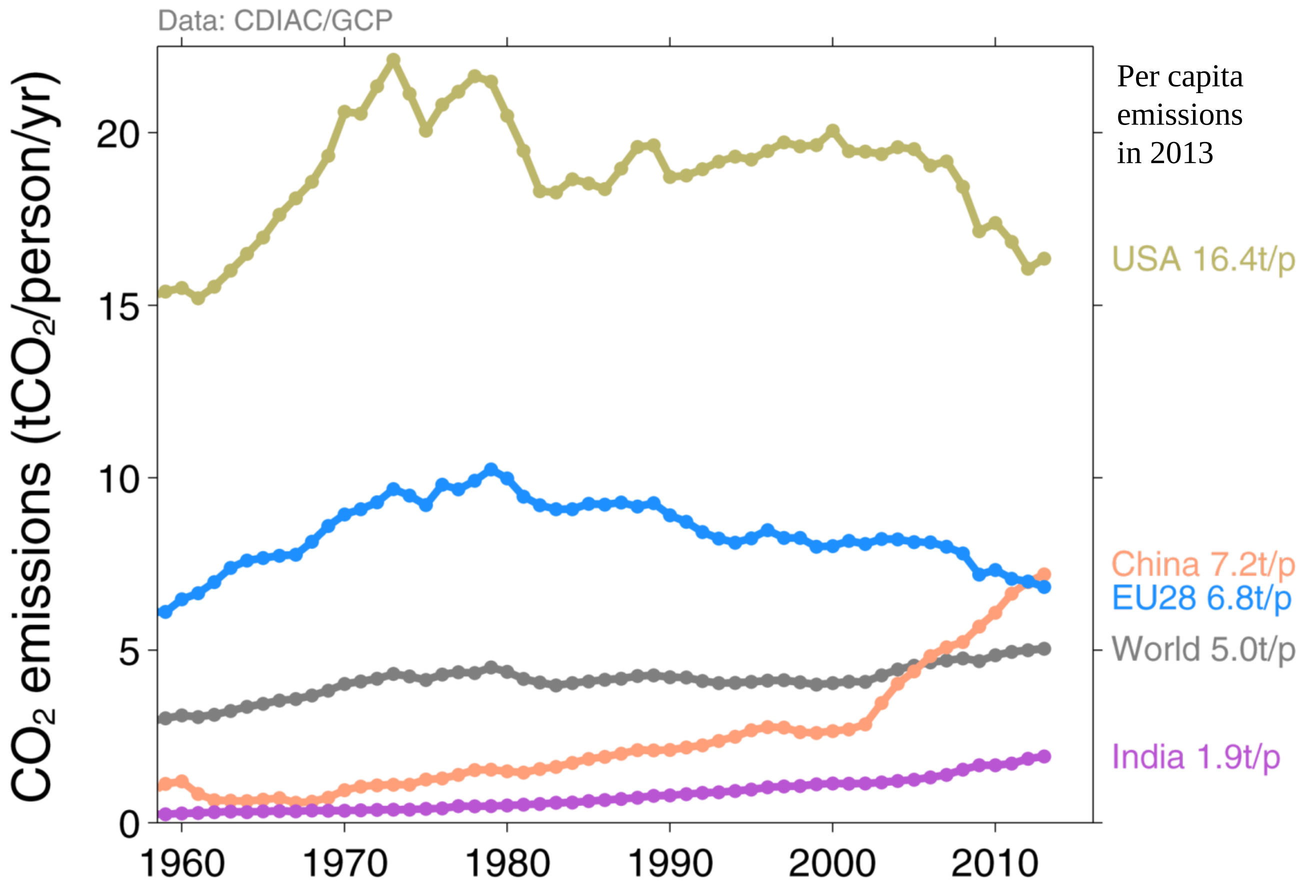


Data: CDIAC/GCP

Bunkers fuel used for international transport is 3% of global emissions
Statistical differences between the global estimates and sum of national totals is 3% of global emissions
Source: CDIAC; Le Quéré et al 2014; Global Carbon Budget 2014

Top Fossil Fuel Emitters (Per Capita)

China's per capita emissions have passed the EU28 and are 45% above the global average



Source: CDIAC; Le Quéré et al 2014; Global Carbon Budget 2014

Global Carbon Budget

The cumulative contributions to the Global Carbon Budget from 1870
Contributions are shown in parts per million (ppm)

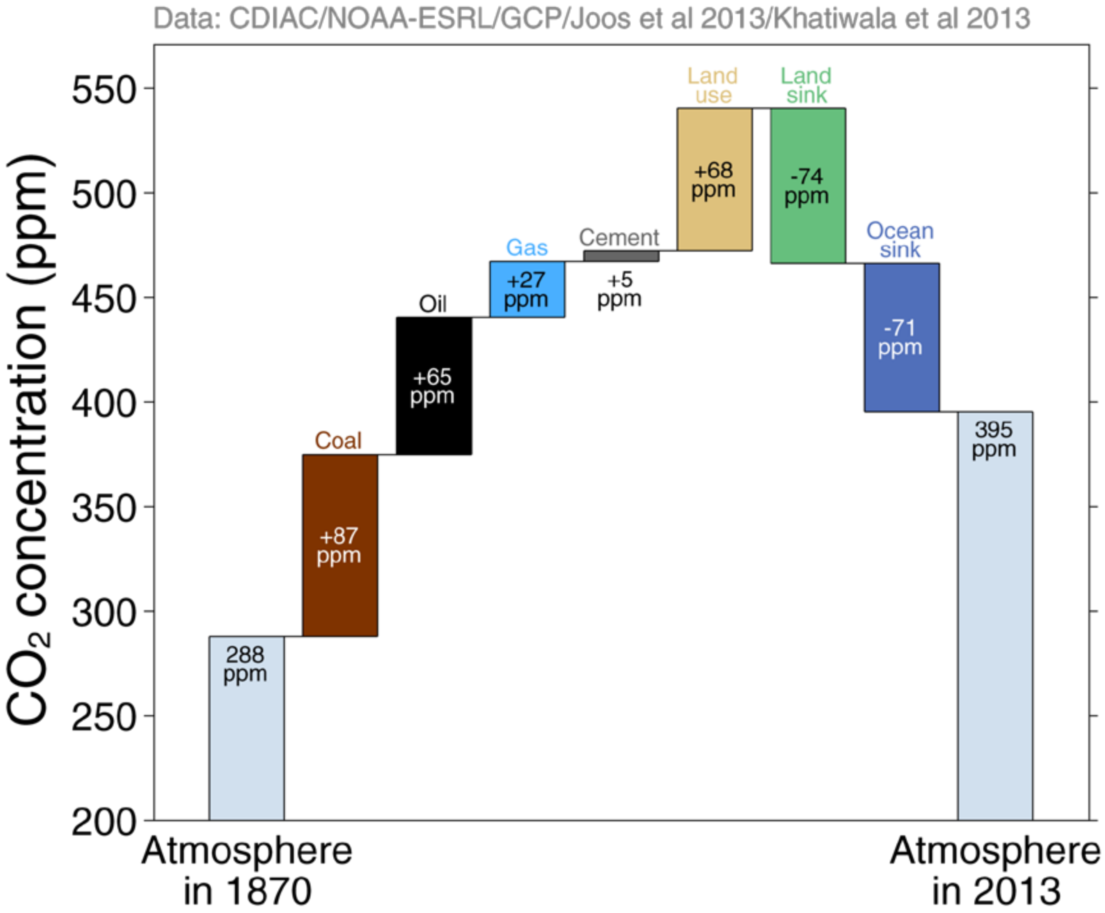


Figure concept from Shrink That Footprint
Source: CDIAC; NOAA-ESRL; Houghton et al 2012; Giglio et al 2013; Joos et al 2013; Khatiwala et al 2013; Le Quéré et al 2014; Global Carbon Budget 2014

What can we do to reduce carbon emissions or to increase carbon sequestration?

Carbon Sequestration

A list of possibilities:

1. Afforestation/Reforestation/Conservation
2. Conservation tillage on croplands (reduction of emissions)
3. Fertilizing the ocean
4. Fertilizing forests
5. Irrigating drylands (pumping and 1% CO_2 in groundwater)
6. More photosynthesis under higher atmospheric CO_2 concentrations
7. Physical and/or chemical removal such as CO_2 injection into the deep sea
8. Is there more to add to this list???

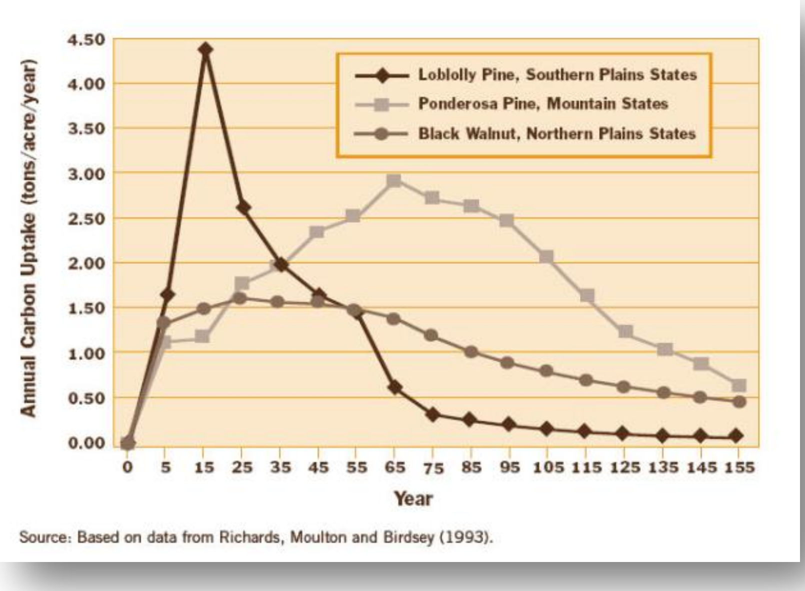
Forestry Practices

“Plantation methods”

- Afforestation of agricultural land
- Reforestation of harvested or burned forest land

Forest management

- Adoption of low-impact harvesting methods
- Lengthening of forest rotation cycles
- Preventing deforestation



Source: Based on data from Richards, Moulton and Birdsey (1993).

Agricultural Practices that Sequester Carbon and/or Reduce Emissions of Other Greenhouse Gases

Key Agricultural Practices	Typical definition	Effect on greenhouse gases
Conservation or riparian buffers	Grasses or trees planted along streams and croplands to prevent soil erosion and nutrient runoff	Increases carbon sequestration
Conservation tillage	30% or more of the crop residue remains on the soil after planting	Enhanced soil sequestration
Grazing land management	Modification to grazing practices (e.g. rotational grazing)	Enhanced soil sequestration

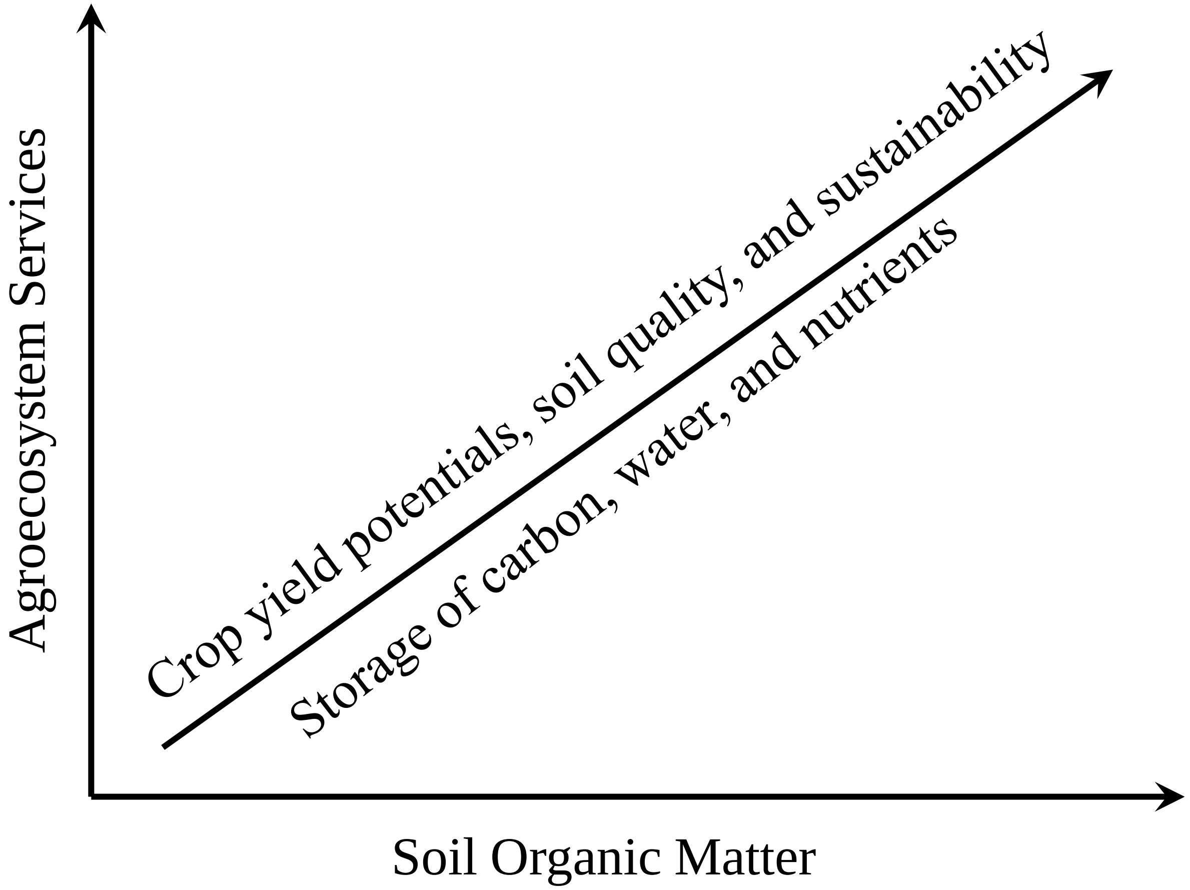
Source: EPA

People like soil C sequestration because:

- Cost-effective
- Improve soil quality
- May increase crop yields
- Longer time than biomass
- Existing management infrastructure

Win-Win situation!

As widely recognized, soil organic matter directly controls the quantity and the quality of many important ecosystem services.



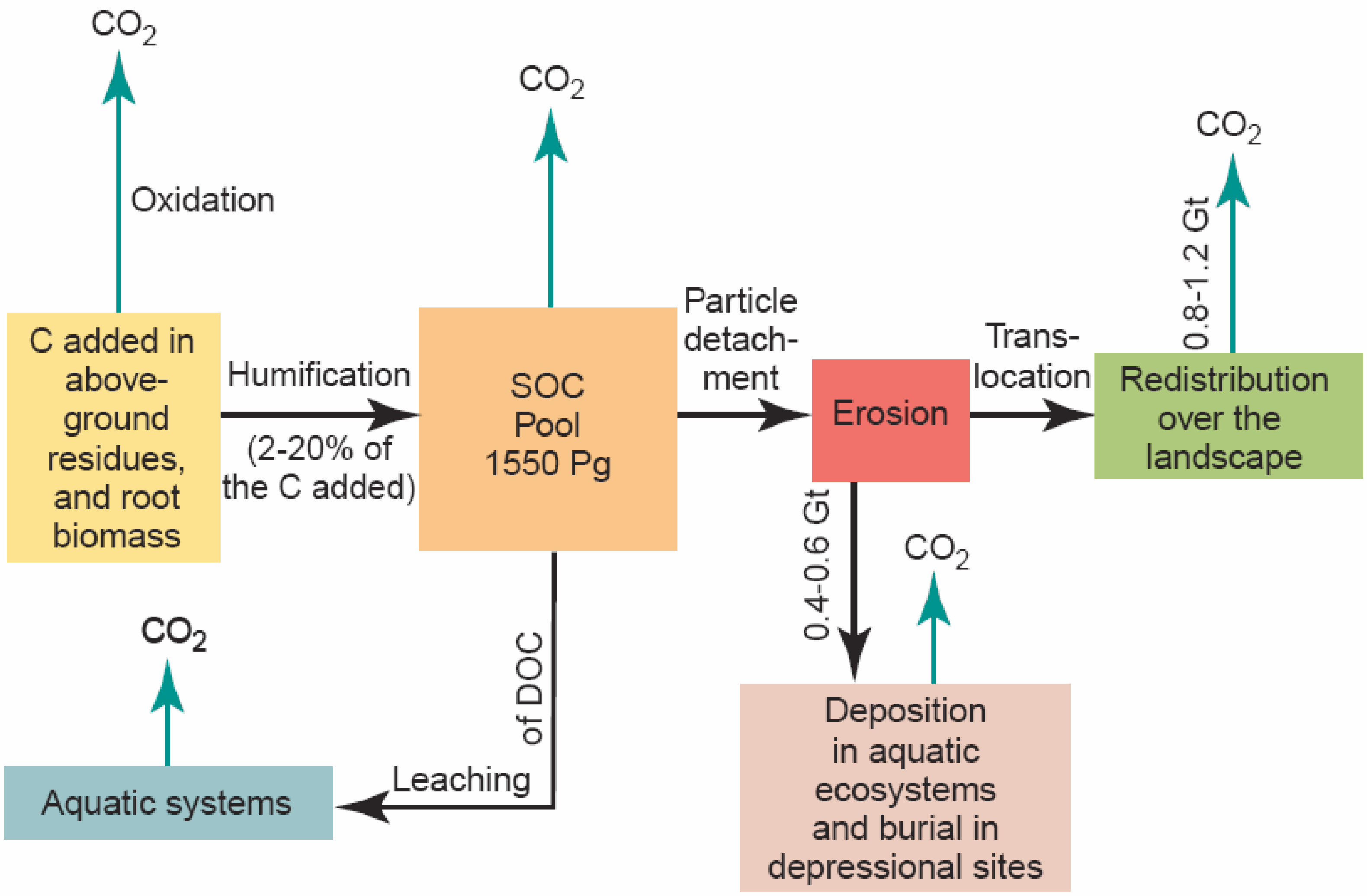
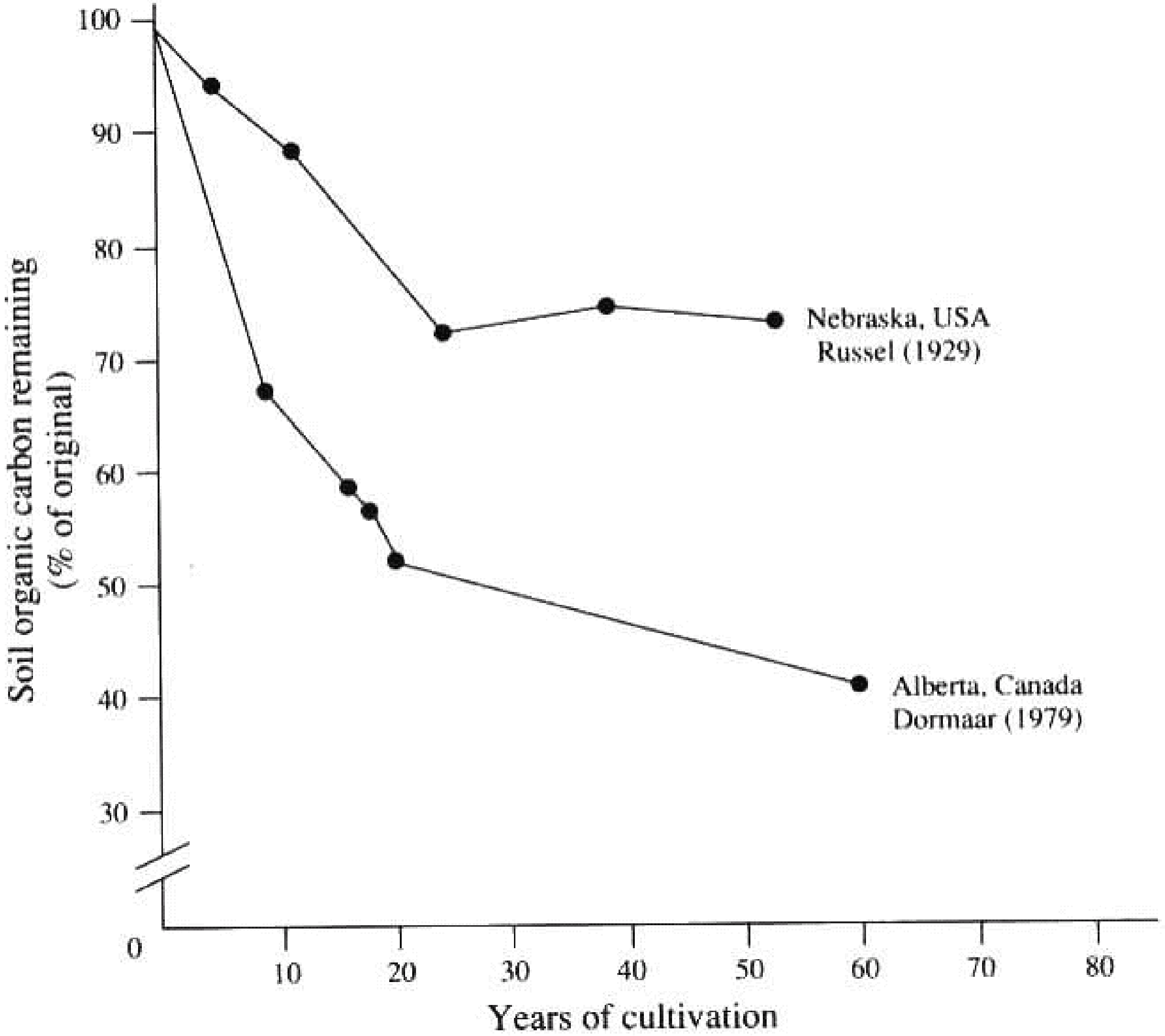


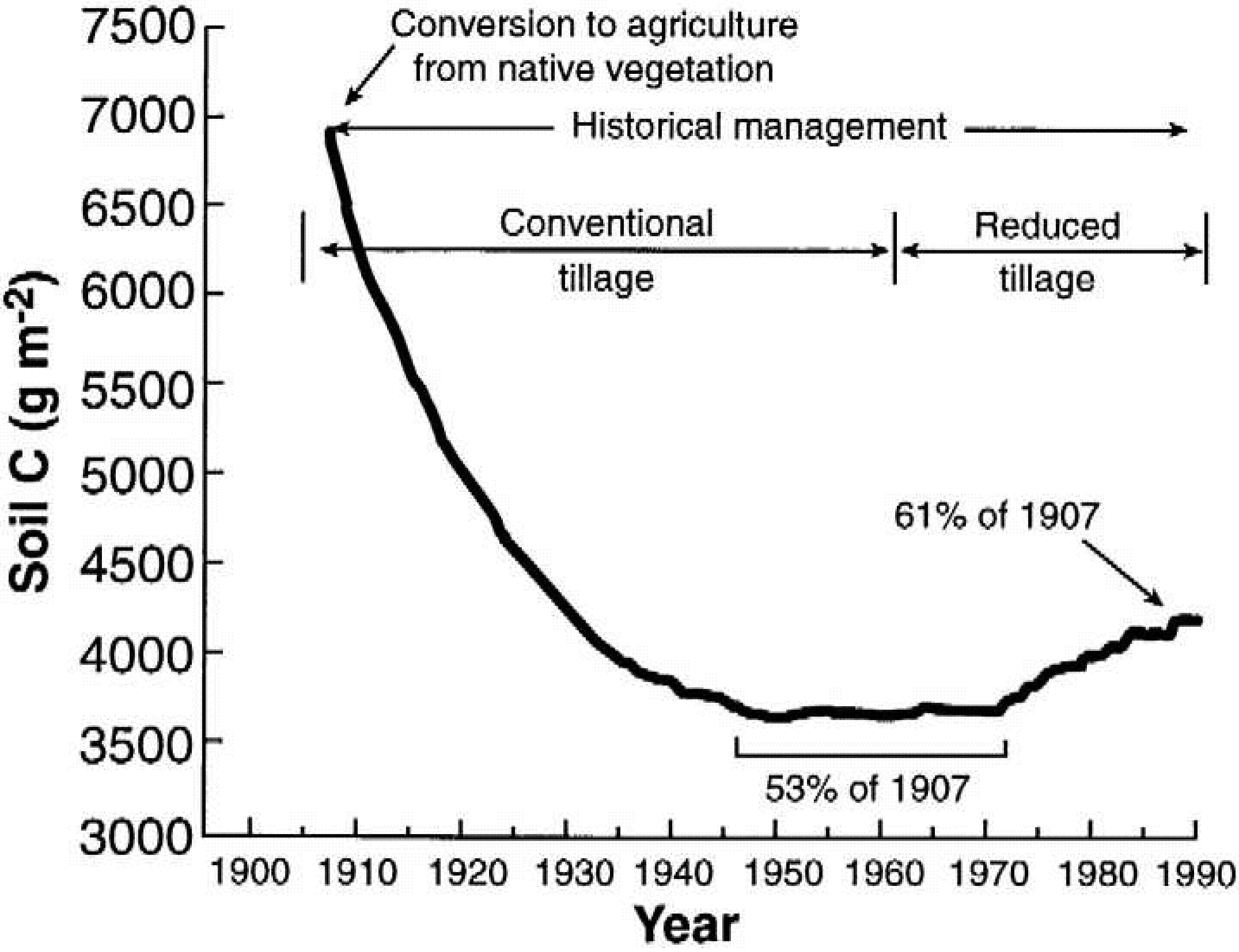
Fig. 1. Processes affecting soil organic carbon (SOC) dynamics. Arrows pointed upward indicate emissions of CO_2 into the atmosphere. There may also be emission of CH_4 under anaerobic conditions, although most well-drained soils are a sink of CH_4. DOC, dissolved organic carbon.

Ratten Lal. 2004. Science

Lost of soil organic carbon from plowing, erosion, and other agricultural practices at two places in North America.



A paper by P. A. Matson (Stanford Univ) et al. (1997) in SCIENCE studied the loss of soil carbon due to cultivation and the recovery of soil carbon due to conservation tillage, in central U. S. corn belt.



What is conservation tillage?

Crops are grown with minimal cultivation of the soil

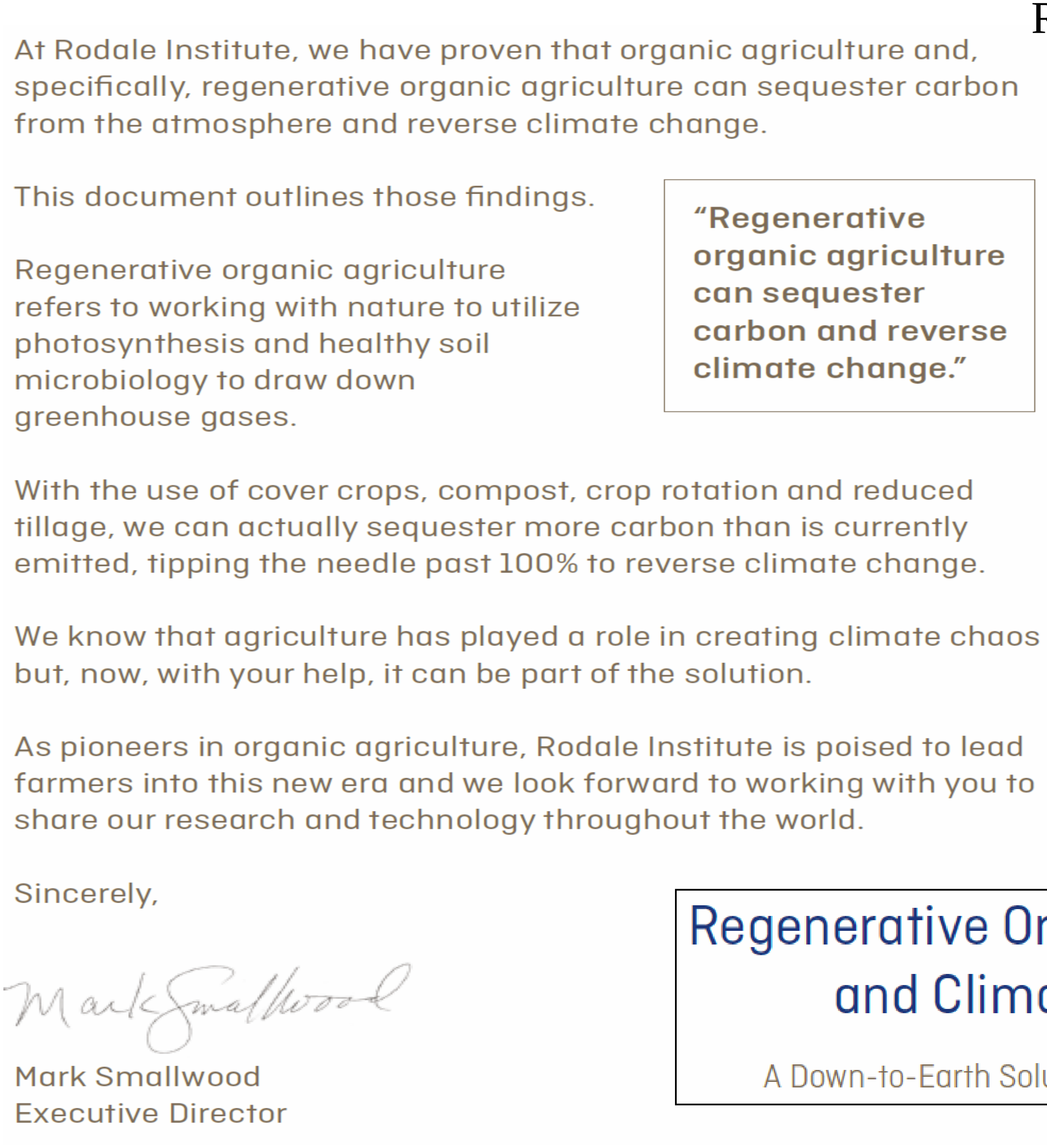
Most stubble or plant residue remains on top of the soil rather than being plowed into the soil.

The new crop is planted into the stubble.

Weeds are controlled with cover crops or herbicides rather than cultivation.

Reduces CO_2 emissions

Rodale Institute White Paper
2014



At Rodale Institute, we have proven that organic agriculture and, specifically, regenerative organic agriculture can sequester carbon from the atmosphere and reverse climate change.

This document outlines those findings.

> **"Regenerative organic agriculture can sequester carbon and reverse climate change."**

Regenerative organic agriculture refers to working with nature to utilize photosynthesis and healthy soil microbiology to draw down greenhouse gases.

With the use of cover crops, compost, crop rotation and reduced tillage, we can actually sequester more carbon than is currently emitted, tipping the needle past 100% to reverse climate change.

We know that agriculture has played a role in creating climate chaos but, now, with your help, it can be part of the solution.

As pioneers in organic agriculture, Rodale Institute is poised to lead farmers into this new era and we look forward to working with you to share our research and technology throughout the world.

Sincerely,

Mark Smallwood

Mark Smallwood
Executive Director

Regenerative Organic Agriculture and Climate Change

A Down-to-Earth Solution to Global Warming

One of the optimistic views: Ratten Lal. 2004. Science

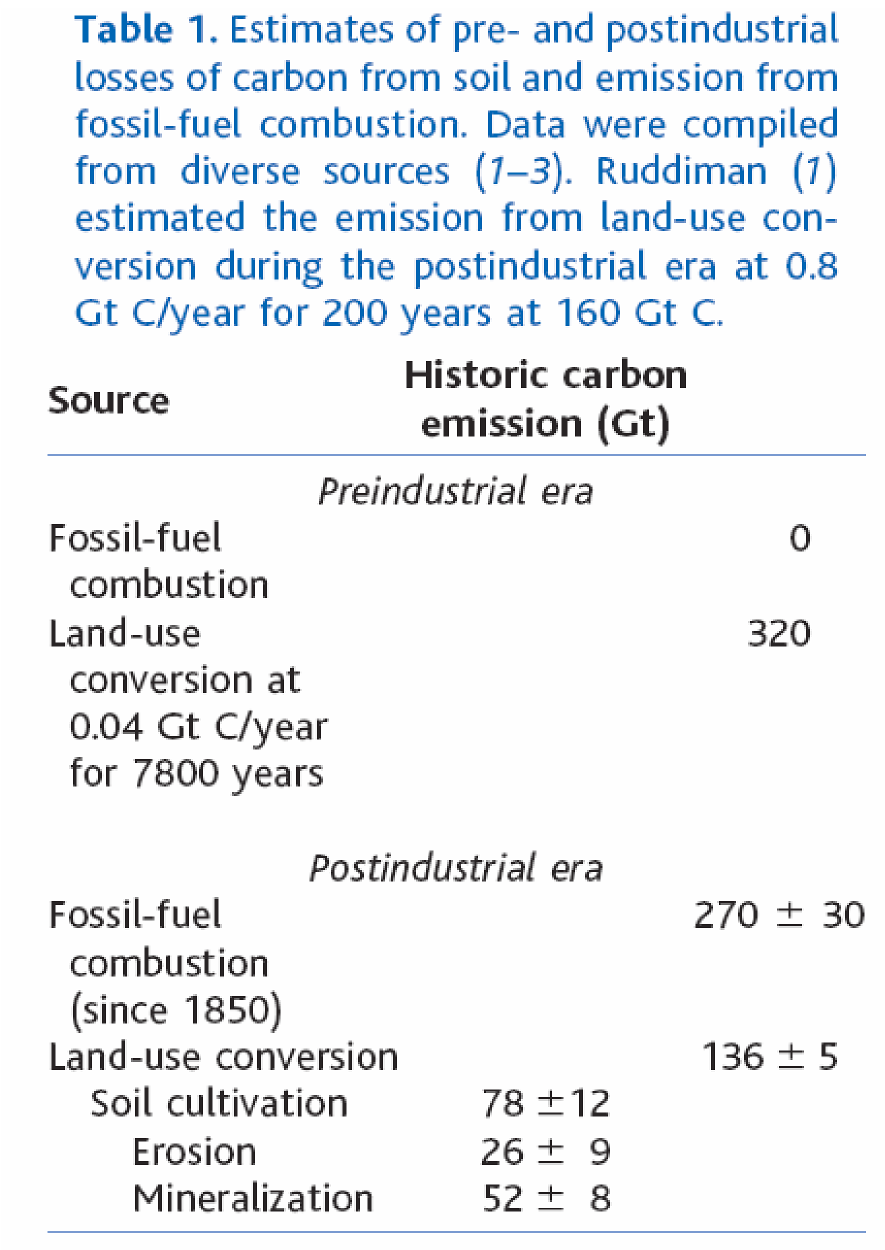


Table 1. Estimates of pre- and postindustrial losses of carbon from soil and emission from fossil-fuel combustion. Data were compiled from diverse sources (*1*–*3*). Ruddiman (*1*) estimated the emission from land-use conversion during the postindustrial era at 0.8 Gt C/year for 200 years at 160 Gt C.

Source		Historic carbon emission (Gt)
	Preindustrial era	
Fossil-fuel combustion		0
Land-use conversion at 0.04 Gt C/year for 7800 years		320
	Postindustrial era	
Fossil-fuel combustion (since 1850)		270 ± 30
Land-use conversion		136 ± 5
Soil cultivation	78 ± 12	
Erosion	26 ± 9	
Mineralization	52 ± 8	

One of the optimistic views: Ratten Lal. 2004. Science

The carbon sink capacity of the world’s agricultural and degraded soils is **50 to 66% of the historic carbon loss of 42 to 78 gigatons of carbon**.

An increase of 1 ton of soil carbon pool of degraded cropland soils may increase crop yield by 20 to 40 kilograms per hectare (kg/ha) for wheat, 10 to 20 kg/ha for maize, and 0.5 to 1 kg/ha for cowpeas. As well as enhancing food security, carbon sequestration has the potential to offset fossil fuel emissions by 0.4 to 1.2 gigatons of carbon per year, or 5 to 15% of the global fossil-fuel emissions.

Limited potential for terrestrial carbon sequestration to offset fossil-fuel emissions in the upper midwestern US

Cinzia Fissore[1,*], Javier Espeleta[1,2], Edward A Nater[1], Sarah E Hobbie[3], and Peter B Reich[4]

Many carbon dioxide (CO_2) emission-reduction strategies currently under consideration rely on terrestrial carbon (C) sequestration to offset substantial proportions of CO_2 emissions. We estimated C sequestration rates and potential land areas for a diverse array of land-cover changes in the Upper Midwest of the US, a "best case" region for this study because of its relatively modest CO_2 emissions and the large areas of cropland potentially available for conversion. We then developed scenarios that apply some of the most widespread mitigation strategies to the region: the first, which aimed to offset 29% of regional CO_2 emissions, required the unrealistic loss of two-thirds of working cropland; the second, which estimated the emission offset attainable by conversion of 10% of harvested croplands (5.8% of the US total), resulted in <5% CO_2 emissions reduction for the region (<1.1% of total US emissions). There is limited capacity for terrestrial C sequestration, so strategies should aim to directly reduce CO_2 emissions to mitigate rising atmospheric CO_2 concentrations.

Front Ecol Environ 2010; 8(8): 409–413, doi:10.1890/090059

The Review by Richards and Stokes (2004)

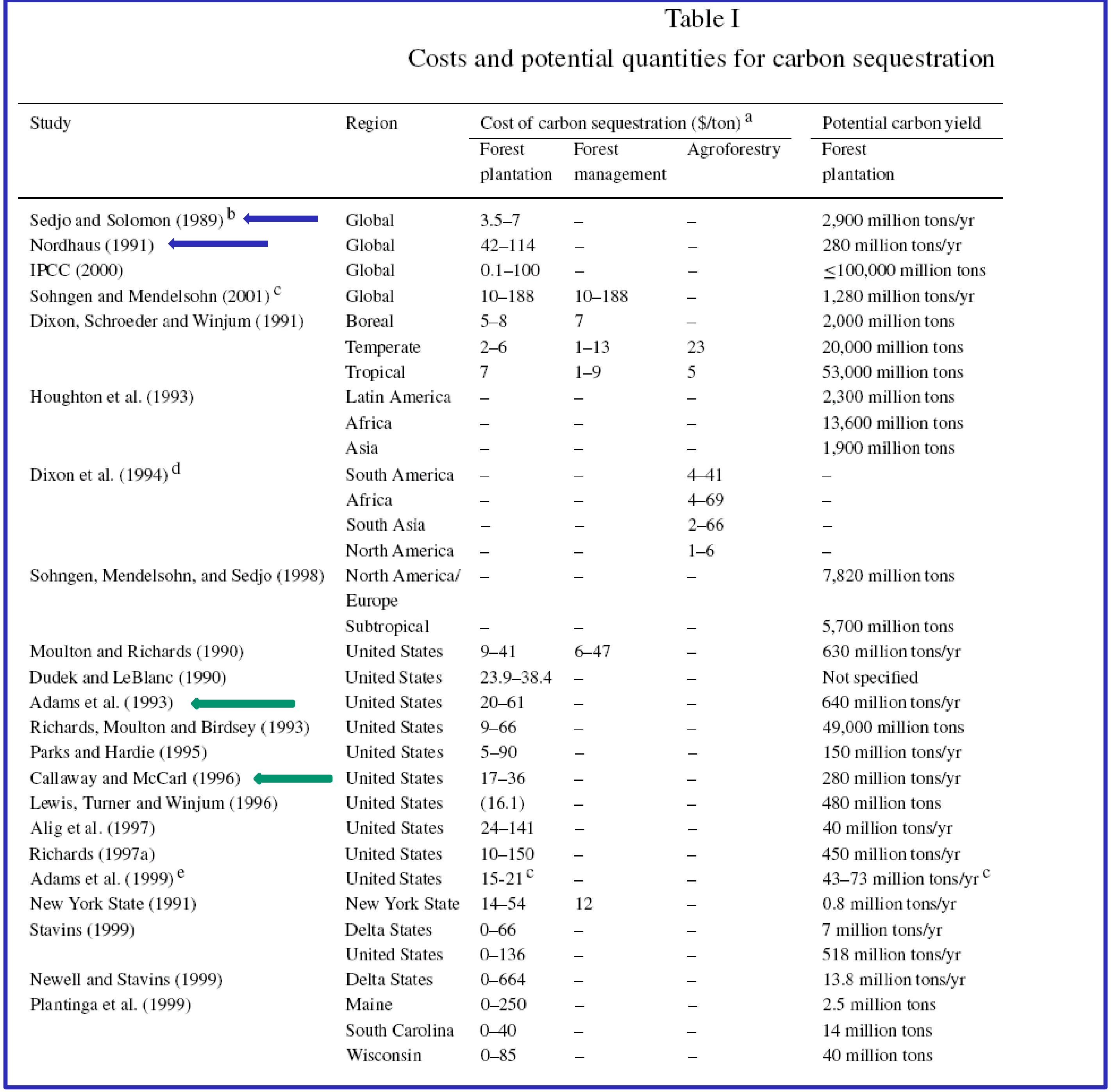


Table I

Costs and potential quantities for carbon sequestration

Study	Region	Cost of carbon sequestration ($/ton)[a]			Potential carbon yield
		Forest plantation	Forest management	Agroforestry	Forest plantation
Sedjo and Solomon (1989)[b]	Global	3.5–7	–	–	2,900 million tons/yr
Nordhaus (1991)	Global	42–114	–	–	280 million tons/yr
IPCC (2000)	Global	0.1–100	–	–	≤100,000 million tons
Sohngen and Mendelsohn (2001)[c]	Global	10–188	10–188	–	1,280 million tons/yr
Dixon, Schroeder and Winjum (1991)	Boreal	5–8	7	–	2,000 million tons
	Temperate	2–6	1–13	23	20,000 million tons
	Tropical	7	1–9	5	53,000 million tons
Houghton et al. (1993)	Latin America	–	–	–	2,300 million tons
	Africa	–	–	–	13,600 million tons
	Asia	–	–	–	1,900 million tons
Dixon et al. (1994)[d]	South America	–	–	4–41	–
	Africa	–	–	4–69	–
	South Asia	–	–	2–66	–
	North America	–	–	1–6	–
Sohngen, Mendelsohn, and Sedjo (1998)	North America/ Europe	–	–	–	7,820 million tons
	Subtropical	–	–	–	5,700 million tons
Moulton and Richards (1990)	United States	9–41	6–47	–	630 million tons/yr
Dudek and LeBlanc (1990)	United States	23.9–38.4	–	–	Not specified
Adams et al. (1993)	United States	20–61	–	–	640 million tons/yr
Richards, Moulton and Birdsey (1993)	United States	9–66	–	–	49,000 million tons
Parks and Hardie (1995)	United States	5–90	–	–	150 million tons/yr
Callaway and McCarl (1996)	United States	17–36	–	–	280 million tons/yr
Lewis, Turner and Winjum (1996)	United States	(16.1)	–	–	480 million tons
Alig et al. (1997)	United States	24–141	–	–	40 million tons/yr
Richards (1997a)	United States	10–150	–	–	450 million tons/yr
Adams et al. (1999)[e]	United States	15-21[c]	–	–	43–73 million tons/yr[c]
New York State (1991)	New York State	14–54	12	–	0.8 million tons/yr
Stavins (1999)	Delta States	0–66	–	–	7 million tons/yr
	United States	0–136	–	–	518 million tons/yr
Newell and Stavins (1999)	Delta States	0–664	–	–	13.8 million tons/yr
Plantinga et al. (1999)	Maine	0–250	–	–	2.5 million tons
	South Carolina	0–40	–	–	14 million tons
	Wisconsin	0–85	–	–	40 million tons

Summary

Potential to capture significant quantities of C for < $50/ton

Sequestration in developing countries may be more cost-effective than in industrialized countries

Vastly different estimates

Fertilize the Oceans?

Introduction of iron to the upper ocean

- ➢Ocean is nutrient-rich but iron deficient
- ➢Supports the growth of phytoplankton
- ➢Will only work where there are unutilized macronutrients: Southern Ocean
- ➢Pinatubo put iron dust into the oceans which generated a decline in atmospheric CO_2

List of experiments:

Ironex I (1993) MLML
Ironex II (1995)
Southern Ocean Iron Release Experiment (SOIREE, 1999)
EisenEx 2000
Subarctic Pacific Iron Experiement for EcosystemDynamics Study (SEEDS, 2001)
Southern Ocean Iron Experiments (SOFex, 2002)
Subarctic Ecosystem Response to Iron Enrichment Study (SERIES 2002)
SEEDS II (2004)
European Iron Fertilization Experiment (EIFEX 2004)
CROZet natural iron bloom and Export experiment (CROZEX 2005)
LOHAFEX (2009)

Side Effects
(mostly unknown)

1. Low oxygen regions in the deep ocean
2. Increased denitrification and production of N_2O
3. Harmful algal blooms
4. Alteration of marine food webs
5. Increased ocean acidity

“Ocean fertilization: dead in the water?”

(Article in Nature, January 2009)

Relative to one unit of added iron, the amount of C sequestered to 200 meter depth was almost 80 times smaller than results from a previous study.

So, ocean fertilization would not have a large effect on the levels of atmospheric CO_2. (Pollard et al. 2009)

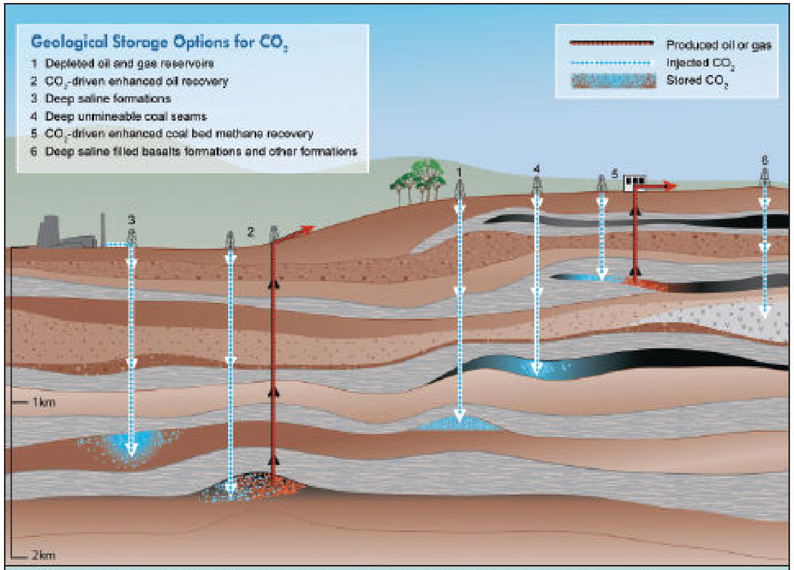
However, Germany recently approved the LOHAFEX project where they will dump 20 tons of iron sulfate into a 300 sq. km. area between Argentina and the Antarctic Peninsula.

Geologic Carbon Sequestration

Storing CO_2 in deep underground reservoirs: depleted oil and gas fields, unmineable coal seams, saline aquifers

Storage formations can occur in both onshore and offshore basins

CO_2 must be transported from fossil-fuel fired power plants via pipeline to geologic reservoirs

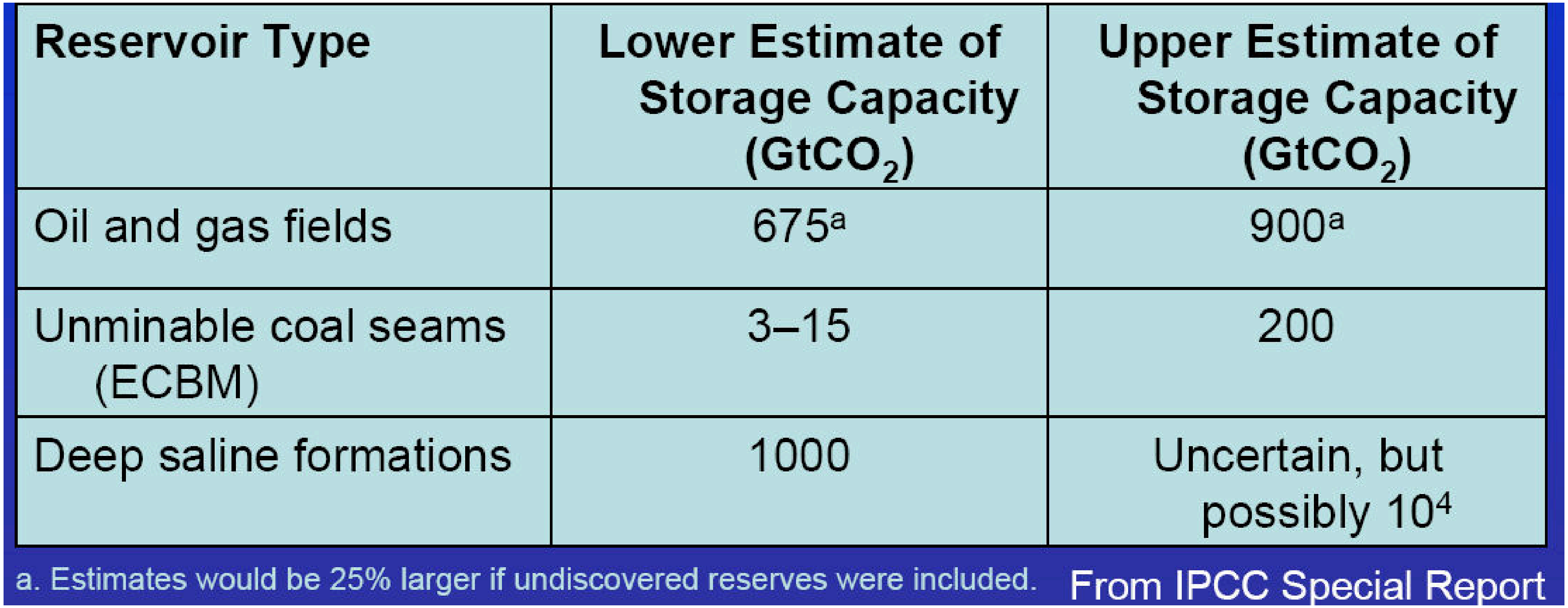


▲ Candidate geologic reservoirs for storing CO_2 lie deep below the surface of the Earth at varying depths.
(FIGURE COURTESY OF THE AUSTRALIAN CO2CRC).

Storage will occur at depths below 800m where pressures and temperatures will usually result in CO_2 being in a liquid state.

Well-sealed cap rock is important.

Capacity of Storage Formations



Reservoir Type	**Lower Estimate of Storage Capacity ($GtCO_2$)**	**Upper Estimate of Storage Capacity ($GtCO_2$)**
Oil and gas fields	675[a]	900[a]
Unminable coal seams (ECBM)	3–15	200
Deep saline formations	1000	Uncertain, but possibly 10^4

[a] Estimates would be 25% larger if undiscovered reserves were included.

From IPCC Special Report

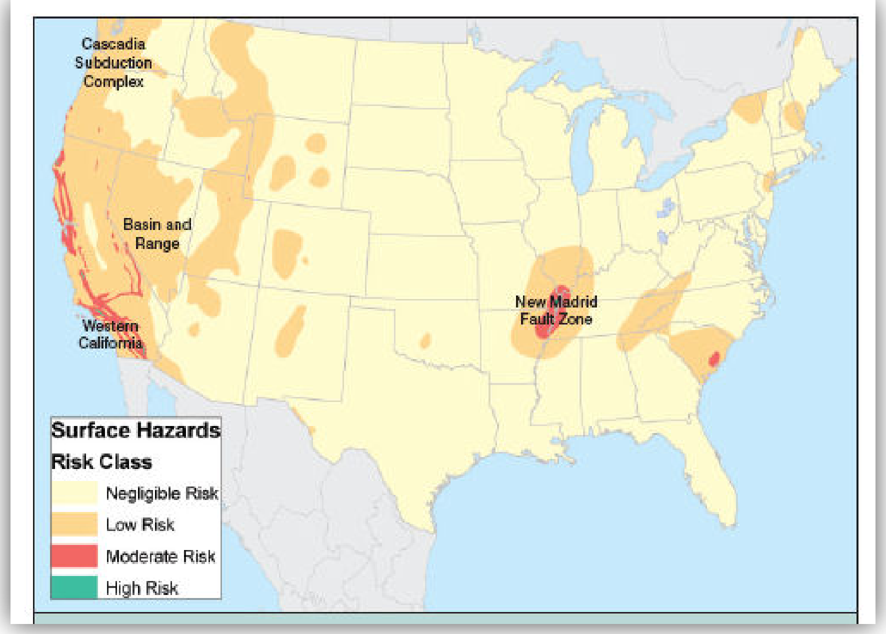
Problems with Geologic Storage

Transport costs

Potential leakage

- Slow, chronic leakage may result in acidification of ground water and other water quality issues

- Sudden catastrophic release could result in death



From: Carbon Dioxide Capture and Geologic Storage: A core element of a global energy technology strategy to address climate change (Dooley, 2006)

Table SPM.5. 2002 Cost ranges for the components of a CCS system as applied to a given type of power plant or industrial source. The costs of the separate components cannot simply be summed to calculate the costs of the whole CCS system in US$/$CO_2$ avoided. All numbers are representative of the costs for large-scale, new installations, with natural gas prices assumed to be 2.8-4.4 US$ GJ^{-1} and coal prices 1-1.5 US$ GJ^{-1} (Sections 5.9.5, 8.2.1, 8.2.2, 8.2.3, Tables 8.1 and 8.2).

CCS system components	Cost range	Remarks
Capture from a coal- or gas-fired power plant	15-75 US$/$tCO_2$ net captured	Net costs of captured CO_2, compared to the same plant without capture.
Capture from hydrogen and ammonia production or gas processing	5-55 US$/$tCO_2$ net captured	Applies to high-purity sources requiring simple drying and compression.
Capture from other industrial sources	25-115 US$/$tCO_2$ net captured	Range reflects use of a number of different technologies and fuels.
Transportation	1-8 US$/$tCO_2$ transported	Per 250 km pipeline or shipping for mass flow rates of 5 (high end) to 40 (low end) $MtCO_2$ yr^{-1}.
Geological storage[a]	0.5-8 US$/$tCO_2$ net injected	Excluding potential revenues from EOR or ECBM.
Geological storage: monitoring and verification	0.1-0.3 US$/$tCO_2$ injected	This covers pre-injection, injection, and post-injection monitoring, and depends on the regulatory requirements.
Ocean storage	5-30 US$/$tCO_2$ net injected	Including offshore transportation of 100-500 km, excluding monitoring and verification.
Mineral carbonation	50-100 US$/$tCO_2$ net mineralized	Range for the best case studied. Includes additional energy use for carbonation.

[a] Over the long term, there may be additional costs for remediation and liabilities.

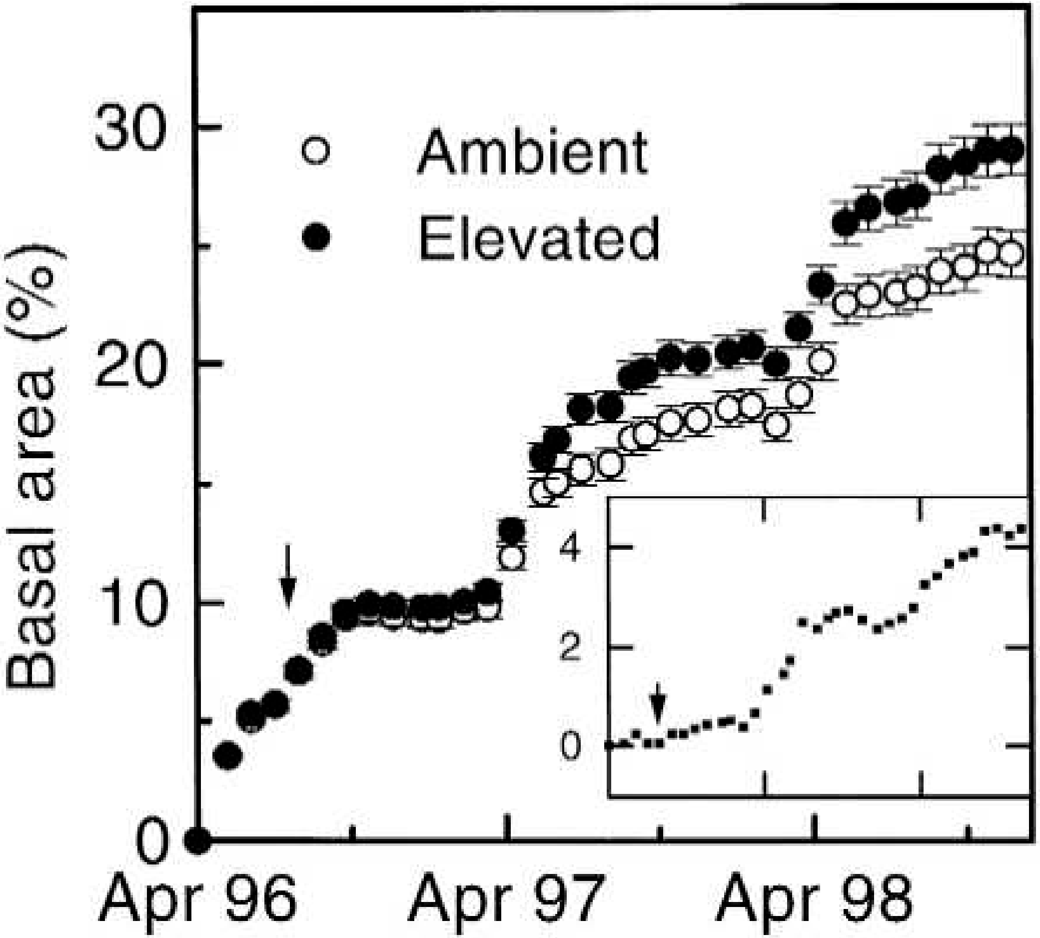
Increased Photosynthesis

Duke's FACE site

Enriching the plots with additional 200ppm of CO_2 over ambient levels

Also have control plots to study basic C and N cycling

NPP & CO_2



Average basal area (±1 SE) for loblolly pine trees growing in ambient (n=102) and elevated (n=101) CO_2. Values are percentages of initial basal area. Insert shows absolute difference between basal area of elevated and ambient trees, and the arrows indicate when CO_2 fumigation was initiated.

nature climate change

LETTERS

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Greening of the Earth and its drivers

Zaichun Zhu[1,2], Shilong Piao[1,2]*, Ranga B. Myneni[3], Mengtian Huang[2], Zhenzhong Zeng[2], Josep G. Canadell[4], Philippe Ciais[2,5], Stephen Sitch[6], Pierre Friedlingstein[7], Almut Arneth[8], Chunxiang Cao[9], Lei Cheng[10], Etsushi Kato[11], Charles Koven[12], Yue Li[2], Xu Lian[2], Yongwen Liu[2], Ronggao Liu[13], Jiafu Mao[14], Yaozhong Pan[15], Shushi Peng[2], Josep Peñuelas[16,17], Benjamin Poulter[18], Thomas A. M. Pugh[8,19], Benjamin D. Stocker[20,21], Nicolas Viovy[5], Xuhui Wang[2], Yingping Wang[22], Zhiqiang Xiao[23], Hui Yang[2], Sönke Zaehle[24] and Ning Zeng[25]

Global environmental change is rapidly altering the dynamics of terrestrial vegetation, with consequences for the functioning of the Earth system and provision of ecosystem services[1,2]. Yet how global vegetation is responding to the changing environment is not well established. Here we use three long-term satellite leaf area index (LAI) records and ten global ecosystem models to investigate four key drivers of LAI trends during 1982–2009. We show a persistent and widespread increase of growing season integrated LAI (greening) over 25% to 50% of the global vegetated area, whereas less than 4% of the globe shows decreasing LAI (browning). Factorial simulations with multiple global ecosystem models suggest that CO_2 fertilization effects explain 70% of the observed greening trend, followed by nitrogen deposition (9%), climate change (8%) and land cover change (LCC) (4%). CO_2 fertilization effects explain most of the greening trends in the tropics, whereas climate change resulted in greening of the high latitudes and the Tibetan Plateau. LCC contributed most to the regional greening observed in southeast China and the eastern United States. The regional effects of unexplained factors suggest that the next generation of ecosystem models will need to explore the impacts of forest demography, differences in regional management intensities for cropland and pastures, and other emerging productivity constraints such as phosphorus availability.

measurements[3–8]. Long-term changes in vegetation greenness are driven by multiple interacting biogeochemical drivers and land-use effects[9]. Biogeochemical drivers include the fertilization effects of elevated atmospheric CO_2 concentration (eCO_2), regional climate change (temperature, precipitation and radiation), and varying rates of nitrogen deposition. Land-use-related drivers involve changes in land cover and in land management intensity, including fertilization, irrigation, forestry and grazing[10]. None of these driving factors can be considered in isolation, given their strong interactions with one another. Previously, a few studies had investigated the drivers of global greenness trends[6,7,11], with a limited number of models and satellite observations, which prevented an appropriate quantification of uncertainties[12].

Here, we investigate trends of leaf area index (LAI) and their drivers for the period 1982 to 2009 using three remotely sensed data sets (GIMMS3g, GLASS and GLOMAP) and outputs from ten ecosystem models run at global extent (see Supplementary Information). We use the growing season integrated leaf area index (hereafter, LAI; Methods) as the variable of our study. We first analyse global and regional LAI trends for the study period and differences between the three data sets. Using modelling results, we then quantify the contributions of CO_2 fertilization, climatic factors, nitrogen deposition and LCC to the observed trends.

Trends from the three long-term satellite LAI data sets consistently show positive values over a large proportion of the

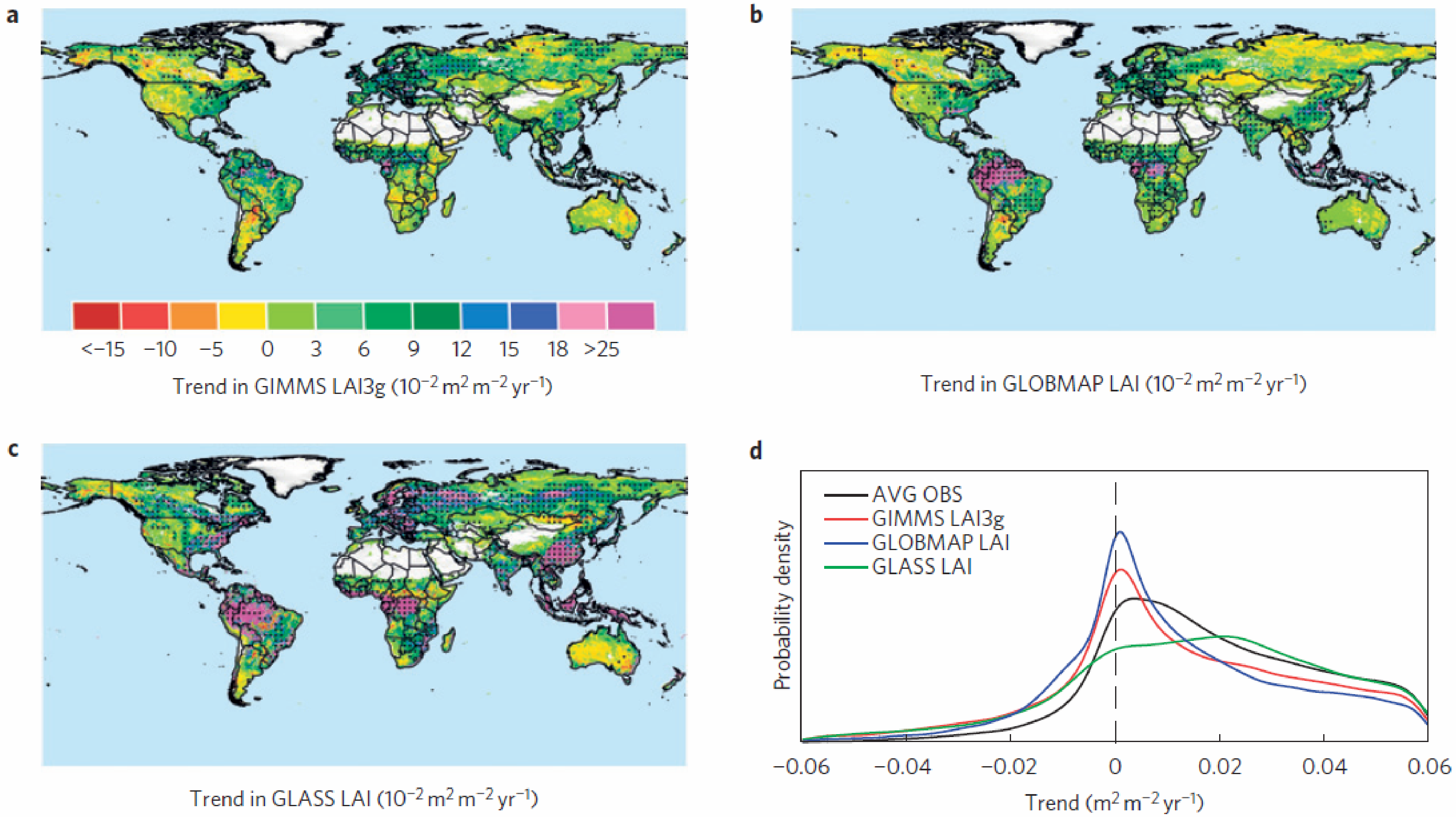
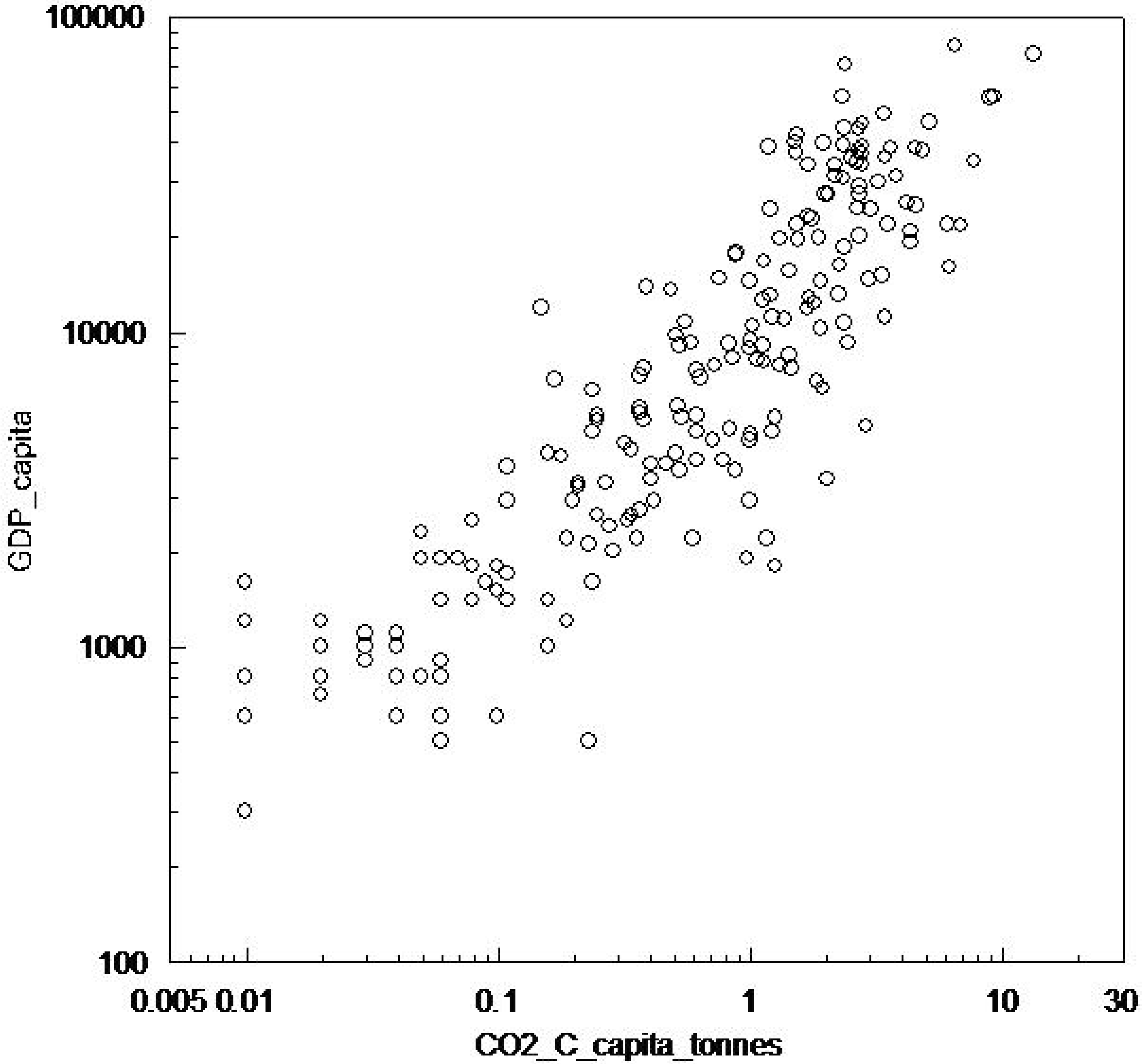
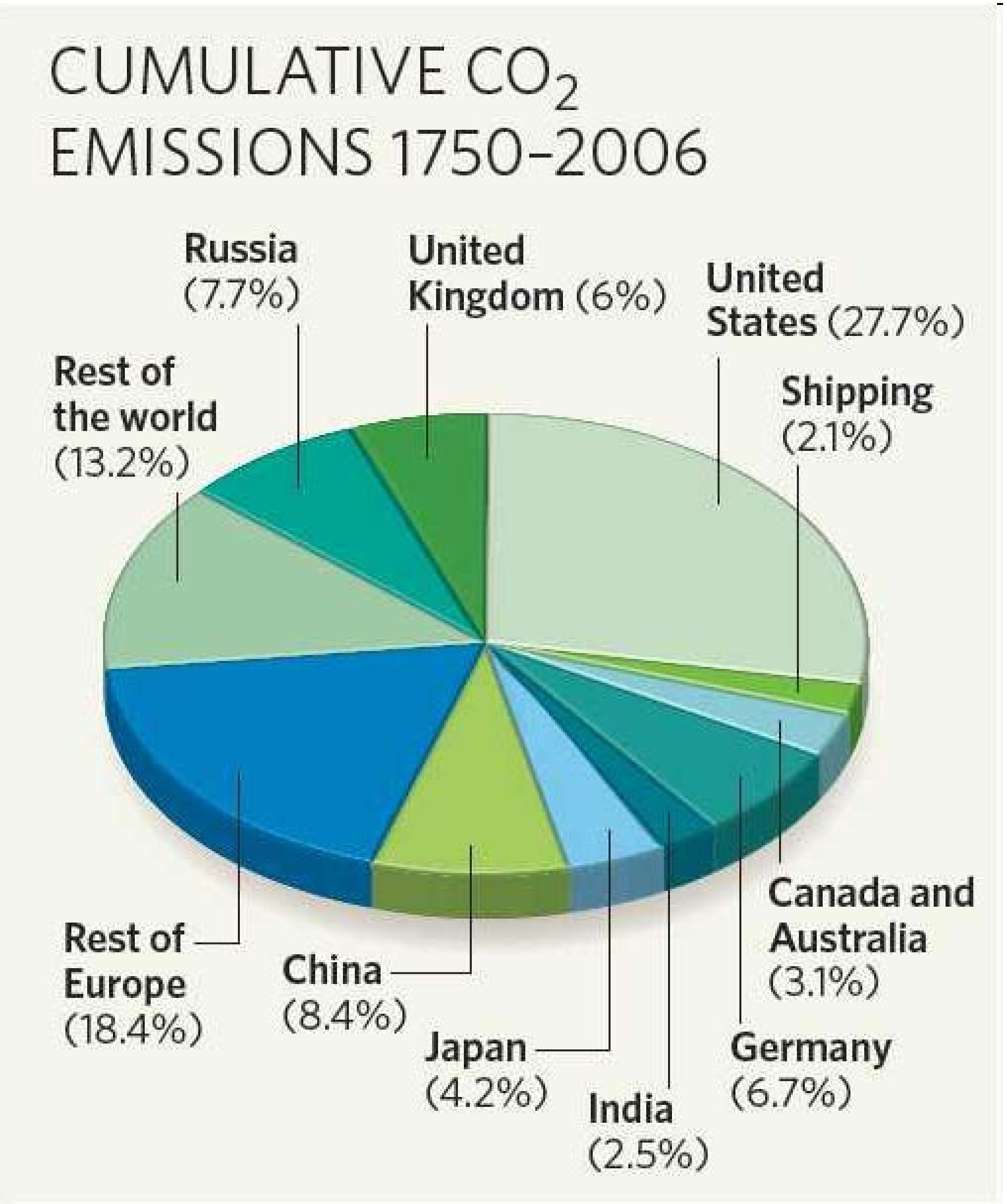


Figure 1 | Trend in observed growing season integrated LAI. a–c, Spatial pattern of trends in growing season integrated LAI derived from three remote sensing data sets. **a**, GIMMS LAI3g. **b**, GLOBMAP LAI. **c**, GLASS LAI. All data sets cover the period 1982 to 2009. Regions labelled by black dots indicate trends that are statistically significant (Mann–Kendall test; $p < 0.05$). **d**, Probability density function of LAI trends for GIMMS LAI3g, GLASS LAI, GLOBMAP LAI and the average of the three remote sensing data sets (AVG OBS).

What can we do to reduce carbon emissions or to increase carbon sequestration?



Source: CO_2 Information Analysis Center, Oak Ridge National Lab.
And for GDP: CIA web page



Source: CO_2 Information Analysis Center, Oak Ridge National Lab.

Summary

1. Since 1995 human activities at the global scale have changed approximately 4% of total annual atmospheric influx. This rate is about 100 times faster than any fast rate of change recorded in the ice cores in the past 500 million years.

2. Since 1995 burning fossil fuels has contributed more than 80% of the total annual human sources of atmospheric CO_2.

3. Deforestation by burning and subsequent conversion to either grasslands or croplands has been one of the major carbon emission sources to the atmosphere, especially at the modern speed of forest destruction.

4. Agricultural management styles, especially soil tillage practices, can significantly influence the global carbon cycle, either storing more carbon in soils or losing more carbon to the atmosphere.

5. We related global and local actions to the global carbon cycle.