State of the Science of Soil Carbon Sequestration

R. César Izaurralde,[1] Charles W. Rice,[2] and James A. Edmonds[1]

[1]Joint Global Change Research Institute

[2]Kansas State University

U.S. National Committee for Soil Science
Keck Center of The National Academies
Washington, DC
May 15-16, 2007

Pacific Northwest National Laboratory
Operated by Battelle for the U.S. Department of Energy

UNIVERSITY OF MARYLAND

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Objectives

- To discuss advances in soil carbon sequestration research and technology
- To identify major gaps in knowledge and technology development with regards to soil carbon sequestration

Questions

- What is our current understanding about soil carbon sequestration?
- Is soil carbon sequestration occurring?
  - If so, what are the rates and extent of it?
- Will soil carbon sequestration make a difference as a technology to mitigate climate change?
- What are the implications of soil carbon sequestration in terms of environmental quality?
- What are the impediments for a full-scale deployment of soil carbon sequestration?

Terrestrial Carbon Sequestration: Definition and Background

- Definition: The implementation of a land management practice that through increased net primary productivity, reduced rate of heterotrophic respiration, or both leads to an increase in ecosystem C storage
  - Examples: planting trees, reducing the intensity of tillage on cropland, or restoring grasslands on degraded lands will all lead to an increase in C storage in plants, soil, or both
- Rationale:
  - Past losses of C from terrestrial stocks (~200 Pg C)
  - Environmental benefits (soil quality, biodiversity)
  - Cost effectiveness compared to other mitigation practices
- In 1995, the 2nd IPCC report (Chapter 23) estimated the potential for soil C sequestration at 40 Pg C during 50-100 yr

Agricultural management plays a major role in greenhouse gas emissions and offers many opportunities for mitigation

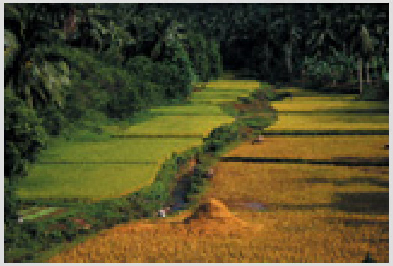
Cropland

- Reduced tillage
- Rotations
- Cover crops
- Fertility management
- Erosion control
- Irrigation management

No-till seeding in USA

Rice paddies

- Irrigation
- Chemical and organic fertilizer
- Plant residue management



Rice fields in The Philippines

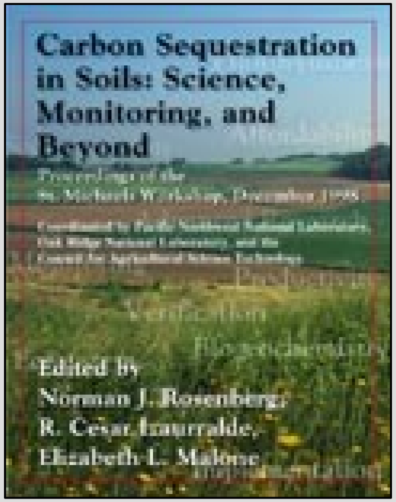
Agroforestry

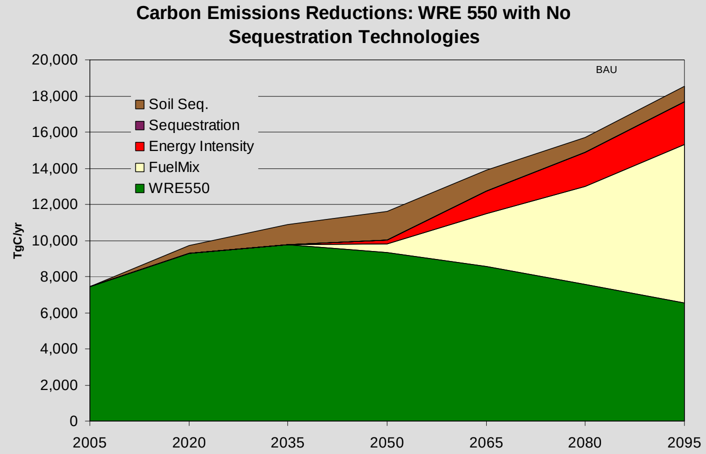
- Improved management of trees and cropland

Maize / coffee fields in Mexico

The St. Michaels Workshop—December 1998

- St. Michaels Workshop addressed C sequestration in agricultural lands
  - Science
  - Monitoring & verification
  - Degraded lands
  - Economics
- The importance of soil C sequestration relative to other technologies was demonstrated
- Results of St. Michaels workshop influenced DOE in the creation of research consortium to study soil C sequestration





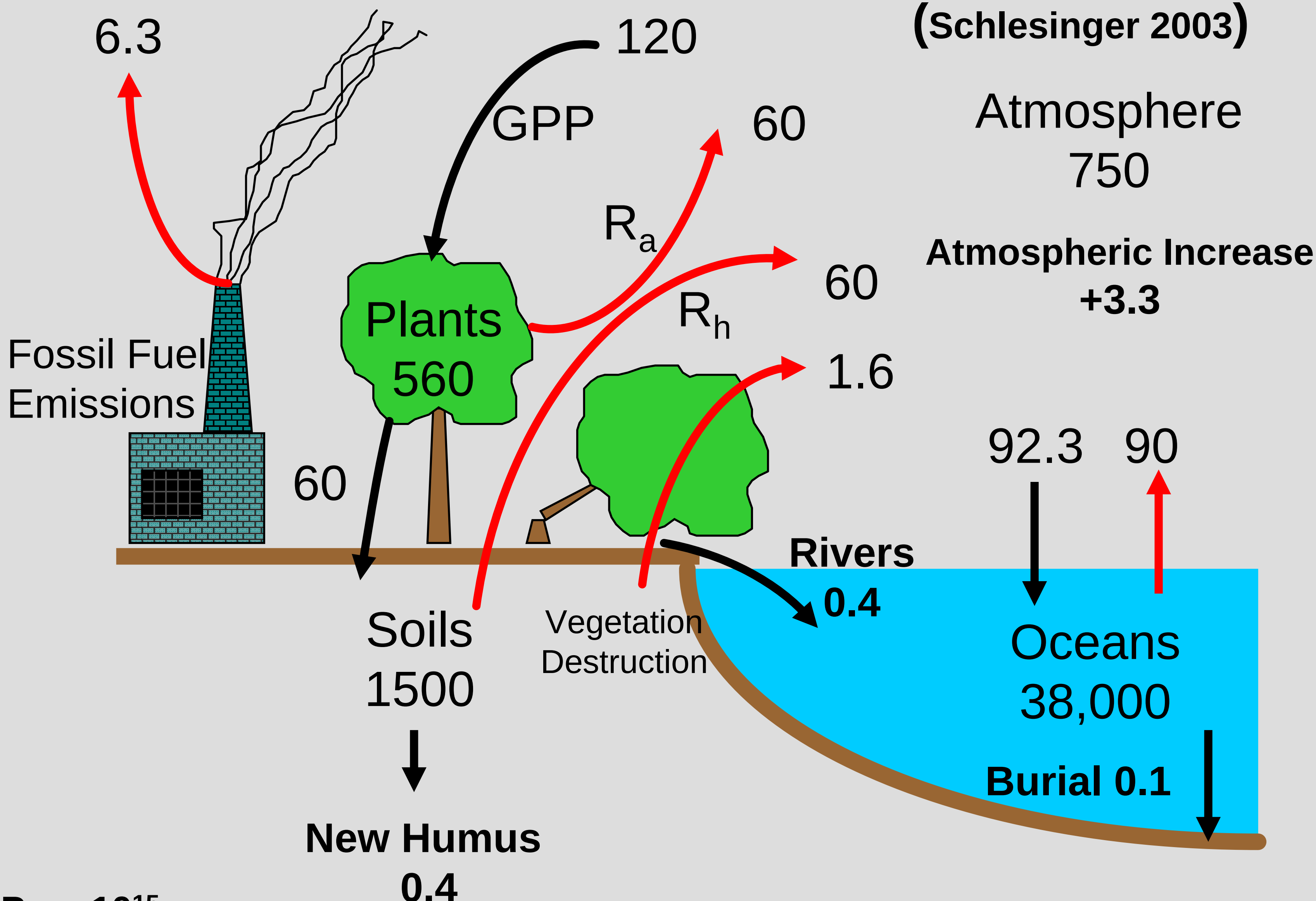
Rosenberg et al. (1999)

US Programs on Carbon Sequestration and Greenhouse Gases

- **CSiTE** (Carbon Sequestration in Terrestrial Ecosystems) Research Consortium - DOE
- **CASMGS** (Consortium for Agricultural Soils Mitigation of Greenhouse GaSes) - USDA
- **GRACEnet** (Greenhouse-gas Reduction through Agricultural Carbon Enhancement network) - USDA
- **NACP** (North American Carbon Program) – NASA, DOE, USDA

Global Carbon Cycle (Pg C)

(Schlesinger 2003)



1 Pg = 10^{15} g
= 1 billion tons

Fluxes and Uncertainties in the Global Carbon Budget (Pg C y^{-1})

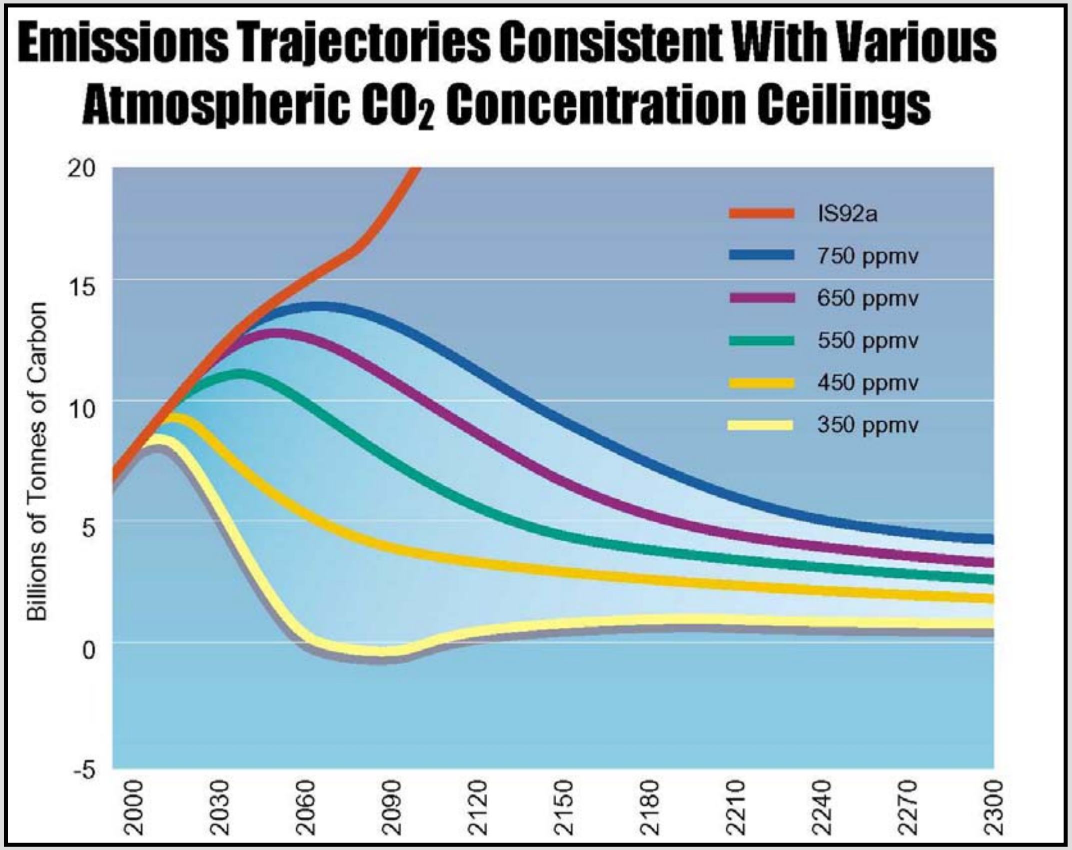
Annual C Fluxes	Mean	Uncertainty
	Source	
Fossil Fuel, Cement	6.3	±0.4
	Net fluxes	
Atmospheric Δ	3.2	±0.1
Net Oc.-Atm. Flux	-1.7	±0.5
Net Land-Atm. Flux	-1.4	±0.7
Land Use Change	0.6 – 1.0	
Residual Sink	-1.3 – -3.1	

1 Pg C = 1 Petagram of C = 1 billion tons of C

Post et al. (2004)

Stabilizing CO_2 Concentrations

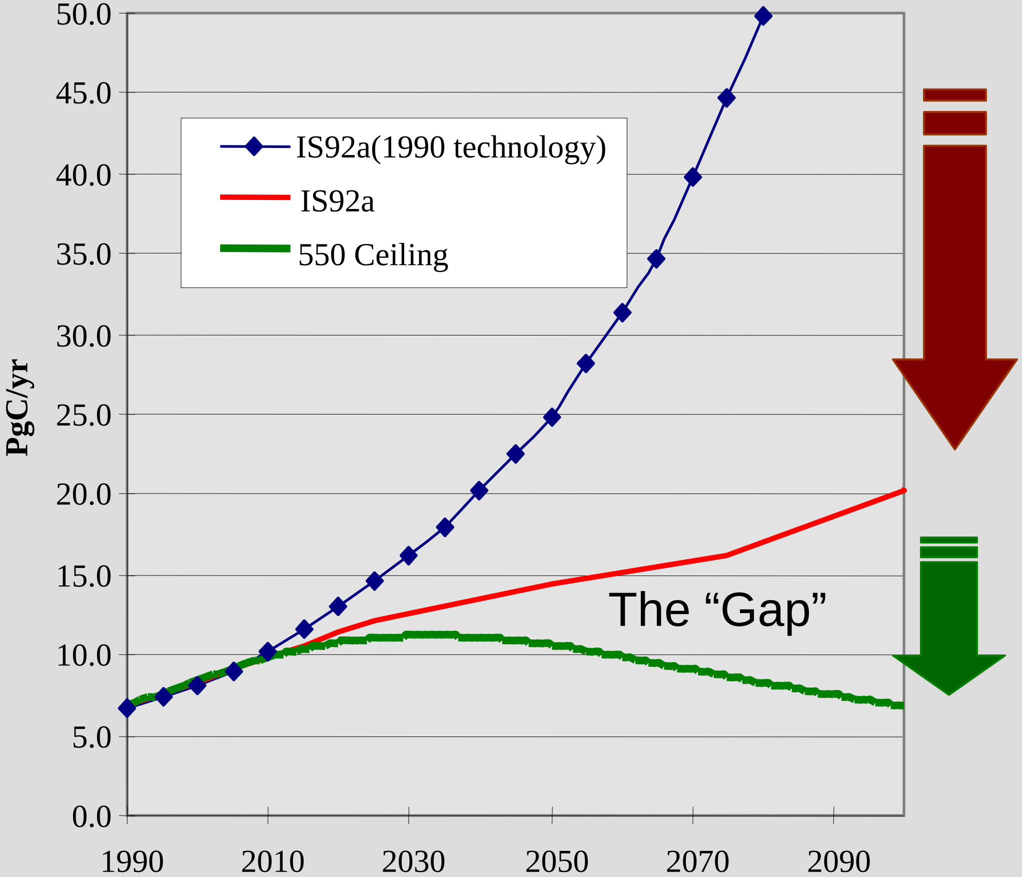
- Stabilization of greenhouse gas concentrations is the goal of the Framework Convention on Climate Change
- Stabilization means that global emissions must peak in the decades ahead and then decline indefinitely thereafter
- Climate change is a long-term, century to millennial problem—with implications for today. It will not be solved with a single treaty, single technology, by a single country, or by a quick fix



Slide courtesy of Jae Edmonds

Filling the Global Carbon Gap

Energy Technologies in the Pipeline Are Not Enough



Assumed Advances

- Fossil Fuels
- Energy intensity
- Nuclear
- Renewables

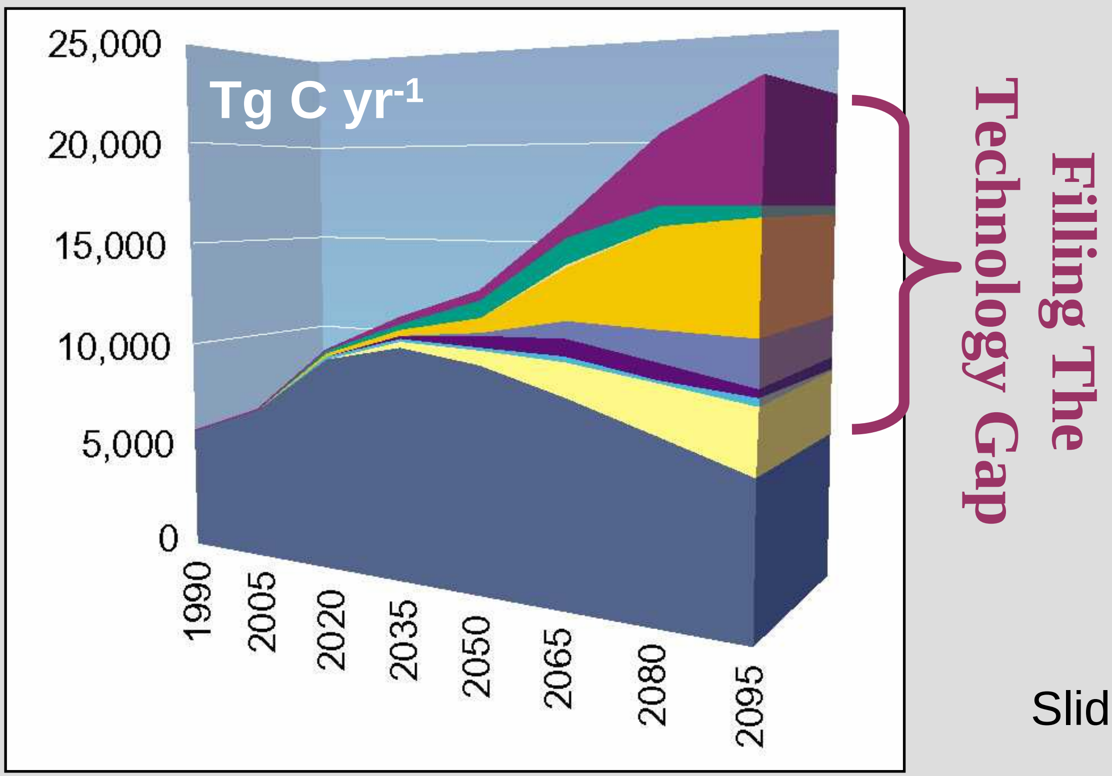
Gap Technologies

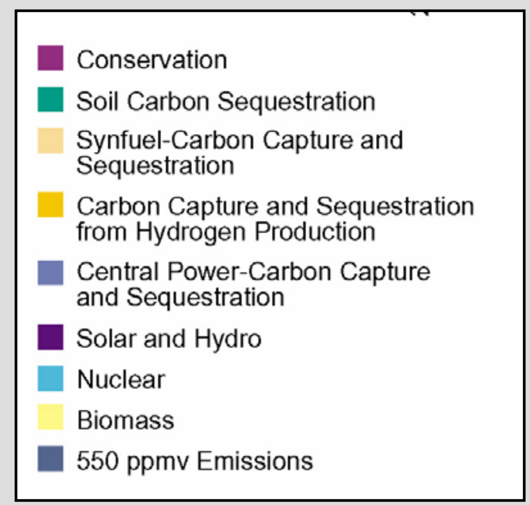
- Improved performance of ref tech.
- Carbon capture & disposal
  - Adv. fossil
- H_2 and Adv. Transportation
- Biotechnologies
  - Soils, Bioenergy, adv. Biological energy

Slide courtesy of Jae Edmonds

Stabilizing CO_2 concentrations means…

- Changing the global energy system
- Developing a least-cost technology portfolio





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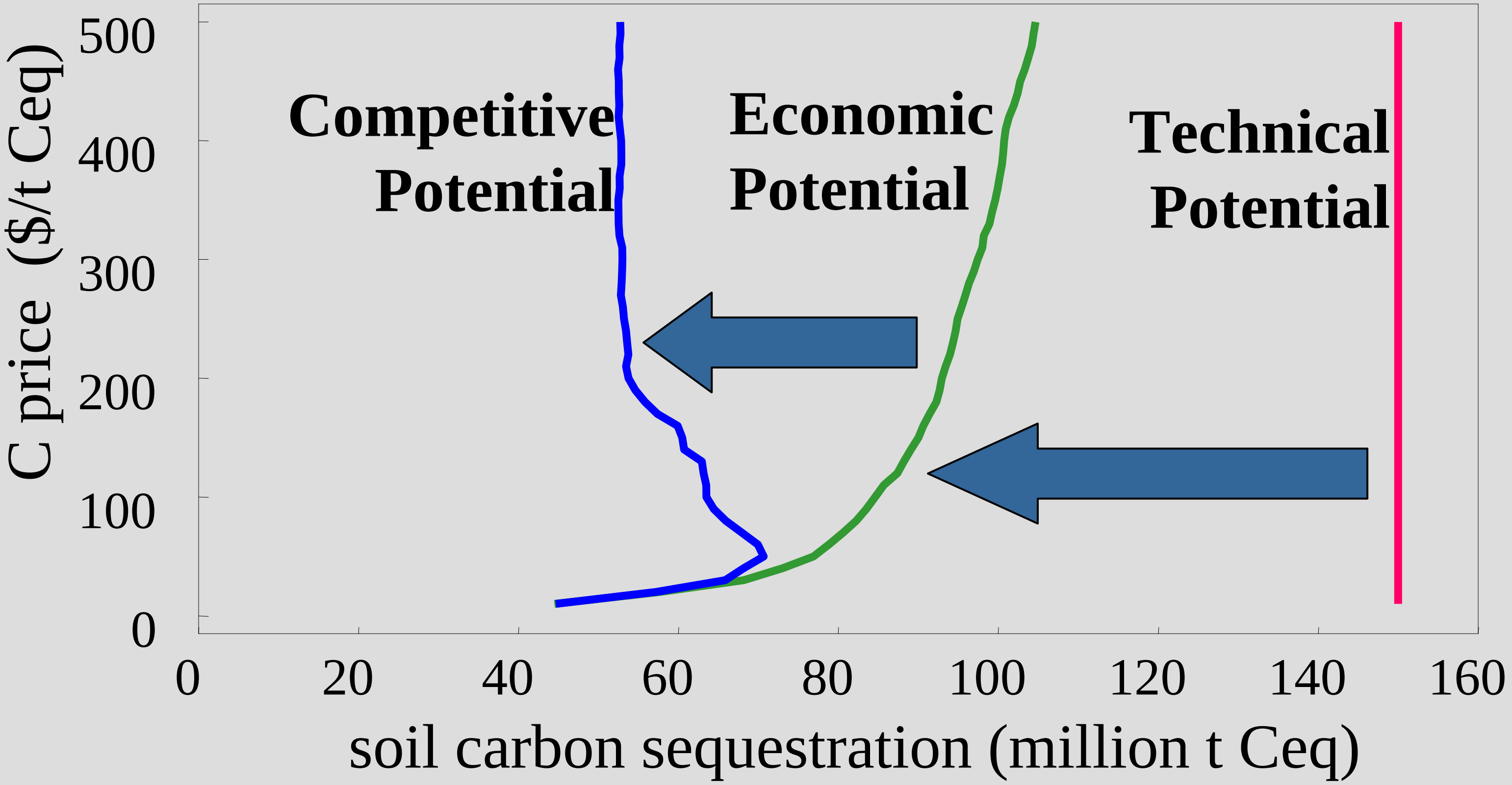
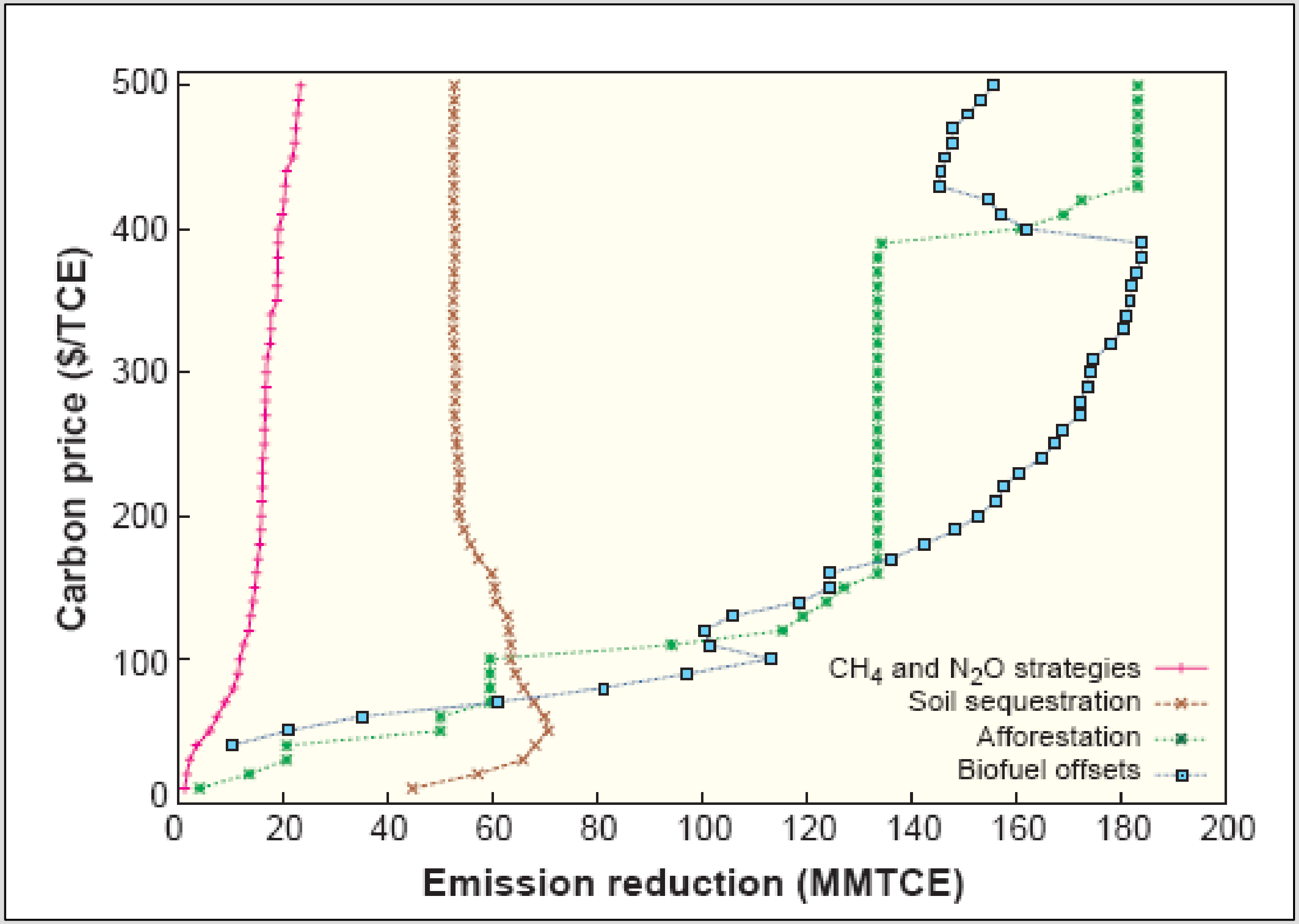
Potential for Sequestration

Example: U.S. ag soil potential:



Competitive economic potentials for agricultural and forest GHG emission mitigation strategies in the US

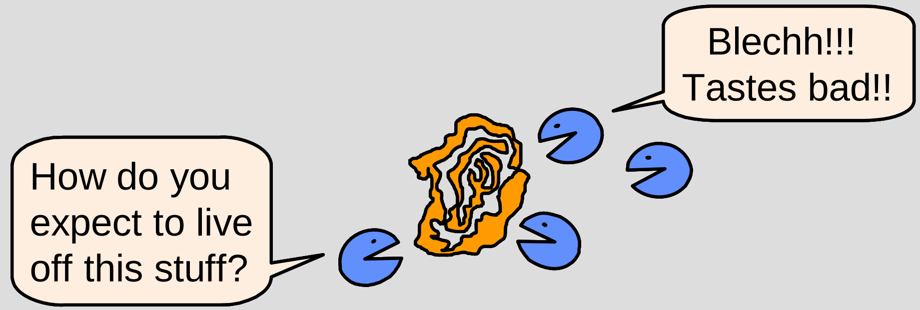


McCarl and Schneider (2001). Science 294:2481-2482.

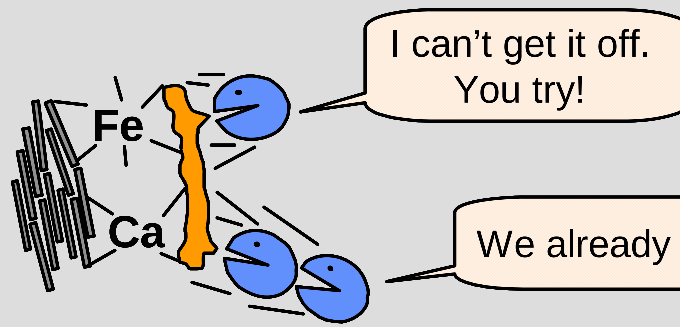
MECHANISMS OF SOIL ORGANIC MATTER STABILIZATION

From Jastrow and Miller, 1998, *In* Soil Processes and the Carbon Cycle, CRC Press.

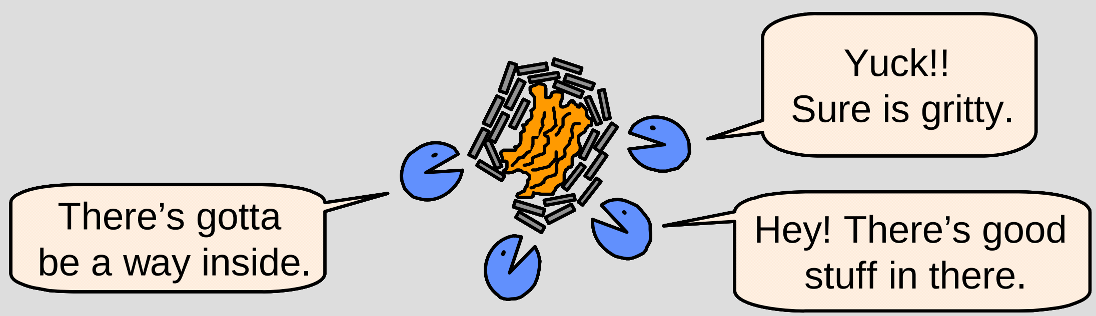
Biochemical Recalcitrance



Chemical Stabilization

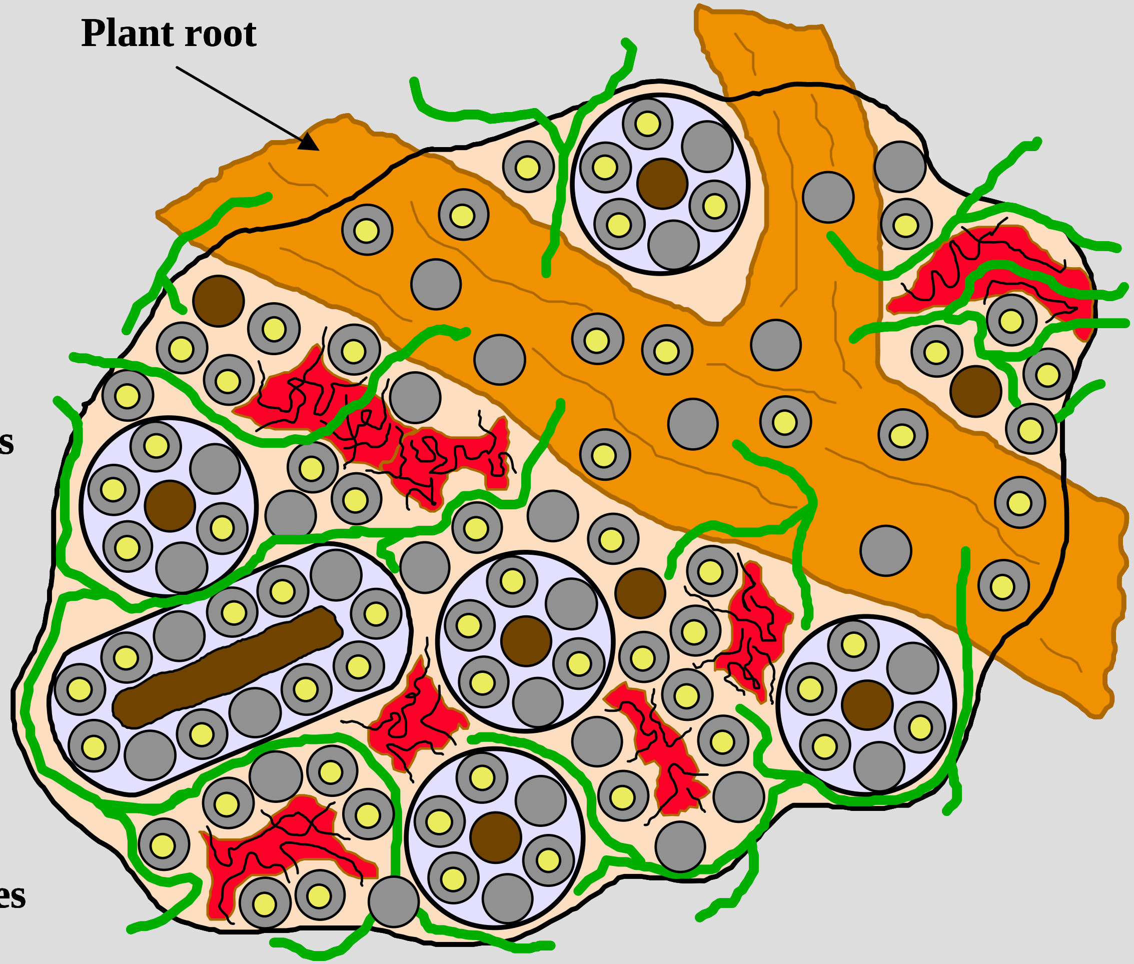


Physical Protection



CONCEPTUAL DIAGRAM OF AGGREGATE HIERARCHY

From Jastrow and Miller, 1998, *In* Soil Processes and the Carbon Cycle, CRC Press.



Microaggregates ~ 90-250 and 20-90 μm

Plant and fungal debris

Silt-sized microaggregates with microbially derived organomineral associations

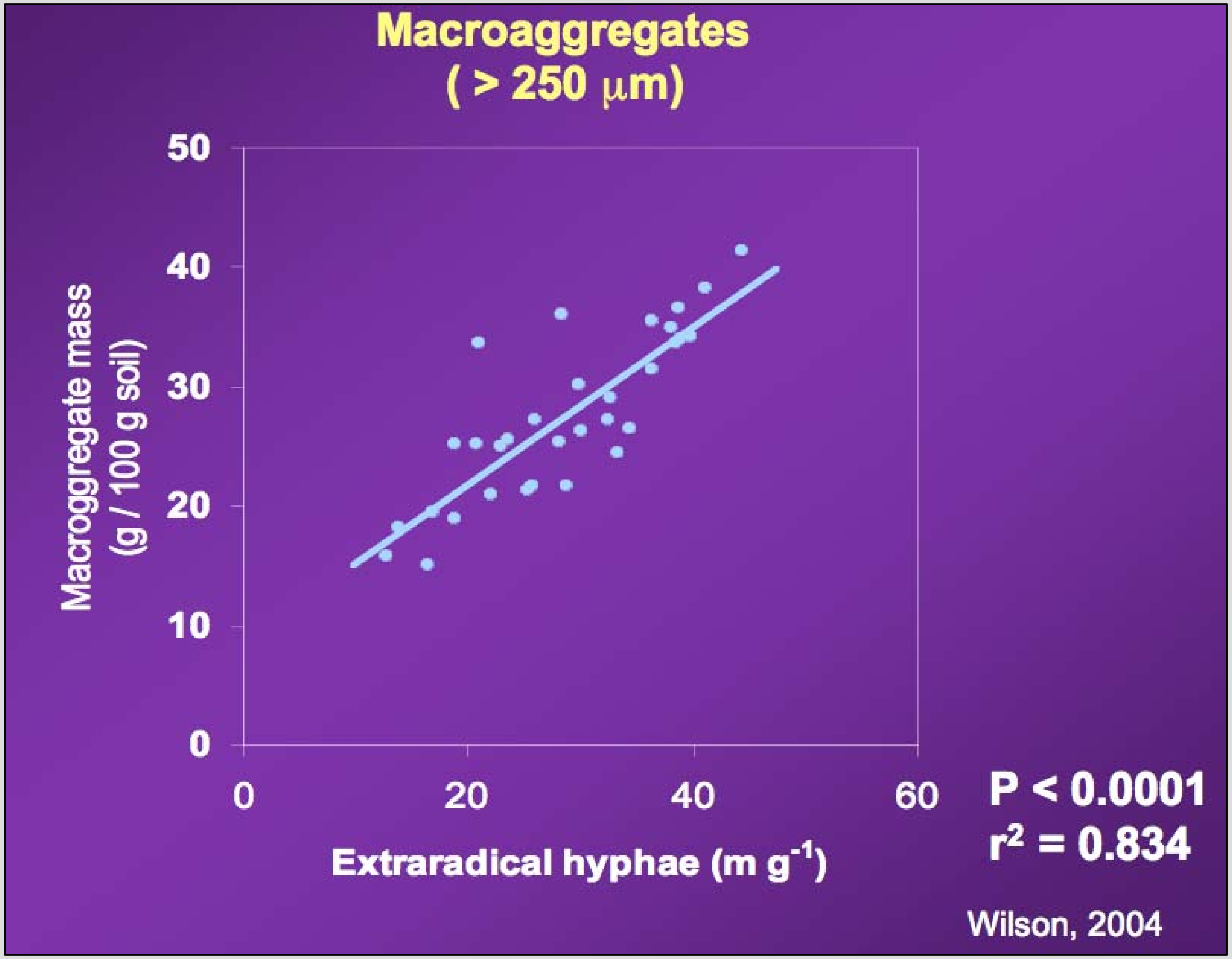
Clay microstructures

Particulate organic matter colonized by saprophytic fungi

Mycorrhizal hyphae

Pore space; polysaccharides and other amorphous interaggregate binding agents

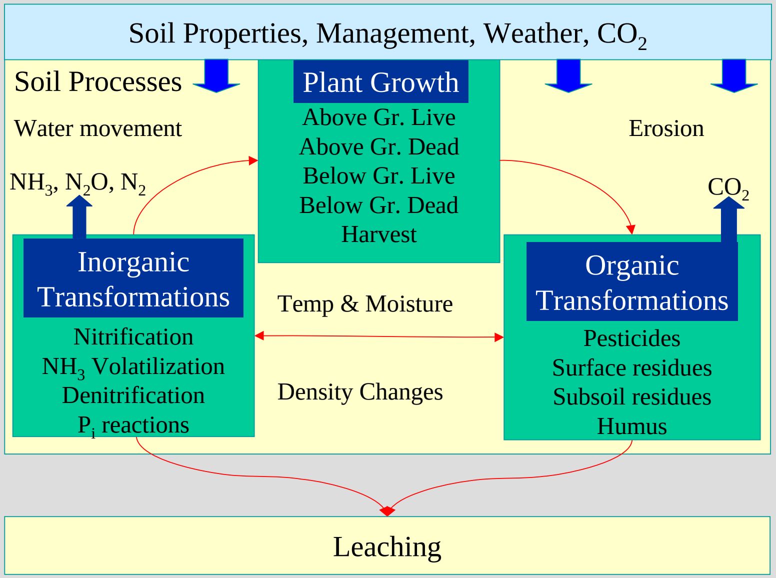
Role of fungi in aggregate formation



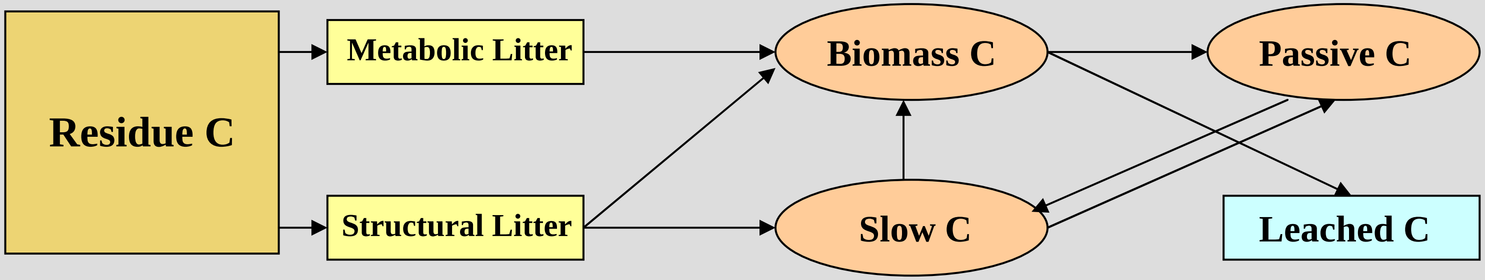
Two Examples of Terrestrial Ecosystem Models

- Century
  - Century
  - DayCent
  - C-STORE
- EPIC
  - EPIC
  - APEX

Processes and Drivers

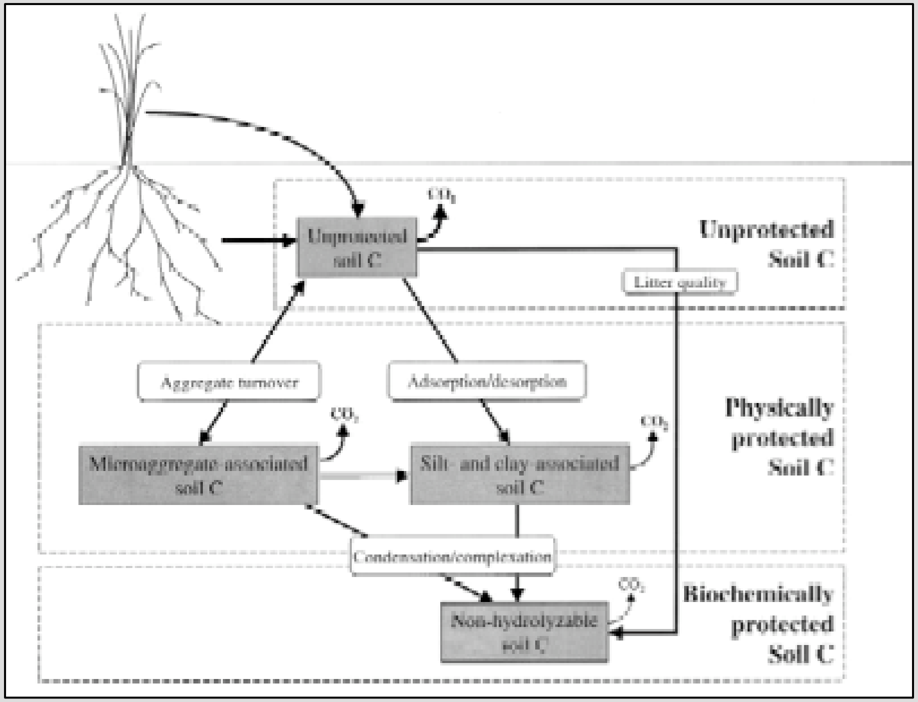


Carbon (and Nitrogen) Flows



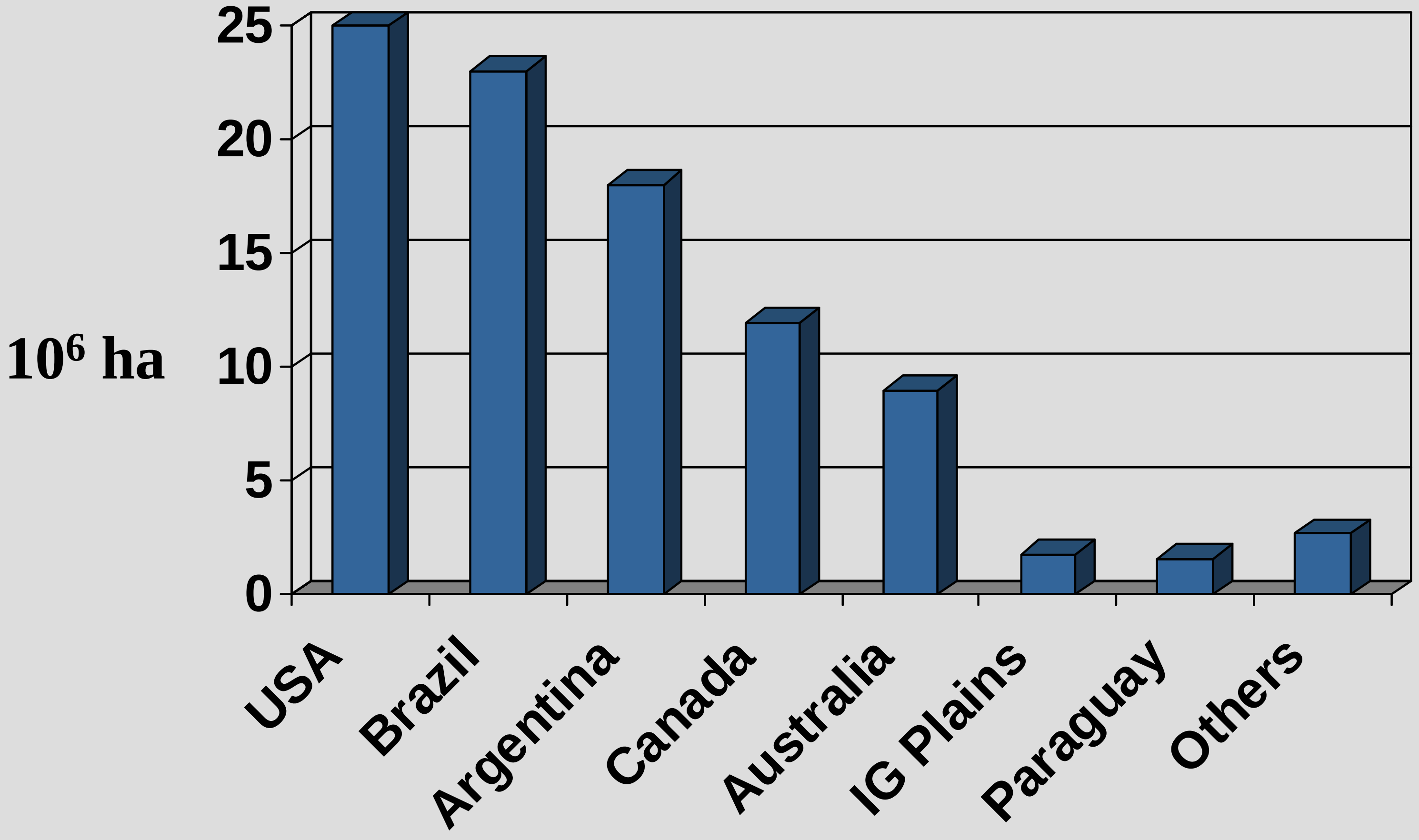
Can soils store C beyond native levels? The concept of C saturation in soils

- Soil C stocks under native conditions reflect the balance between gains and losses of C
- When managed, soils usually lose C but under certain circumstances can gain C beyond their original level
- Six et al. (2002) proposed the whole-soil C saturation concept
- Mechanisms of protection include
  - Physical stabilization
  - Stabilization in silt and clay fractions
  - Biochemical stabilization (recalcitrant C compounds)



Six et al. (2002)

Adoption of no-till worldwide estimated at 93 Mha by 2005



http://www.grdc.com.au/growers/gc/gc64/supplement/evolving.htm

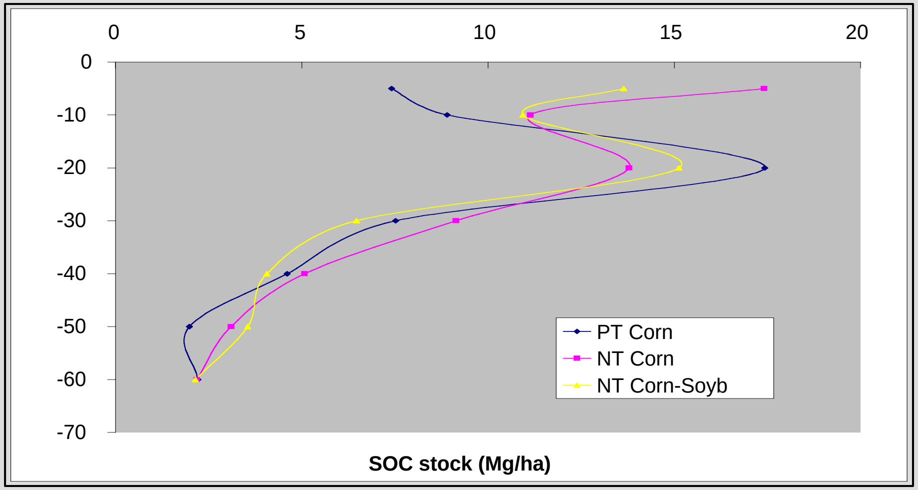
Global potential and rates of soil organic C sequestration

	Mean	SD	Activities
	***Global potential*, Pg C yr^{-1}**		
IPCC (1996)	0.663	0.218	Ag. soils, set aside, wetland, degraded land
Lal & Bruce (1999)	0.163	0.018	Bio offset, crop syst., CT, erosion, degraded land
	***Global historical rates*, Mg C ha^{-1} yr^{-1}**		
West & Post (2002)	0.57	0.14	No till
	***Global estimates for current no till*, Pg C yr^{-1} (2005)**		
	0.053		

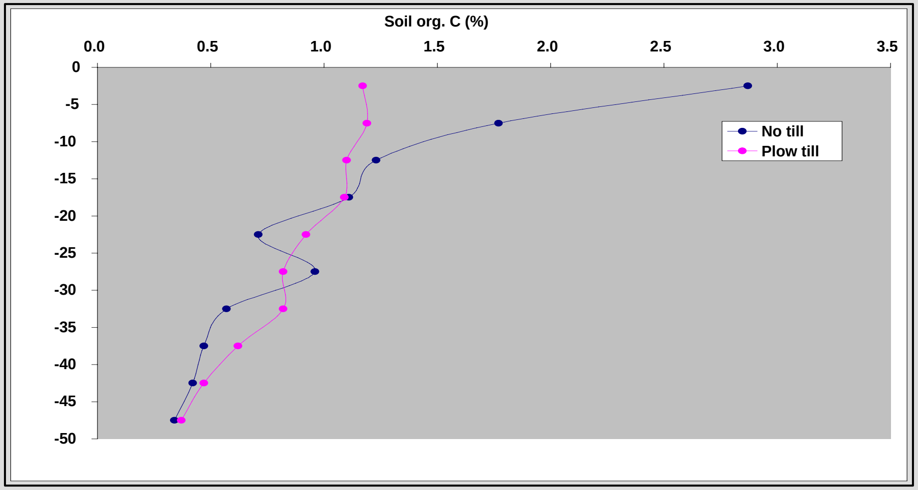
"Tillage and soil carbon sequestration, what do we really know?"

Baker et al. (2006)

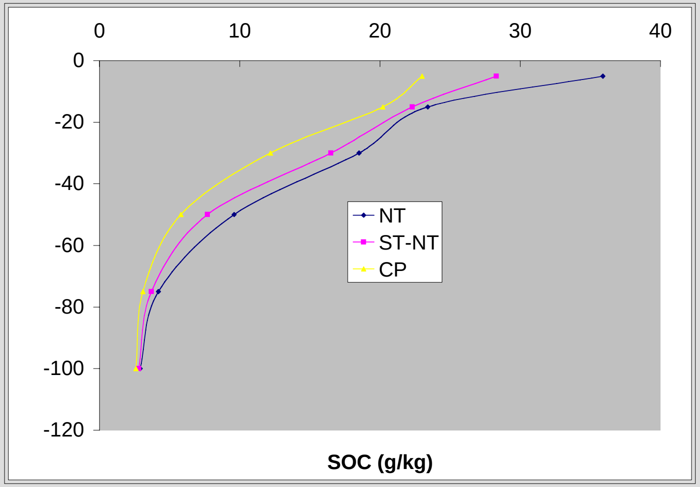
- Baker et al. (2006) argue that
  - No-till may not lead to soil C sequestration
  - Results showing no-till advantage due to sampling bias (too shallow depth of sampling)



Puget et al. (2005)



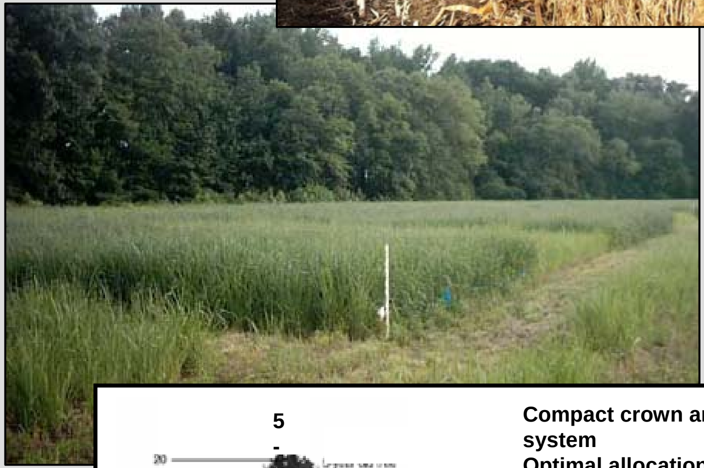
Juo and Lal (1979)

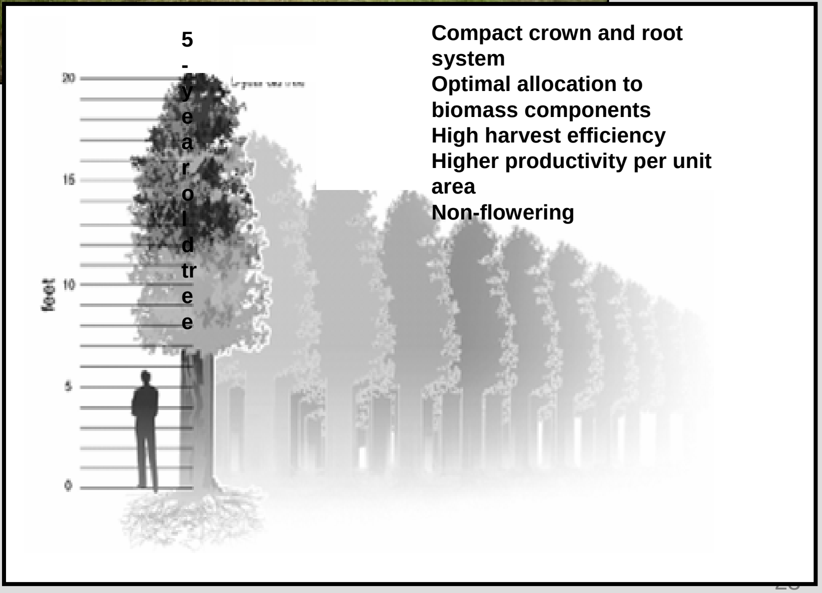


Omonode et al. (2006)

Biomass Energy Crops

- Plant biomass can be used to produce liquid fuels, electricity, and heat
  - Agricultural crops (grain and residues)
  - Forest residues
  - Municipal solid wastes
- New traits for biomass energy crops
  - Attributes
    - Native, perennial, fast growing, pest resistant, non-agronomic
  - Examples
    - Switchgrass
    - Poplar
- Research needs
  - Determine effects of bioenergy crops on energy production and the C cycle
  - Examine their role on land use and competition with food and fiber crops
  - Evaluate impacts on managed and unmanaged ecosystems
- CSiTE program currently conducting research on herbaceous biomass crops (switchgrass) and soil C sequestration





Biochar: The Application of an Ancient Practice to Sequester Carbon and Improve Soils

- Creation of dark earths through application of charred materials by Amazon Basin natives
  - 250 Mg C ha^{-1} vs. 100 Mg C ha^{-1}
- Biochar acts as a soil conditioner
  - Enhances plant growth
  - Improves soil physical and biological properties (over un-charred organic matter)
- Opportunities for biochar soil management systems
  - Shifting cultivation
  - Charcoal production
  - Recycling of agricultural wastes
  - Energy production using bio-fuels
  - Cropping for biochar using fast-growing trees

'Normal' soil

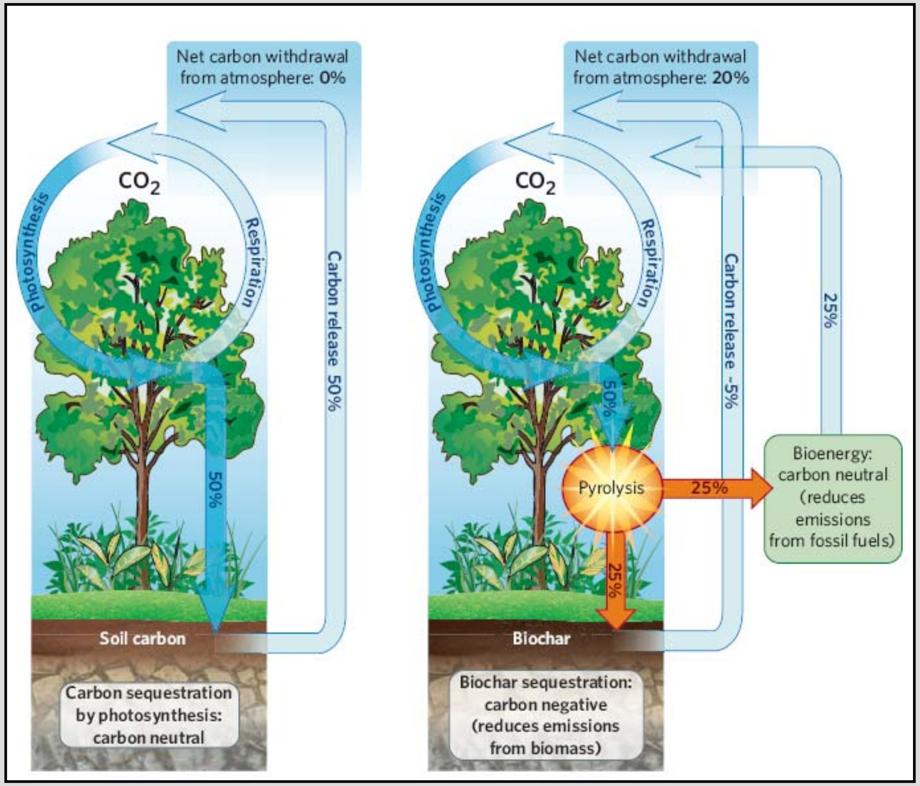
Terra Preta

Lehmann et al. (2006)

"The million-dollar question: can biochar sequestration and the associated bioenergy production make a real difference to national and global C budgets?"

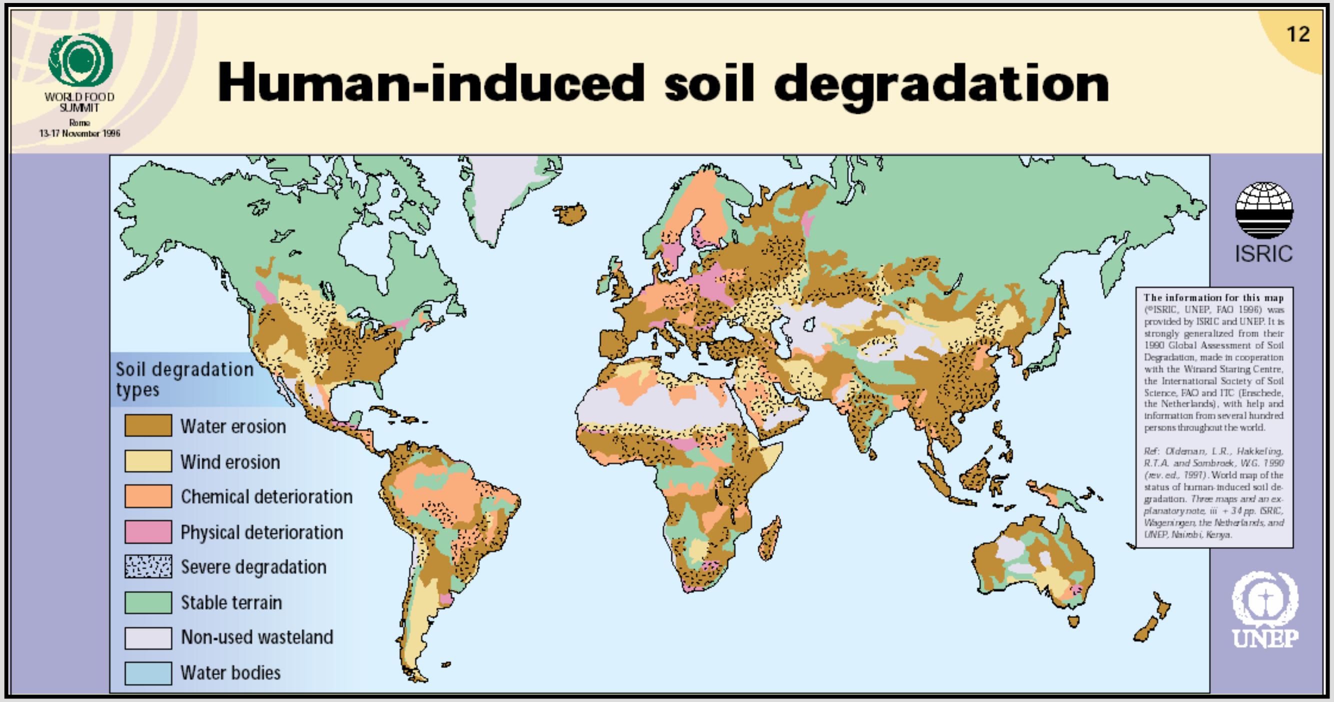
Lehmann (2007) Nature 447:143-144

- Biochar approaches could sequester about 10% of US national emissions (160 Tg C yr^{-1})
  - Pyrolysis of forest residues (3.5 Mg DM ha^{-1} yr^{-1} over 200 Mha)
  - Pyrolysis of fast-growing vegetation (20 Mg DM ha^{-1} yr^{-1} over 30 Mha)
  - Pyrolysis of crop residues (5.5 Mg DM ha^{-1} yr^{-1} over 120 Mha)
- Biochar sequestration in conjunction with bioenergy from pyrolysis, an attractive technology at $37 per Mg of CO_2
- Relatively easy to monitor
- Environmental benefits



Impacts of land use change and management on soil and environmental quality

- Land use and land use change have affected
  - Soil and environmental quality
  - Terrestrial carbon stocks
- Preservation of land and water quality is essential to address climate change



KBS Long-Term Ecological Research (LTER) Site

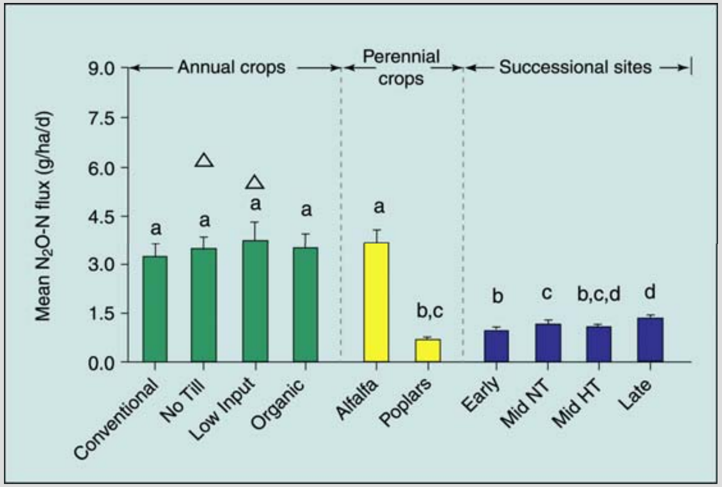
Robertson et al. Science 289:1922-1925 (2000)

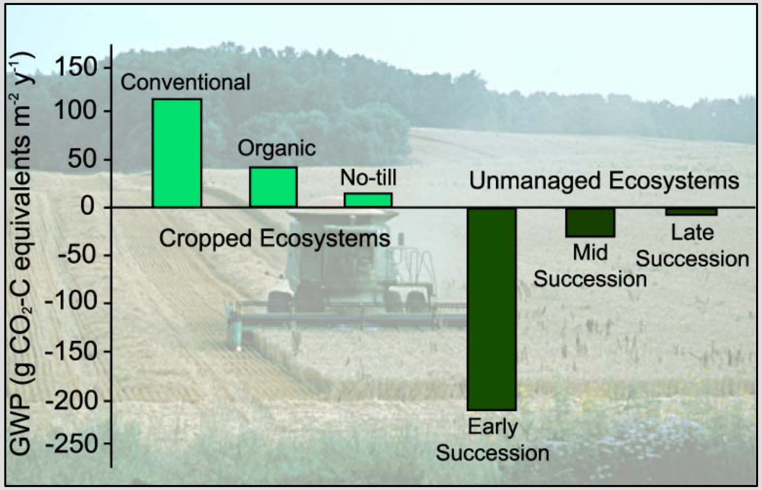
Ecosystem Type	Management Intensity
Annual Crops (Corn - Soybean - Wheat)	
Conventional tillage	High
No-till	↓
Low-input with legume cover	↓
Organic with legume cover	↓
Perennial Crops	↓
Alfalfa	↓
Poplar trees	↓
Successional Communities	↓
Early successional old field	↓
Mid successional old field	↓
Late successional forest	Low

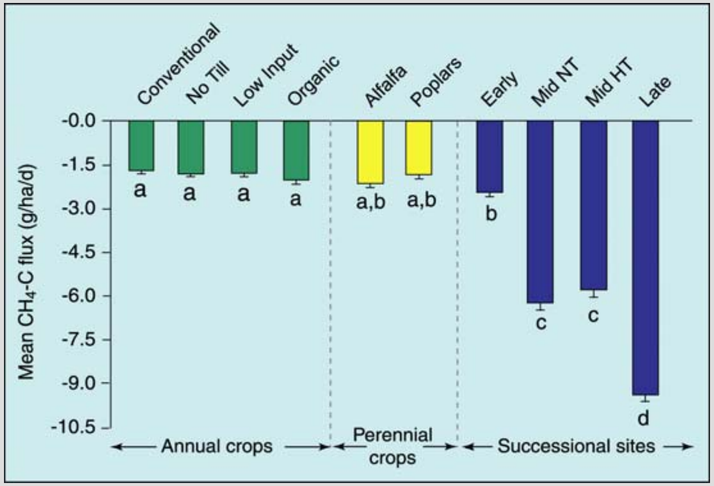
Full Carbon Accounting in Agroecosystems

Robertson et al. Science 289:1922-1925 (2000)

1. Soil C Oxidation
2. Fuel
3. Nitrogen Fertilizer
4. Lime ($CaCO_3$) and Ca in Irrigation Water
5. Non-CO_2 Greenhouse Gases
   - N_2O
   - CH_4

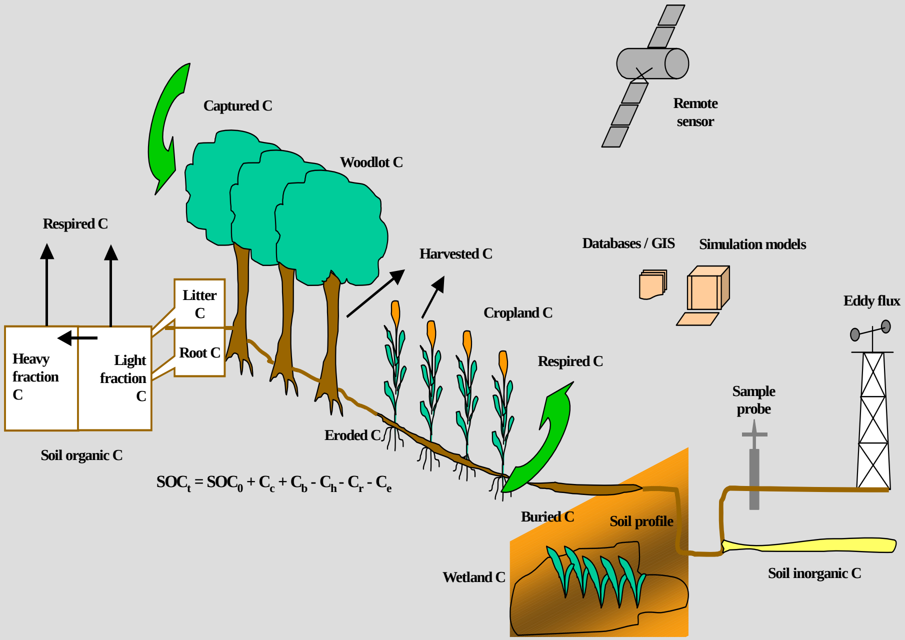






Detecting and up scaling changes in soil carbon

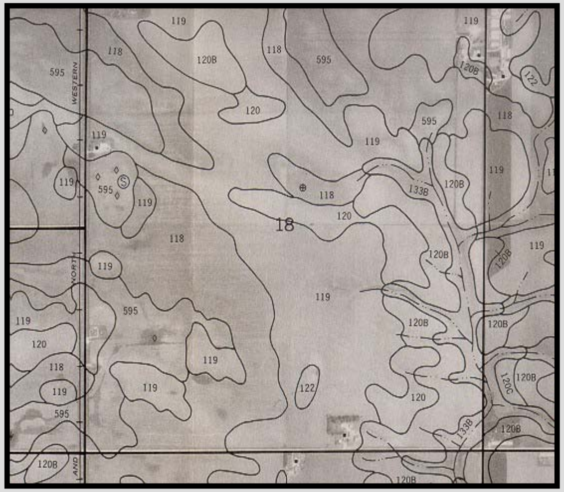
- Detecting soil C changes
  - Difficult on short time scales
  - Amount changing small compared to total C
- Methods for detecting and projecting soil C changes (Post et al. 2001)
  - Direct methods
    - Field and laboratory measurements
    - Eddy covariance
  - Indirect methods
    - Accounting
      - Stratified accounting
      - Remote sensing
      - Models



Post et al. (2001)

Measuring and monitoring soil C sequestration: a new challenge?

Long term experiments have been essential tools to understand the temporal dynamics of soil C



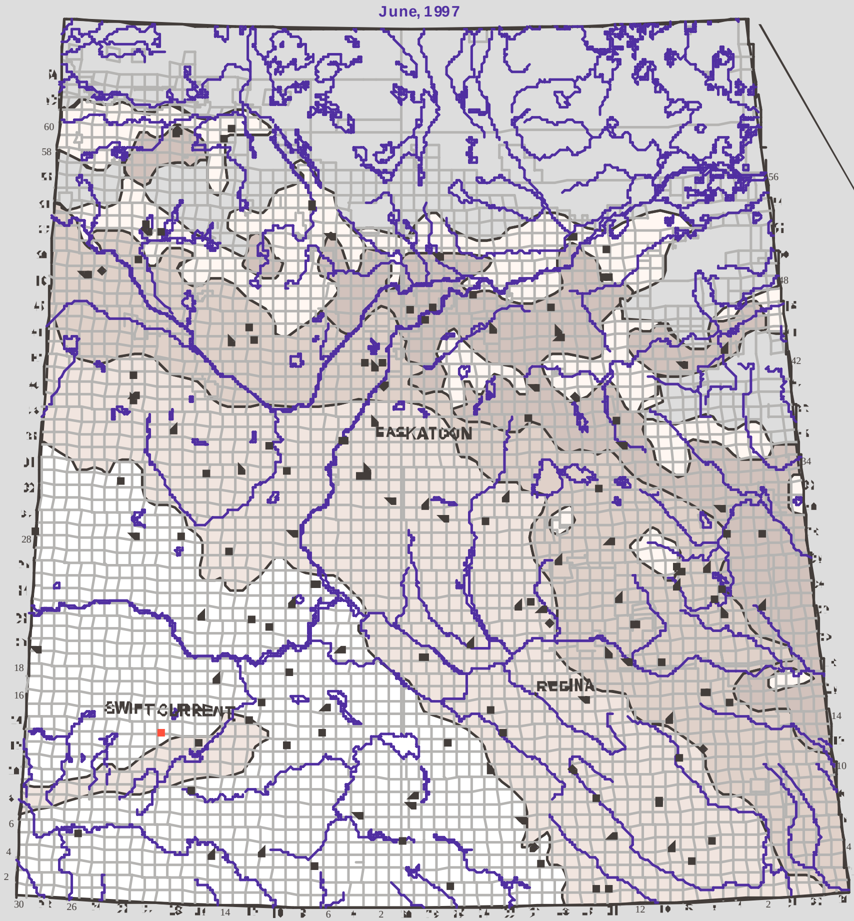
Soil survey maps can be used to estimate the spatial distribution of soil organic C stocks

The challenge consists in developing cost-effective methods for detecting changes in soil organic C that occur in fields as a result of changes in management

Detecting soil C changes in a 3-yr period

Saskatchewan

Verification Sites

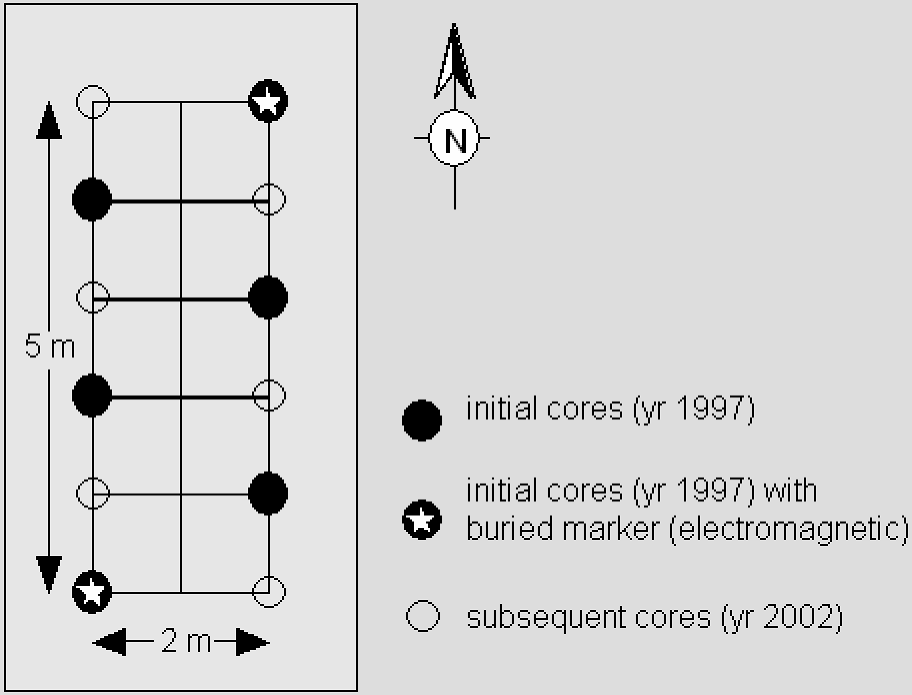


CANADA

McConkey et al. (2001)

Sampling protocol used in the Prairie Soil Carbon Balance (PSCB) project

- Use “microsites” (4 x 7 m) to reduce spatial variability
- Three to six microsites per field
- Calculate SOC storage on an equivalent mass basis
- Analyze samples taken at different times together
- Soil C changes detected in 3 yr
  - 0.71 Mg C ha^{-1} – semiarid
  - 1.25 Mg C ha^{-1} – subhumid



Ellert et al. (2001)

McConkey et al. (2001)

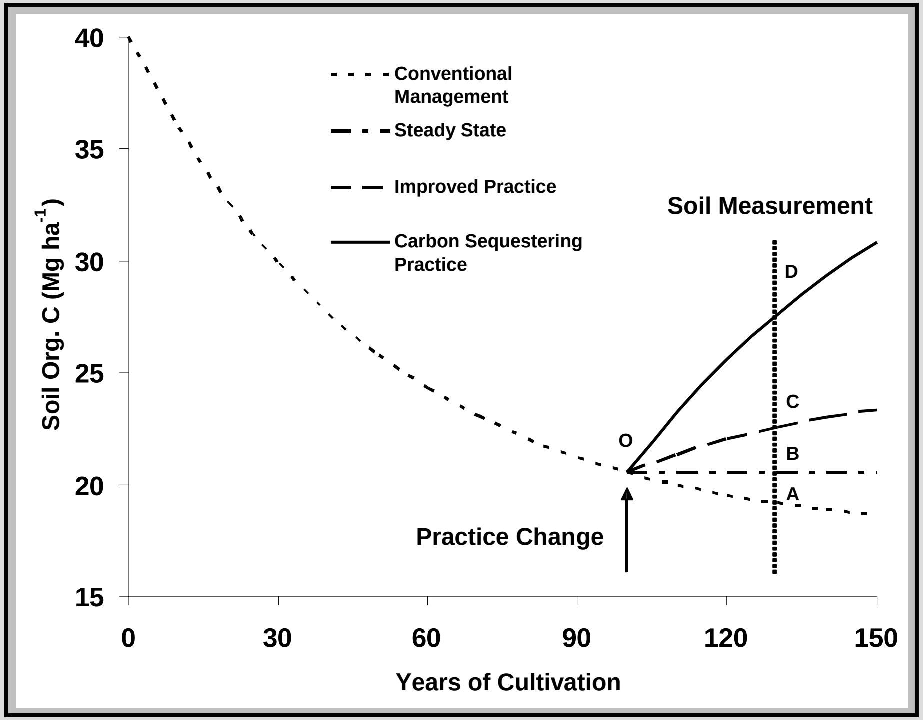
Examples of Feasibility and Pilot Projects on Soil Carbon Sequestration

Region	Land Use	Land management change
Saskatchewan, Canada	Cropland	Direct seeding / cropping intensification
Pacific Northwest, USA	Cropland	Direct seeding / cropping intensification
Oaxaca, Mexico	Crop / natural fallow secondary forest	Fruit tree intercrops with annual crops / Conservation tillage
Pampas, Argentina	Cropland	Direct seeding
Senegal	Agroforestry	Nutrient management, N fixation agroforestry
Mali	Agroforestry	Tree conservation / Ridge tillage
Kazakhstan	Cropland	Agriculture to grassland

Izaurralde (2005)

Detecting soil C changes

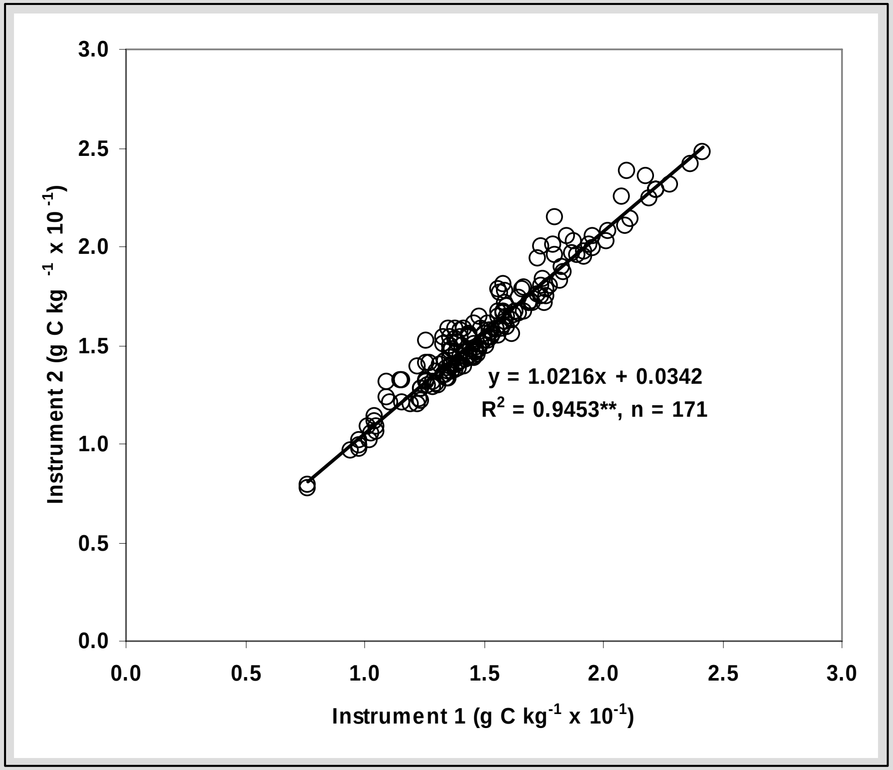
- Soil C changes are usually small (0.1 – 0.5 kg C m^{-2}) compared to soil C stocks (2 – 8 kg C m^{-2})
- Four cases
  - Conventional management
  - Steady state
  - Improved practice
  - Carbon sequestering practice



Izaurralde and Rice (2006)

Determination of Soil C: Standard and Advanced Methods

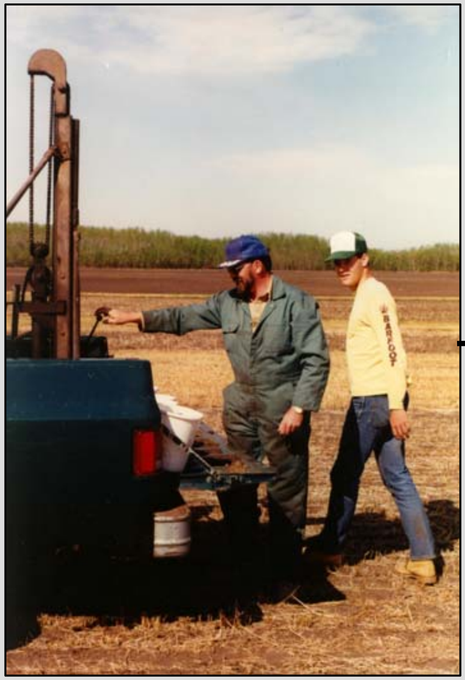
- Standard laboratory methods
  - Wet Combustion
  - Dry Combustion
- Advanced instrumentation for field measurement
  - Laser Induced Breakdown Spectroscopy (LIBS)
  - Near Infrared / Mid Infrared Spectroscopy (NIRS / MIRS)
  - Inelastic Neutron Scattering
- Research and technology needs
  - National and international efforts needed to cross-calibrate methods against standard (soil) samples
  - Compare methods under field conditions



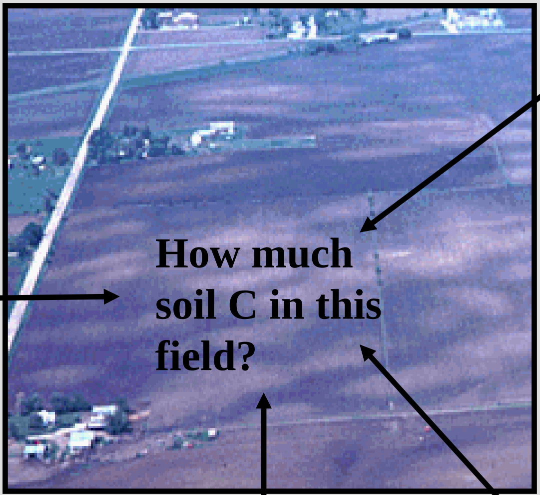
Total soil C as measured by two dry combustion instruments

Izaurralde (2005)

How can soil C be accurately be measured at the field scale?
How do emerging technologies compare against standard methods?



Standard methods:
Soil sampling; wet / dry combustion



Mid / Near Infrared Spectroscopy (MIR / NIR)

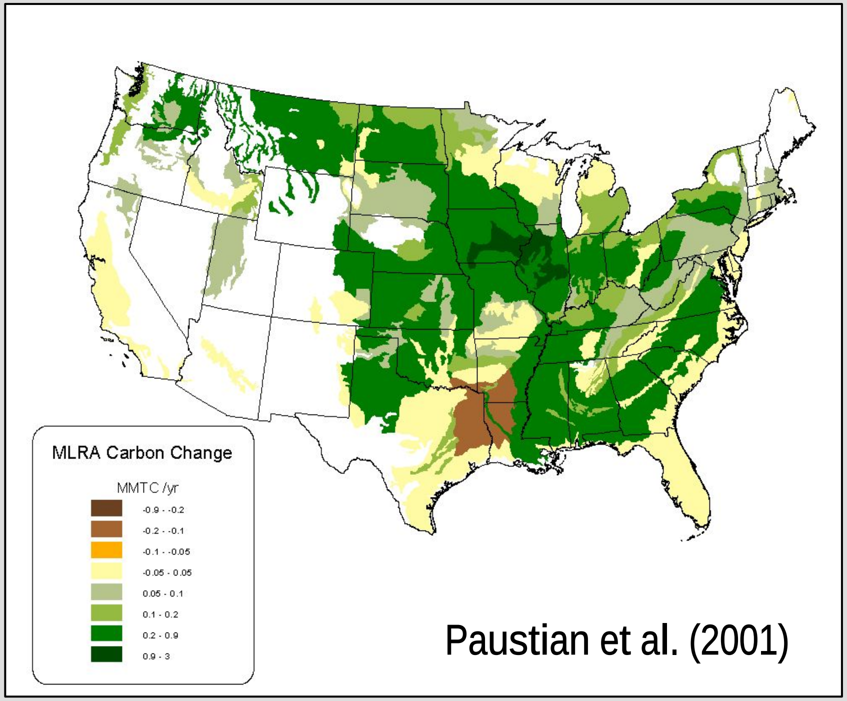
Inelastic Neutron Scattering (INS)

Laser Induced Breakdown Spectroscopy (LIBS)

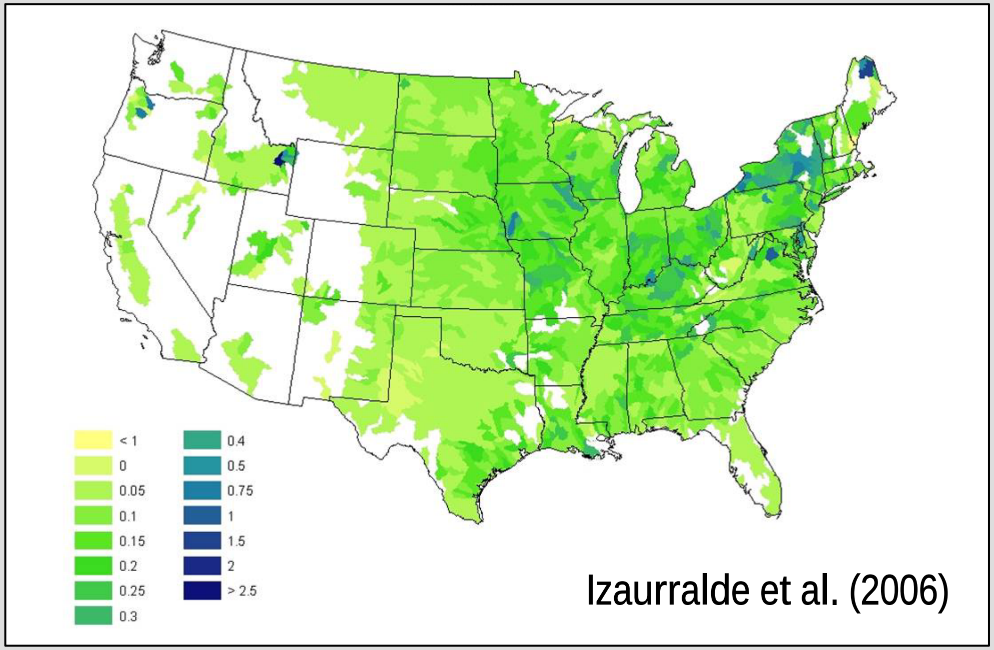
USAID
FROM THE AMERICAN PEOPLE

Estimates of US Terrestrial C Sinks

- Pacala et al. (2001), Hurtt et al. (2002)
  - Pacala et al. (2001) estimated that U.S. lands absorbed C at rates of 0.37-0.71 Pg yr^{-1} during the 1980s
  - Hurtt et al. (2002) projected a decrease of the U.S. C sink during this century but the degree of this reduction will depend on future land use and fire suppression
- Lal, Kimble, Follett & Cole (1998)
  - US potential rate of agricultural lands C sequestration: 0.080 - 0.200 Pg C yr^{-1}
- Paustian et al. (2001)
  - IPCC methodology: 0.020 Pg C yr^{-1} on 168 Mha
  - Century modeling: 0.021 Pg C yr^{-1} on 149 Mha
- Izaurralde et al. (2006)
  - EPIC modeling: 0.015 – 0.018 Pg C yr^{-1} depending on climate change scenario



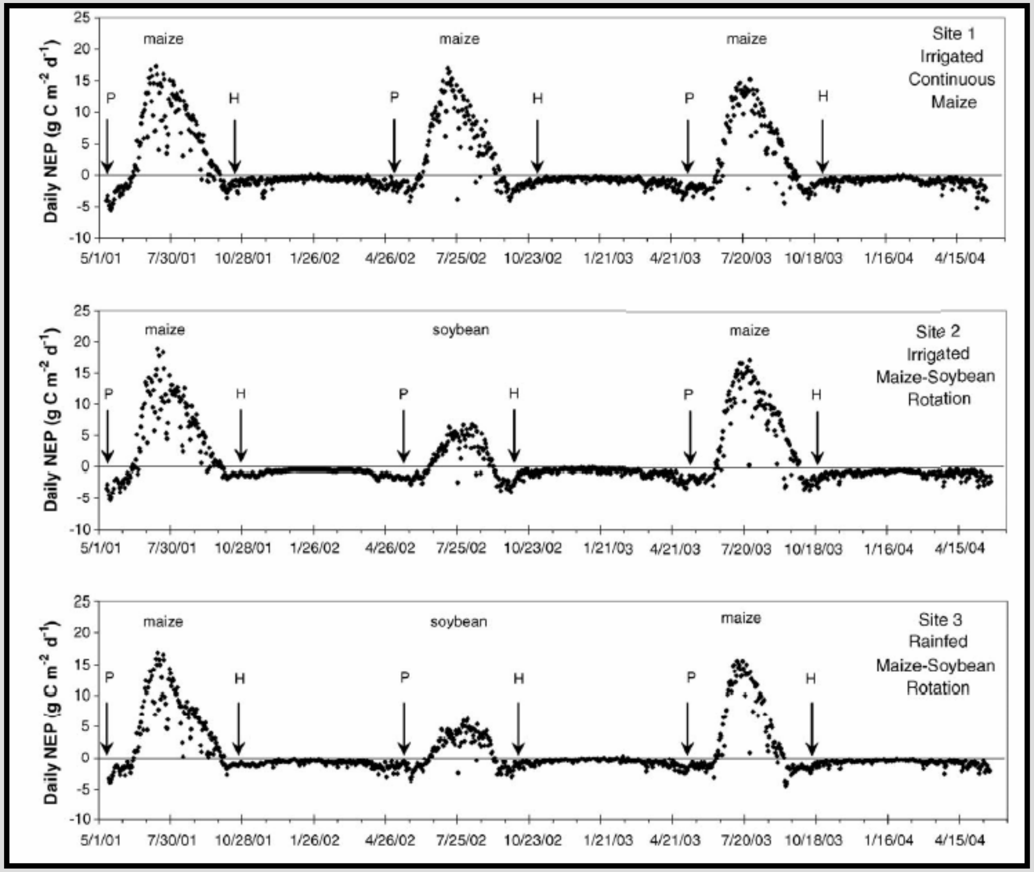
Paustian et al. (2001)



Izaurralde et al. (2006)

Measuring CO_2 exchange at field scale with tower eddy covariance

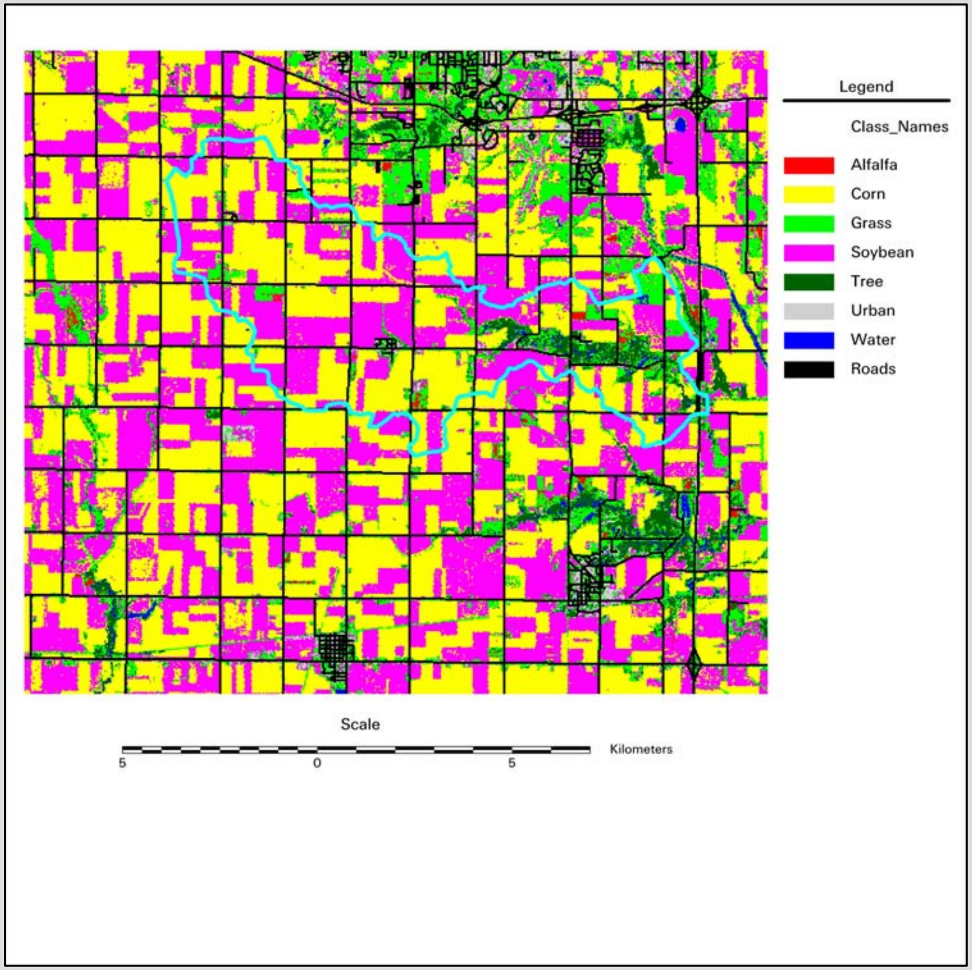
- Three sites under no tillage
- Net Ecosystem Production: maize >> soybeans
- During the first 3 years
  - Rainfed maize-soybean was C neutral
  - Irrigated cont. maize was nearly C neutral
  - Irrigated maize-soybean was a moderate C source
- Direct measurements of soil C did not detect significant differences



Verma et al. 2005. AMF 131:77-96.

Remote Sensing and Carbon Sequestration

- Remote sensing useful for assessing
  - Vegetation
    - Type
    - Cover
    - Productivity
  - Water, soil temperature
  - Tillage intensity?
- Remote sensing cannot be used to measure soil C directly unless soil is bare
- Several satellite and airborne sensors useful for LAI, NPP, crop yields, and soil cover
  - AVHRR, MODIS
  - Landsat, SPOT
  - IKONOS, Quickbird
  - AVIRIS, LIDAR



Crop identification for spatial modeling. Courtesy: P Doraiswamy, USDA-ARS, Beltsville, MD

…from IPCC WG III, 4th Assessment Report

- "Agricultural practices collectively can make a significant contribution at low cost to increasing soil carbon sinks, to GHG emission reductions, and by contributing biomass feedstocks for energy use (*medium agreement*, *medium evidence*)
  - A large proportion of the mitigation potential of agriculture (excluding bioenergy) arises from soil carbon sequestration, which has strong synergies with sustainable agriculture and generally reduces vulnerability to climate change
  - Stored soil carbon may be vulnerable to loss through both land management change and climate change
  - Considerable mitigation potential is also available from reductions in methane and nitrous oxide emissions in some agricultural systems
  - There is no universally applicable list of mitigation practices; practices need to be evaluated for individual agricultural systems and settings
  - Biomass from agricultural residues and dedicated energy crops can be an important bioenergy feedstock, but its contribution to mitigation depends on demand for bioenergy from transport and energy supply, on water availability, and on requirements of land for food and fibre production. Widespread use of agricultural land for biomass production for energy may compete with other land uses and can have positive and negative environmental impacts and implications for food security"

Summary

- Significant progress in understanding soil C sequestration in terms of
  - Mechanisms
  - Comparative advantages with regards to other mitigation technologies
- Research and Technology Needs
  - Incorporate new concepts of measurable soil C pools into models
  - Investigate the roles of bioenergy crops and biochar in relation to soil C sequestration
  - Develop / adapt comparable methodologies to measure soil C changes across spatial and temporal scales in developed and developing countries
  - Develop comprehensive view of soil C sequestration (value, permanence, capacity, accounting, ecosystem health)
- Conduct Outreach Activities