Terrestrial Ecosystems:
Carbon Sequestration Technology Options

Gary K. Jacobs*

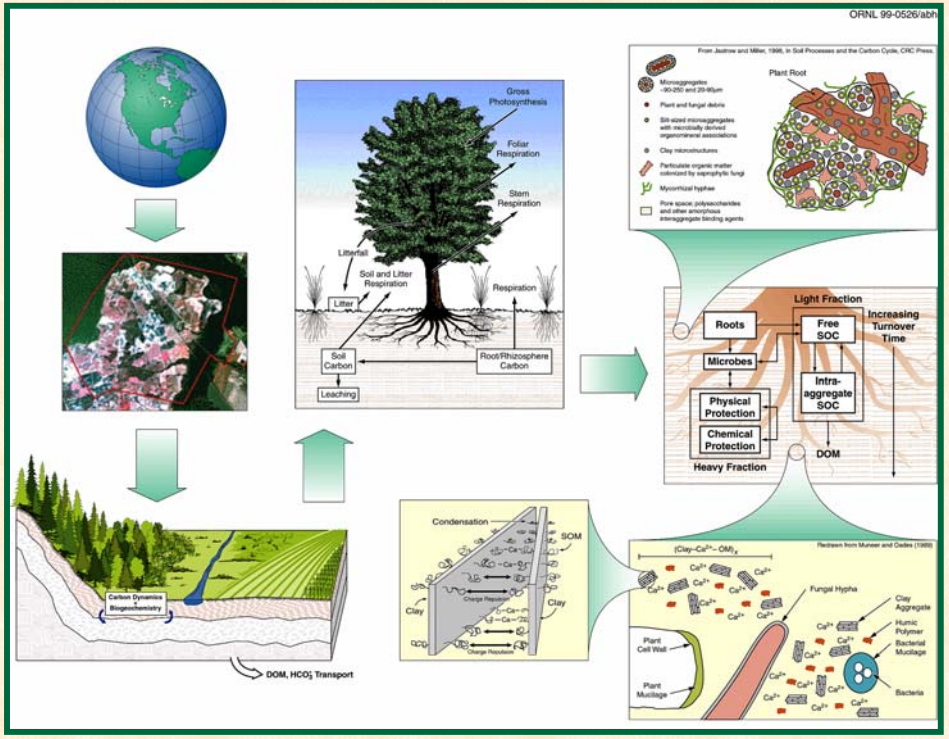
***With acknowledgements and apologies to many**

DOE Consortium for Research on ***Enhancing***
Carbon
Sequestration
in
Terrestrial
Ecosystems

Environmental Sciences Division
Oak Ridge National Laboratory
U.S. Department of Energy

What is sequestration in terrestrial ecosystems?

- **Protect, recover, and manage existing resources**
- **Via direct intervention, *enhance*:**
  - **Net primary productivity**
  - **Partitioning to long-lived pools**
  - **Longevity of pools**

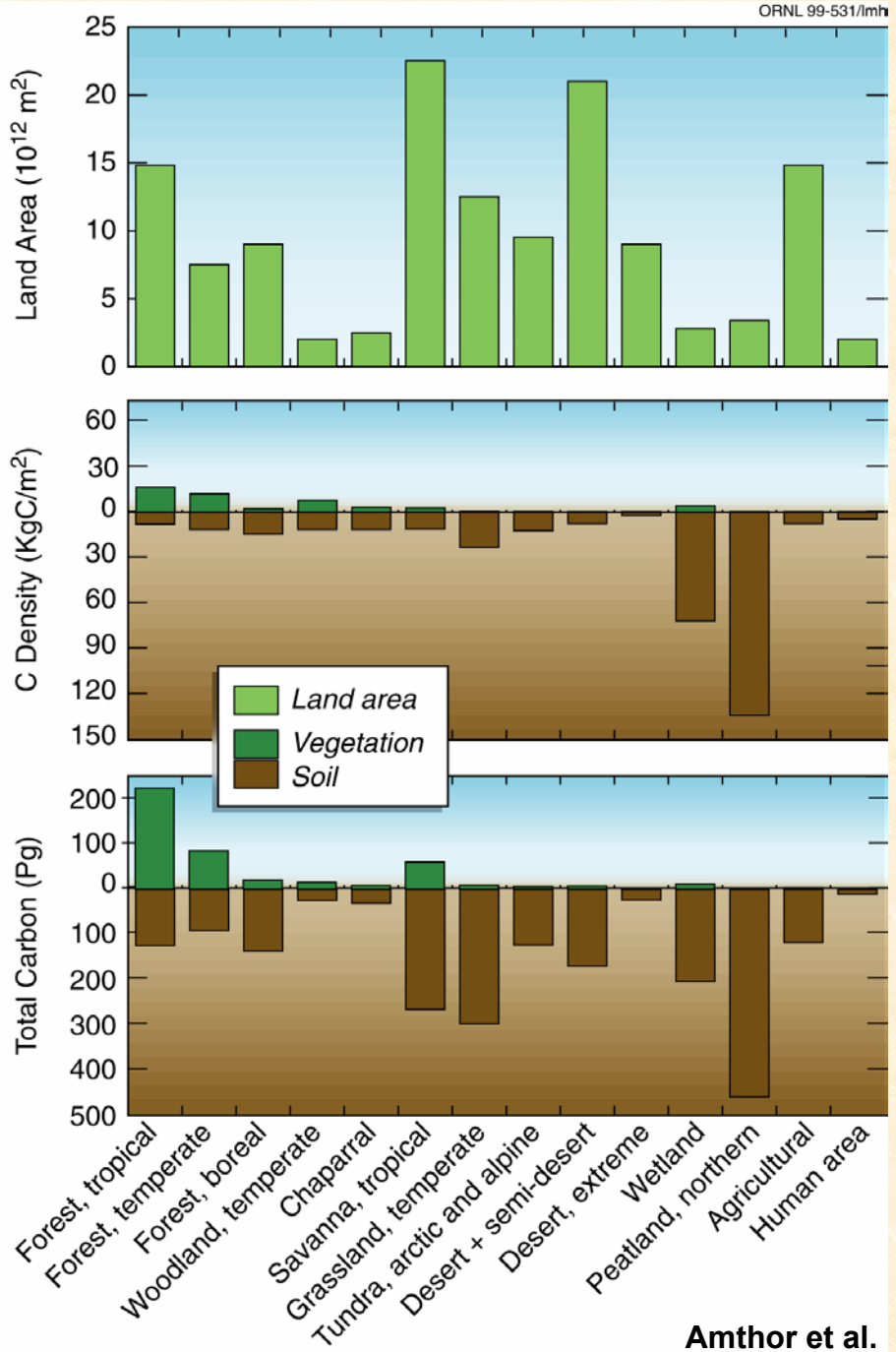


Terrestrial ecosystems will not be able to keep up with with fossil fuel emissions, but offer significant opportunities to "buy time" and provide other benefits

How can we shift the rate and capacity of carbon storage?

Current Rates	Gt C/y
Terrestrial Uptake	+2.0
Land Use Change	-1.5
Net	+0.5

If we can shift them, then what are the implications?

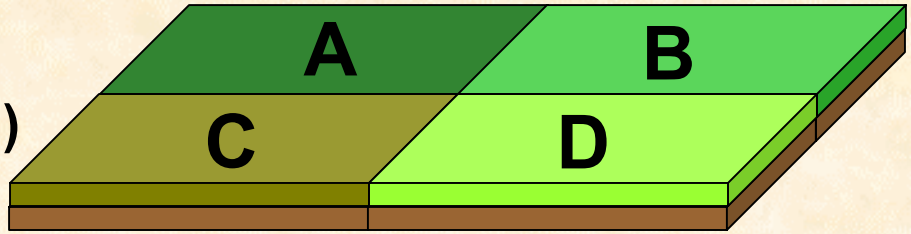


Amthor et al.

How would you enhance the potential?

Must consider finite resources and trade-offs

- Increase Net Primary Productivity
  - Biomass pool size
  - Inputs to litter & soil
    - Fertilize, irrigate, switch species
  - Turnover rates are important
- Partition C into long-lived pools
  - Long-lived biomass (wood)
  - Protected soil organic C (SOC)
  - Recalcitrant SOC



- Alter longevity of C pools
  - Convert grass-to-wood
  - Reduce soil disturbance, alter litter quality, modify soil metabolic processes
  - Create long-lived products

Global potential – What is it?

We know it is uncertain

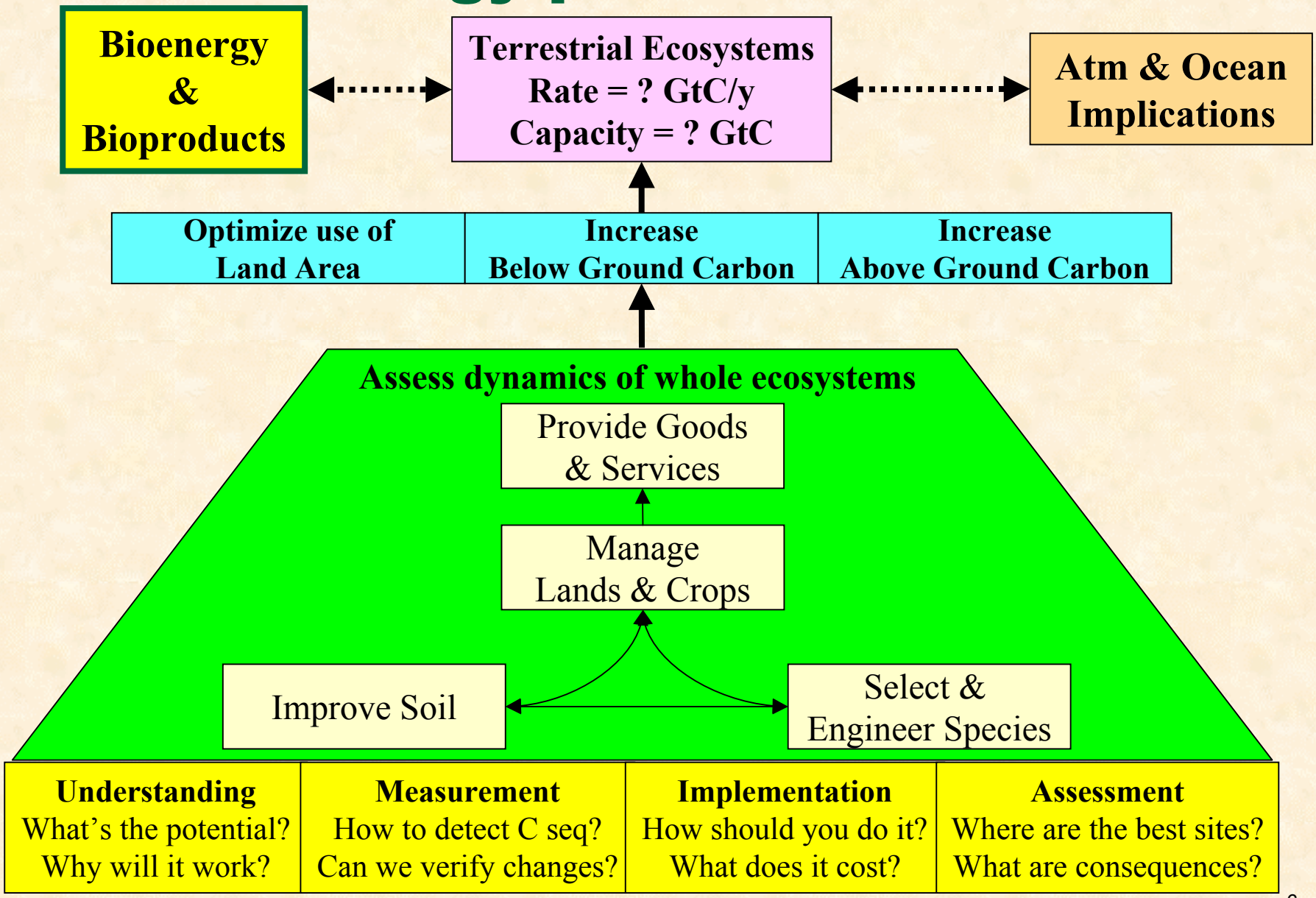
- **Right now, for several decades (10 – 50 years)?**
  - **Maintain current rates** **2** **Gt C/y**
  - **Slow land use change** **1** **Gt C/y**
  - **Reverse land use change:**

What is the integrated impact on Earth's climate system?

TOTAL **? 6 ?** **Gt C/y**

- **Total of 50 to 250 Gt C over several decades is significant**
- **Challenges**
  - **Implementation of near-term options to buy some time**
  - **Uncertain capacity – can we increase rate and capacity?**
  - **Net carbon (GHG) accounting**
  - **Environmental consequences uncertain**
  - **Future behavior of ecosystems**

The technology platform (US DOE/SC/FE/1)



Select & Engineer Species:

Genes Control Carbon for *Fuel, Power, Products, Sequestration)*

ORNL 2001-00404/abh

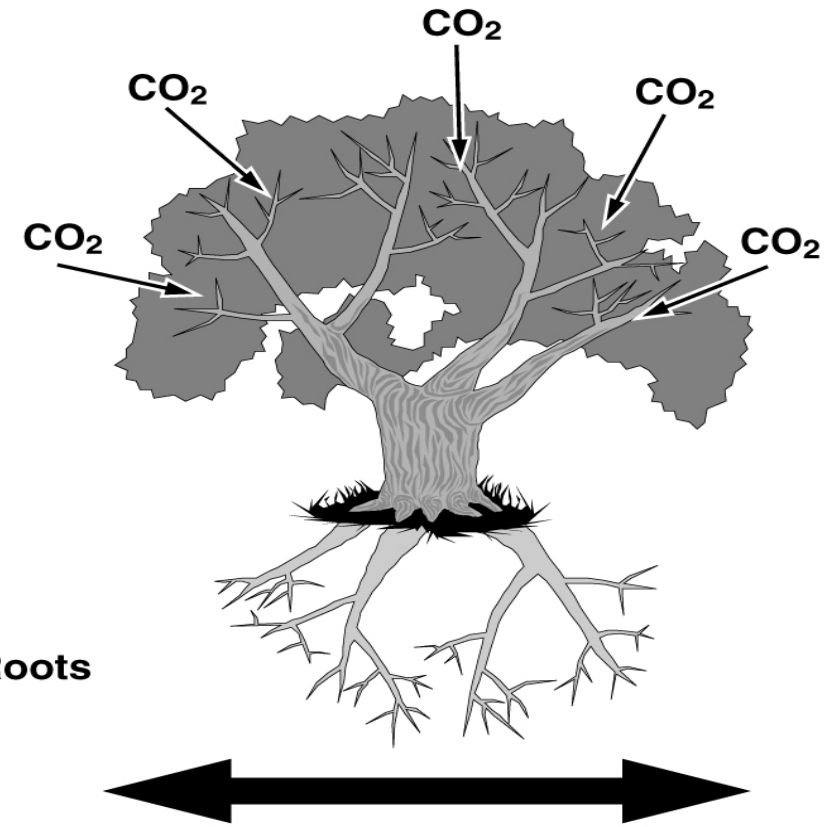
Above Ground

Leaves
Branches
Stem

Carbon Allocation Genes

Below Ground

Tap Root
Structural Roots
Fine Roots



Above Ground

30% Lignin
20% Hemicellulose
40% Cellulose

Carbon Partitioning Genes

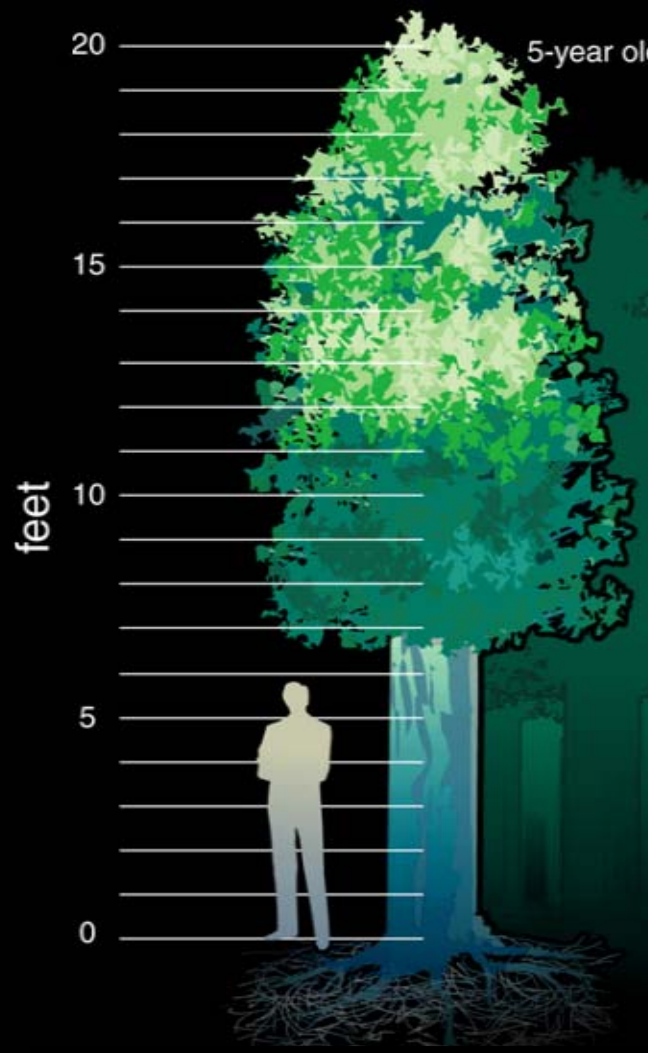
Below Ground

?% Lignin
?% Hemicellulose
?% Cellulos

Populus Genomics

- DOE's Office of Science is having *Populus* sequenced at the Joint Genome Institute
- Important for energy and ecosystem R&D
  - Competition
  - C Allocation
  - Wood chemistry
  - Environmental adaptation

http://www.jgi.doe.gov



Greater carbon allocation to stem

Less extensive root system

No response to competition

Reduced height growth

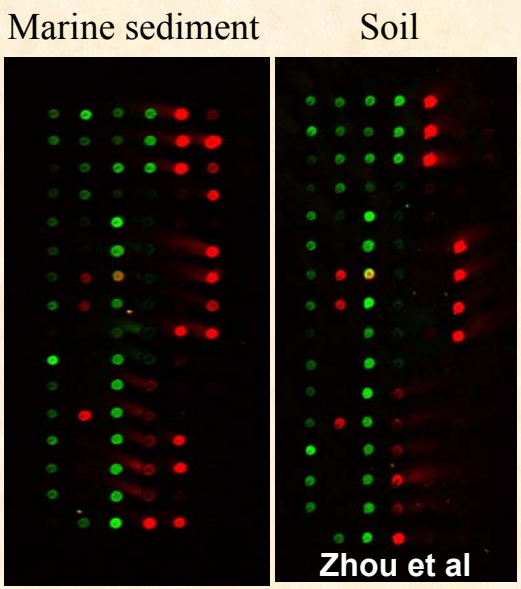
Improved wood chemistry

Pest resistance

Graham and others

Microbial Genomics

- **Understand C & N cycles**
  - **Shift community structure to promote sequestration functions**

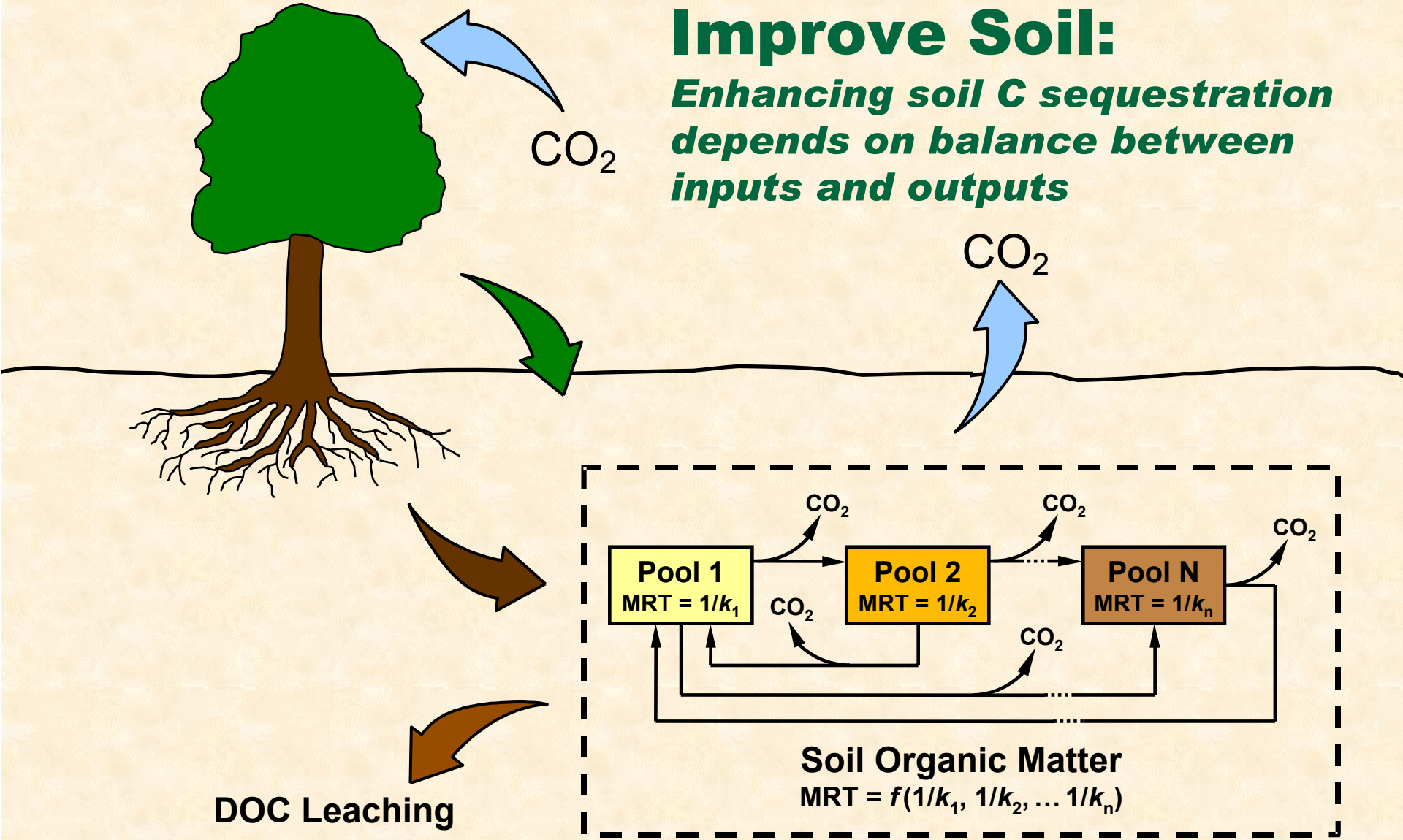


- **Develop complementary plant cell wall chemistries and microbial processing "machines"**

Himmel, Graham, and others

Improve Soil:

Enhancing soil C sequestration depends on balance between inputs and outputs

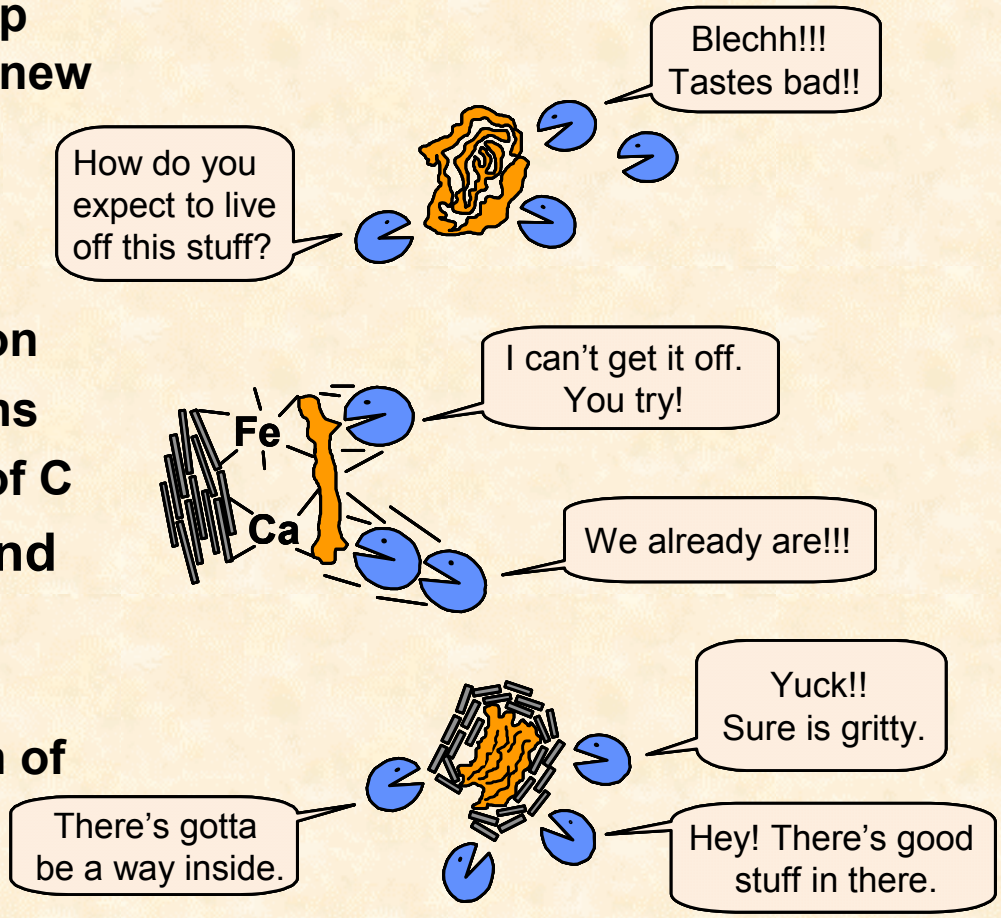


Changes in pool sizes, residence times, and/or fluxes could affect the balance

Jastrow

Mechanisms to stabilize soil organic C

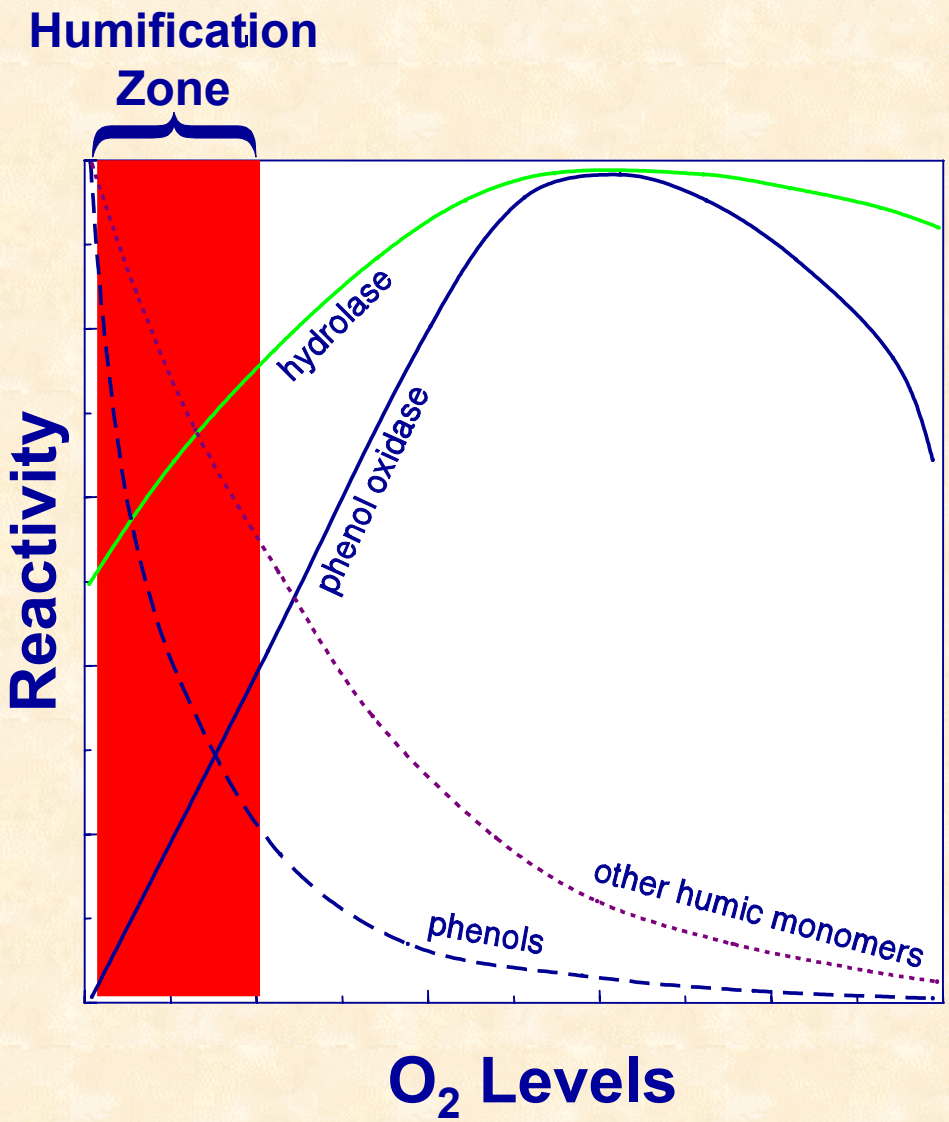
- **Alter root density, depth**
  - **Existing cultivars, redevelop historical ones, or develop new ones**
- **Optimize physicochemical conditions**
  - **Physical/chemical protection**
  - **Humification redox reactions**
  - **Promote deeper transport of C**
- **Shift decomposition rates and products**
  - **Modify chemistry**
  - **Shift structure and function of microbial communities**



Jastrow and Miller

Can we optimize humification?

- Redox conditions
  - Wetting/drying cycles
- Fe/Mn oxide content
  - Fertilization
- Enzyme activities
  - High-phenolic cropping, green manures, fungal/bacterial ratios



Capacity & Longevity of Soil Organic C

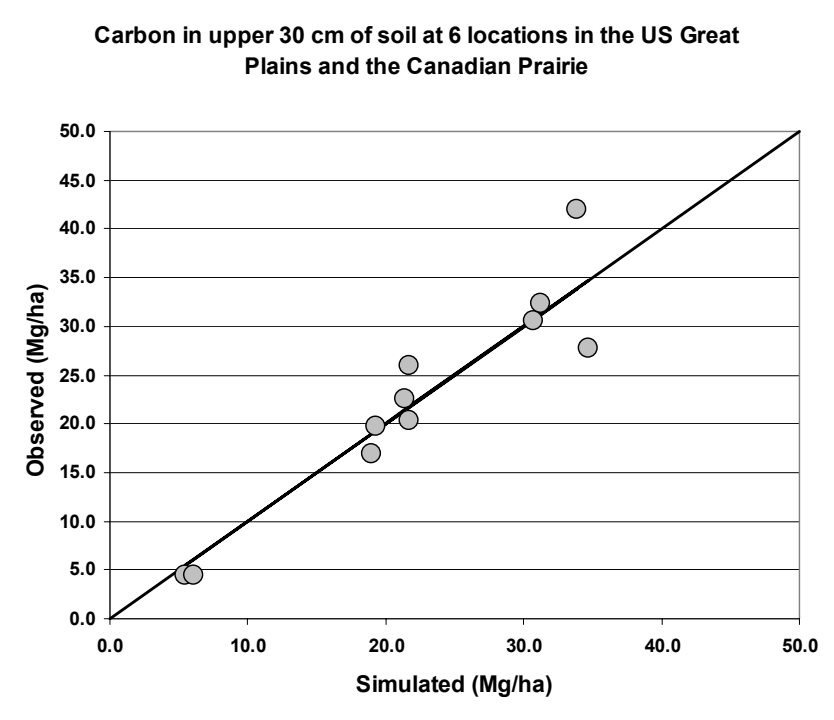
- Deeper subsoils offer attractive target for accumulation and protection of C
  - Common soils with large potential capacity
- Enhance solubilization and vertical transport of active C pool
  - Selective fertilization
- Organic C stabilized by minerals (Fe-oxide coatings)
  - Reduced bioavailability and transport

Anthropogenically enriched | Adjacent nonenriched soil

Jardine

What are the consequences of soil C sequestration strategies?

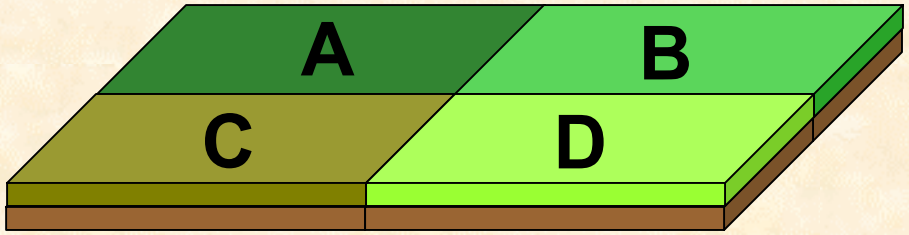
- Comprehensive tools to model C balance and environmental consequences
  - Nutrient availability and productivity
  - Non-CO_2 greenhouse gases
  - Erosion and oxidation of organic C to CO_2
- Simulation improvements (EPIC)
  - C and N cycles
  - Testing against land-use change and cropping systems



Izaurralde et al 2001

Manage lands and crops

- Shift ecosystems
- Consider full GHG accounting
- How long do the products last?
- Economics are important



Restoration of Tallgrass Prairie at Fermilab

- Restoration of native tallgrass prairie began inside the main accelerator ring in 1975
- Annual plantings create a chronosequence of restorations encompassing over 400 hectares, both inside and outside of the ring

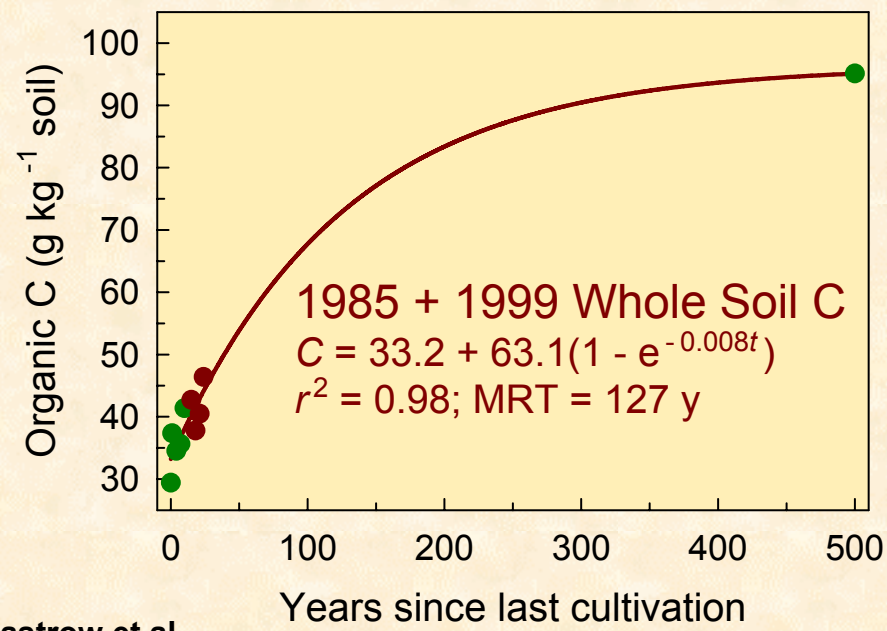
- Tallgrass prairie is dominated by C4 grasses, but also includes a diversity of perennial forbs
- Peak standing crops can be over 1 kg dry wt m^{-2} aboveground and 2 kg dry wt m^{-2} belowground

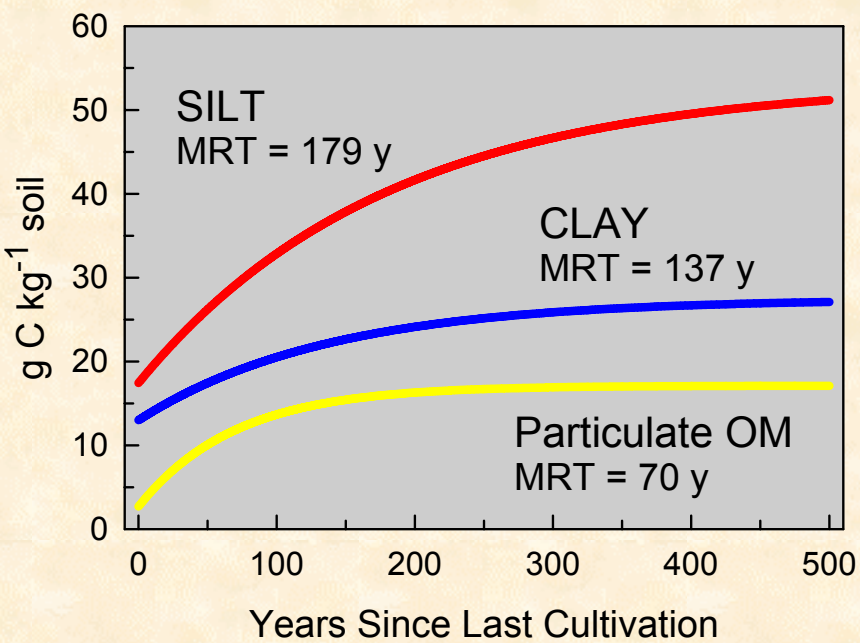
Julie Jastrow

Prairie restoration at FermiLab:

Carbon can accumulate …

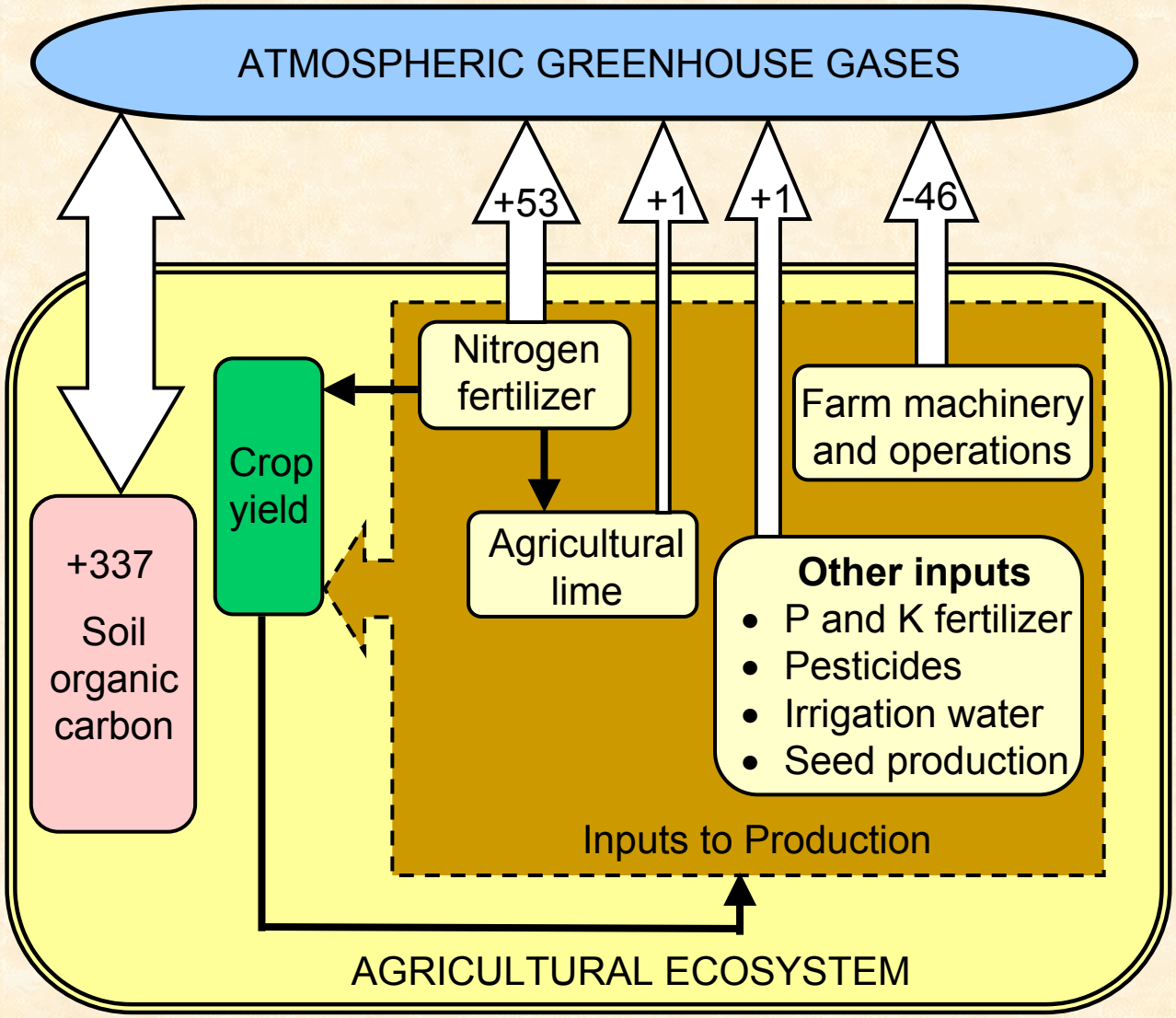
- **Accrual occurs without fertilization**
- **Soil protective capacity not yet exceeded**
  - **C and N accumulating in organomineral fractions (silt and clay) with longer residence times**





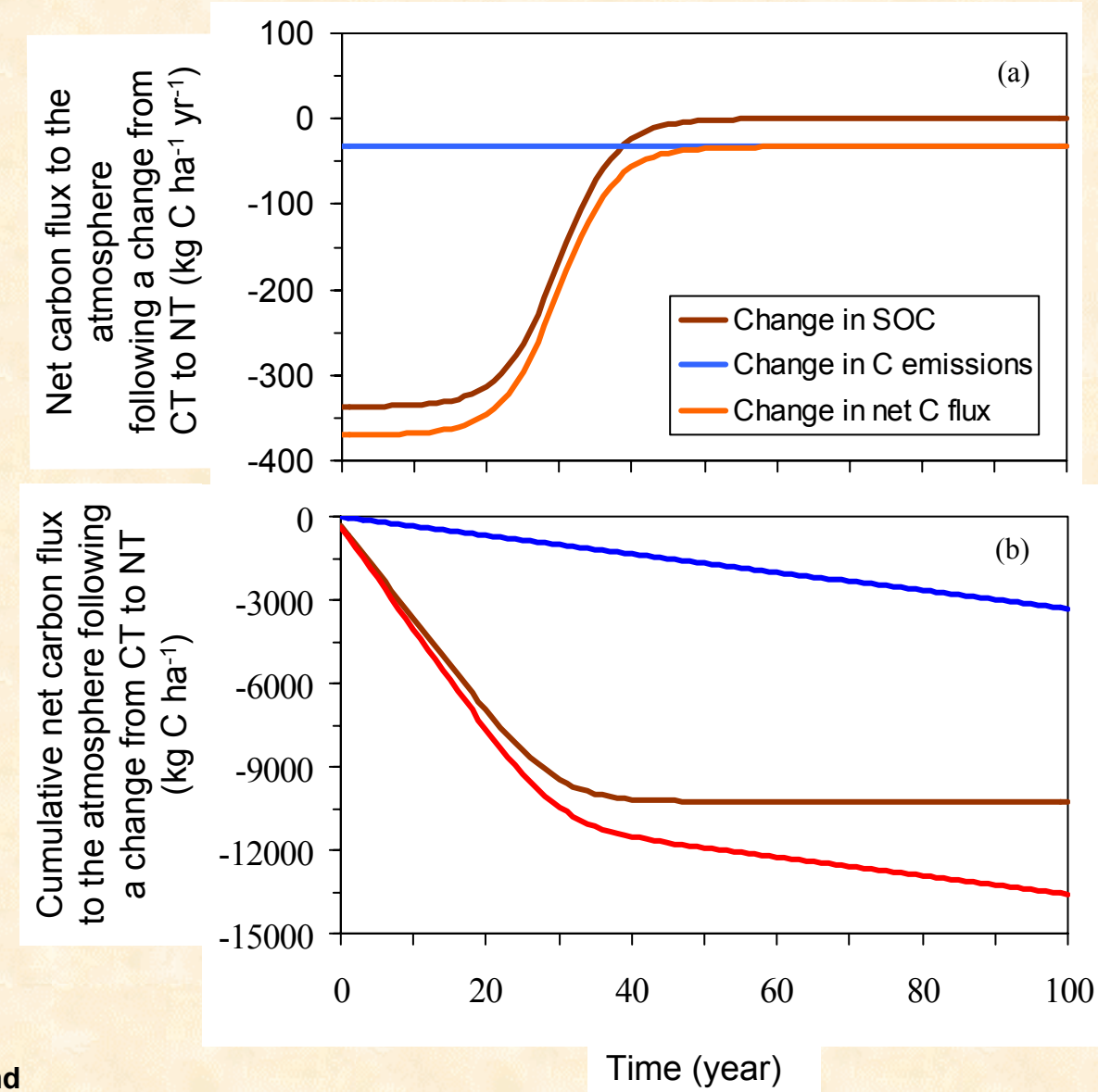
Jastrow et al

Full C (GHG) accounting of shift from conventional- to no-till practices



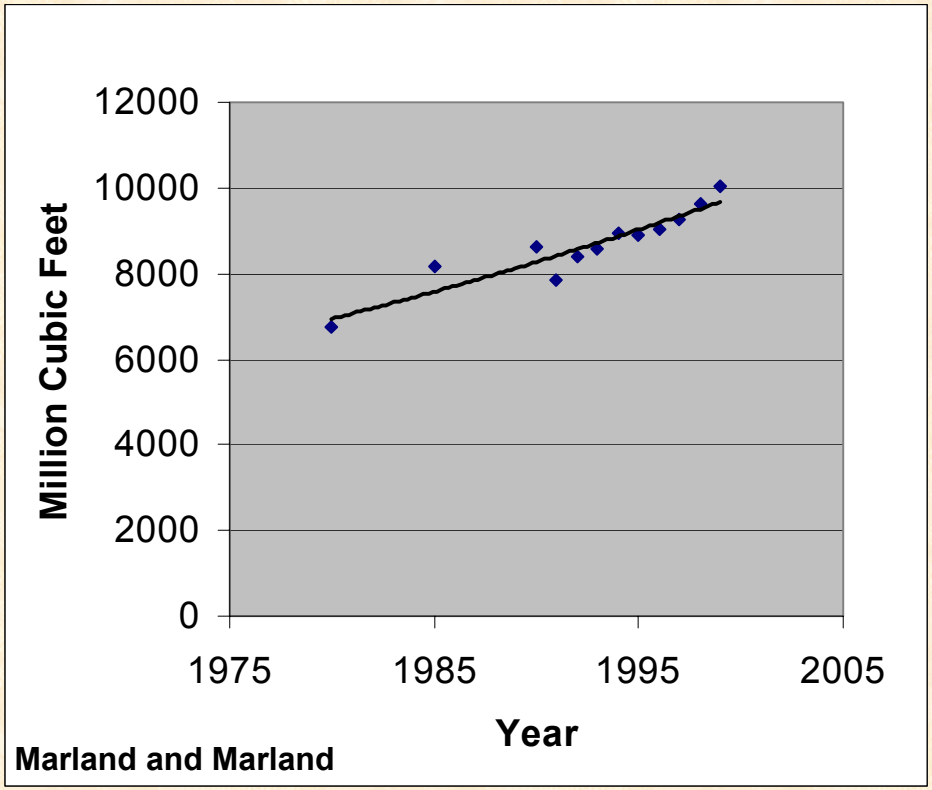
West and Marland

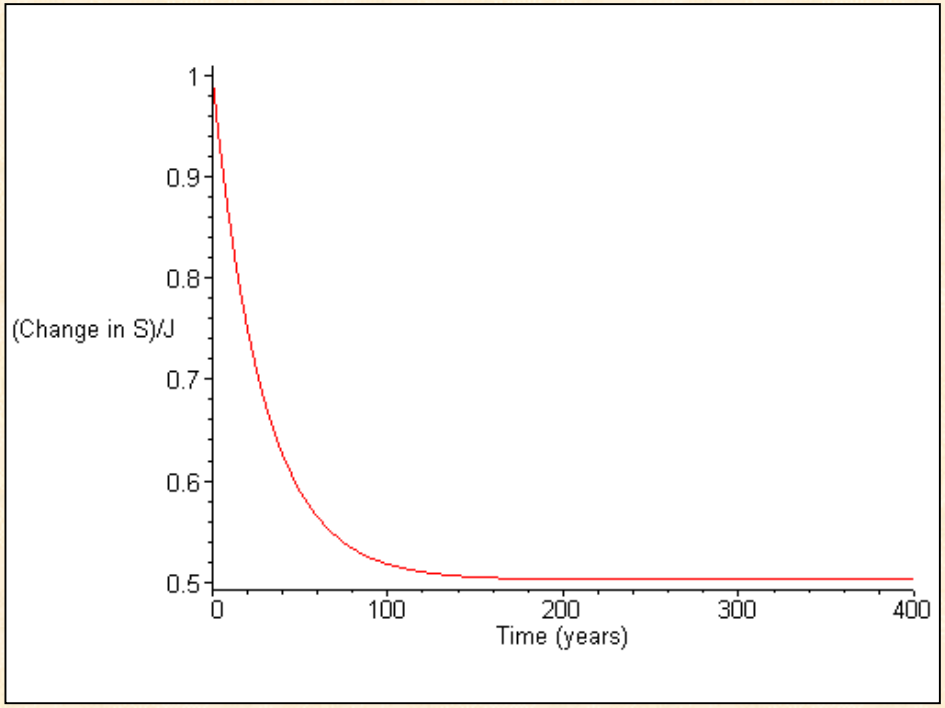
Shifting management practices makes a difference



How long do C products last?

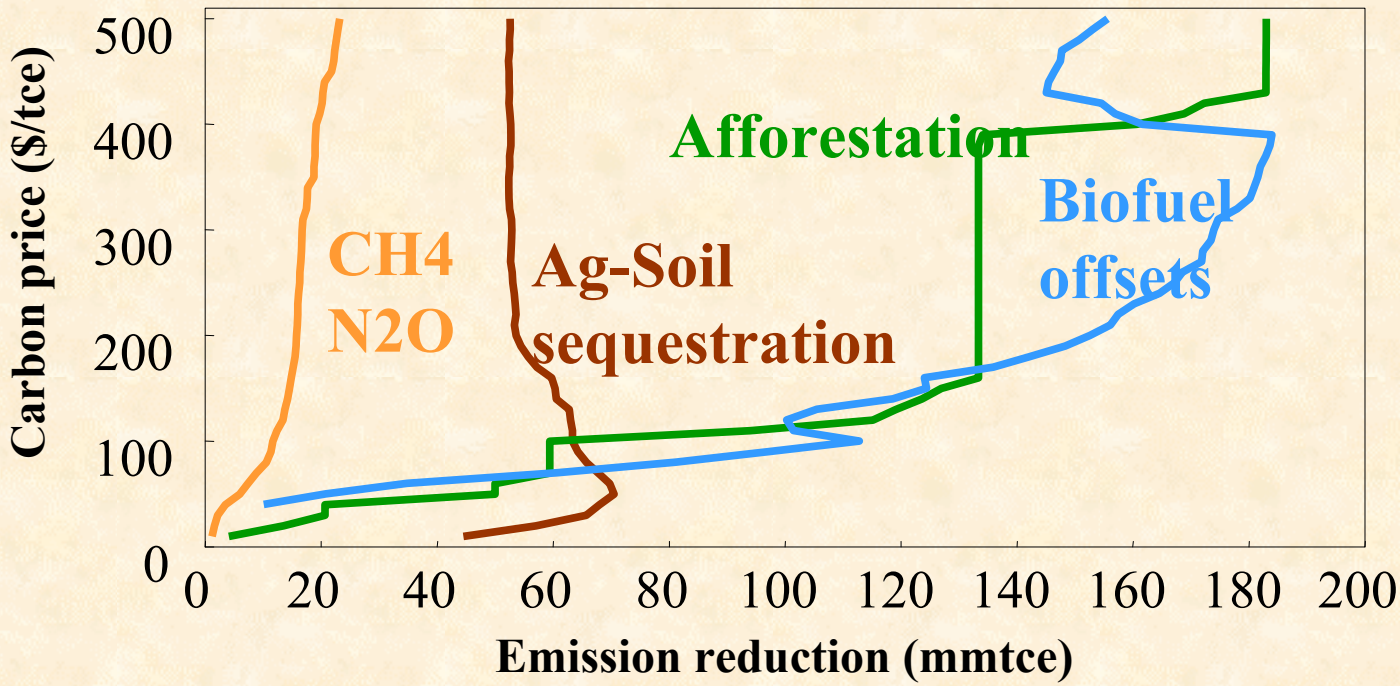
- Production and "oxidation" rates important
- Example: US Lumber consumption
  - Assume first order decay rate of 40-y half life
  - Increase in stocks reaches steady state of ~½ rate of consumption after about 100 y





Economics matters

- Portfolio of strategies desirable
- Price level can drive strategies

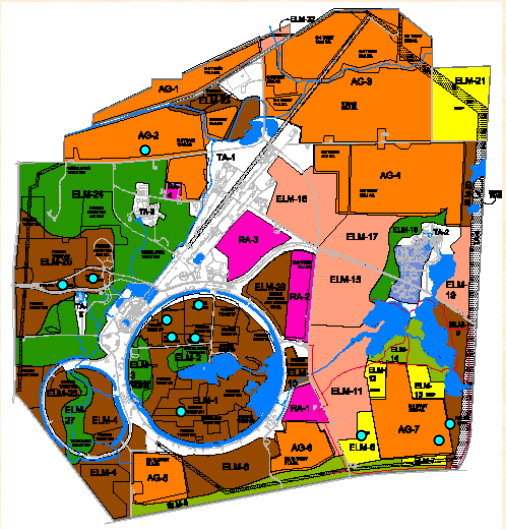


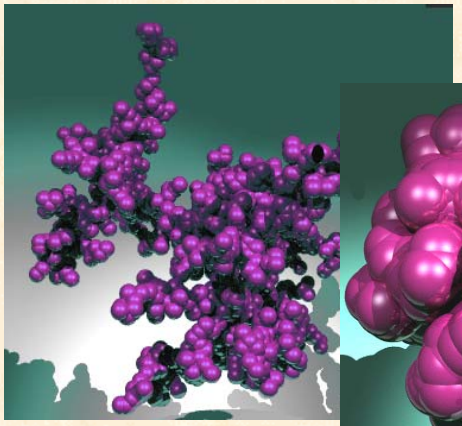
McCarl and Schneider (2001)

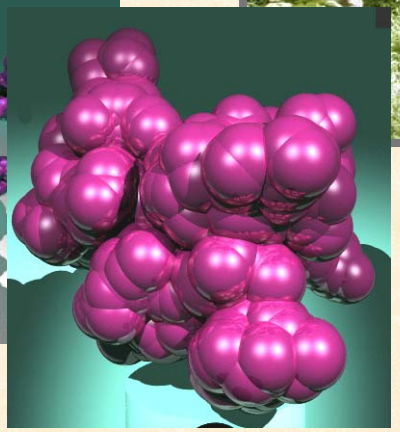
How much difference can R&D make?

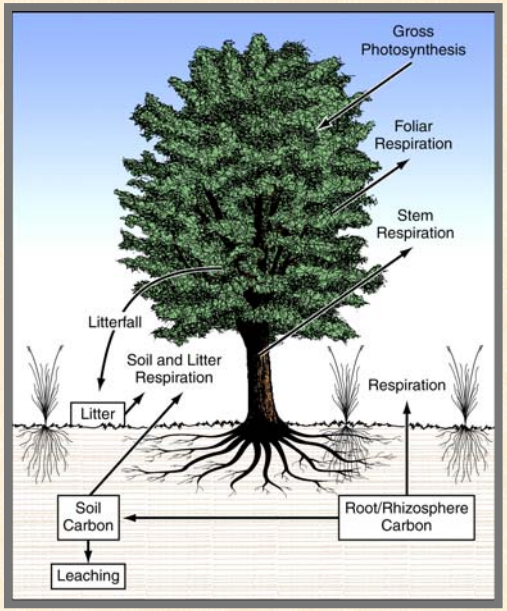
- Near-term opportunity
  - Prior estimate of ~5 Gt C/y for several decades
  - Global forests now ~3 Gt C/y (Dahlman et al.)
    - 300 $gC/m^2/y$ NEP $\times$ 10^{13} m^2 forests
- Can we do better?
  - R&D will improve our technology
- Humans now use ~20 Gt C/y of photosynthesis products (Rojstaczer et al.), so we have the ability to "manage" the terrestrial system
- Crop productivity increases
  - 70 to 250% from 1950 through 1999 (USDA)
  - 90 to 157% future projection (English and Chuang)

R&D Needs

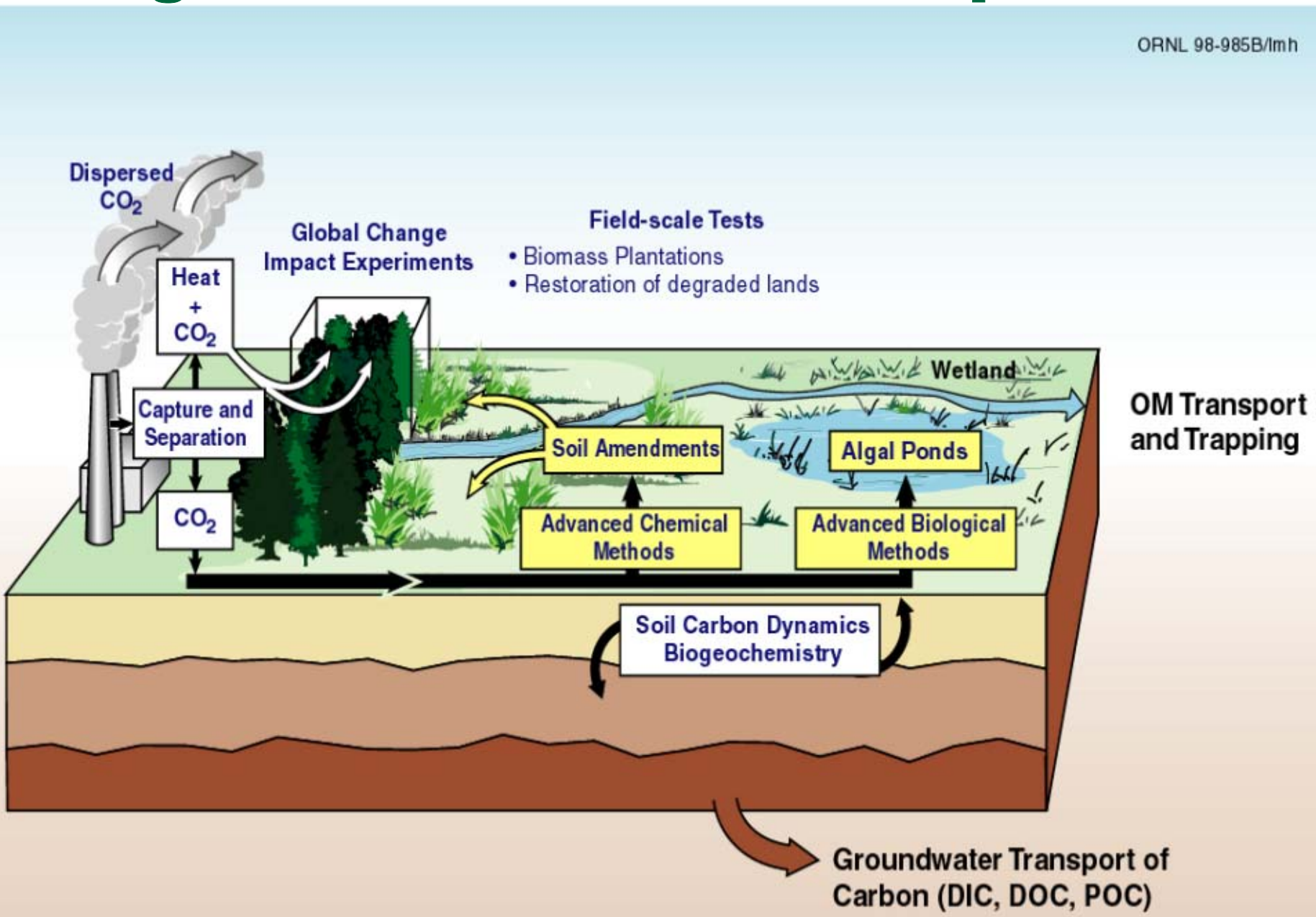







Gross Photosynthesis
Foliar Respiration
Stem Respiration
Litterfall
Soil and Litter Respiration
Respiration
Litter
Soil Carbon
Root/Rhizosphere Carbon
Leaching

Large-scale tests will be important

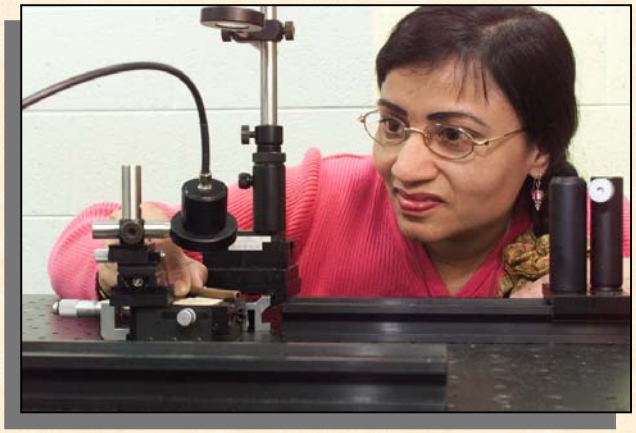


The Bottom Line

- Much is known already
- Don't expect terrestrial ecosystems to solve the problem, but potential sequestration is significant, near-term, and cost effective (with other benefits)
  - Land, long-term commitments, and economics constrain
- Technological advances could enhance potential substantially
  - Linking to bioenergy and bioproducts offers complementary advances
- Integrated evaluations important (as for all options)
  - Full accounting of GHG, climate impacts, environmental consequences
- Science, in parallel with test systems, is needed

Backup slides

Soil C Measurement

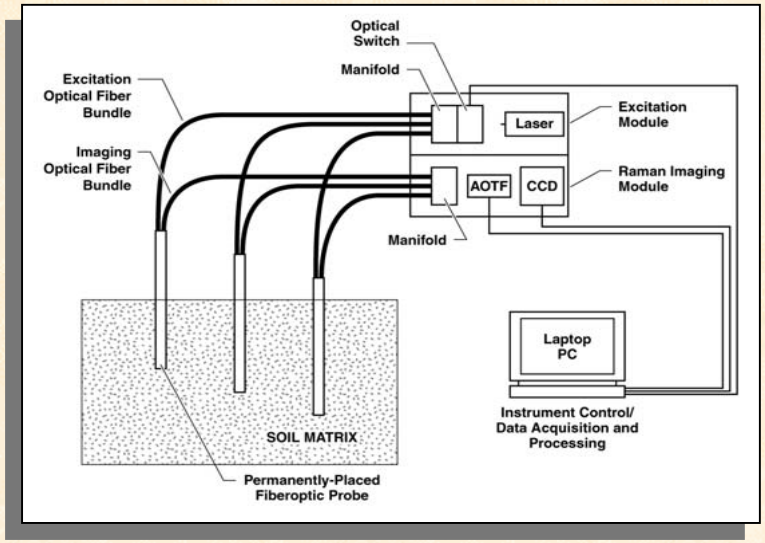


Laser-induced Breakdown Spectroscopy

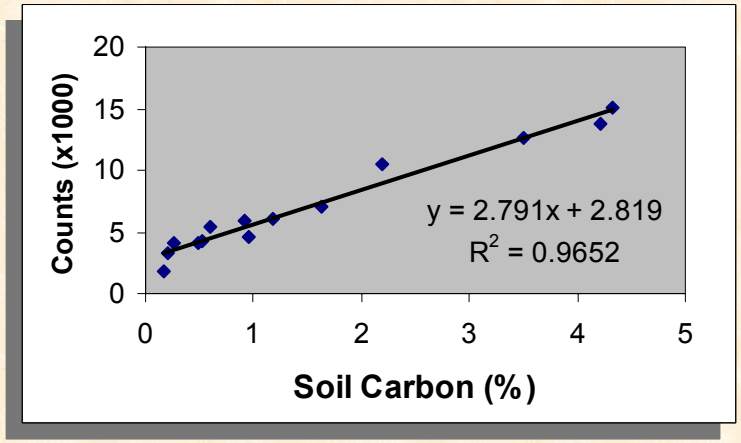
- Excellent correlation between LIBS and soils of known carbon concentration
- Also good correlation with soil nitrogen

Raman Spectroscopy

- Electro-tunable Surface Enhanced Raman Scattering (SERS) technique for detecting humic and fulvic acid in soils.
- Working on a novel hybrid electro-SERS technique also for humic and fulvic acid.



Soil C Measurement

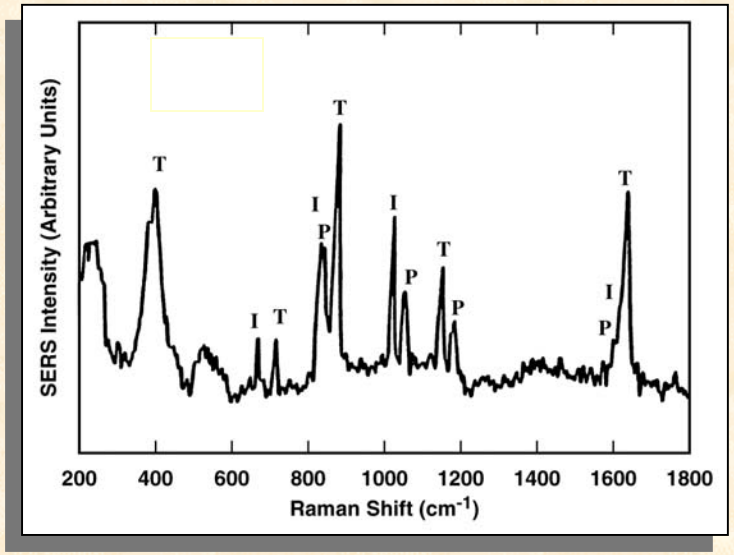


Laser-induced Breakdown Spectroscopy

- Excellent correlation between LIBS and soils of known carbon concentration
- Also good correlation with soil nitrogen

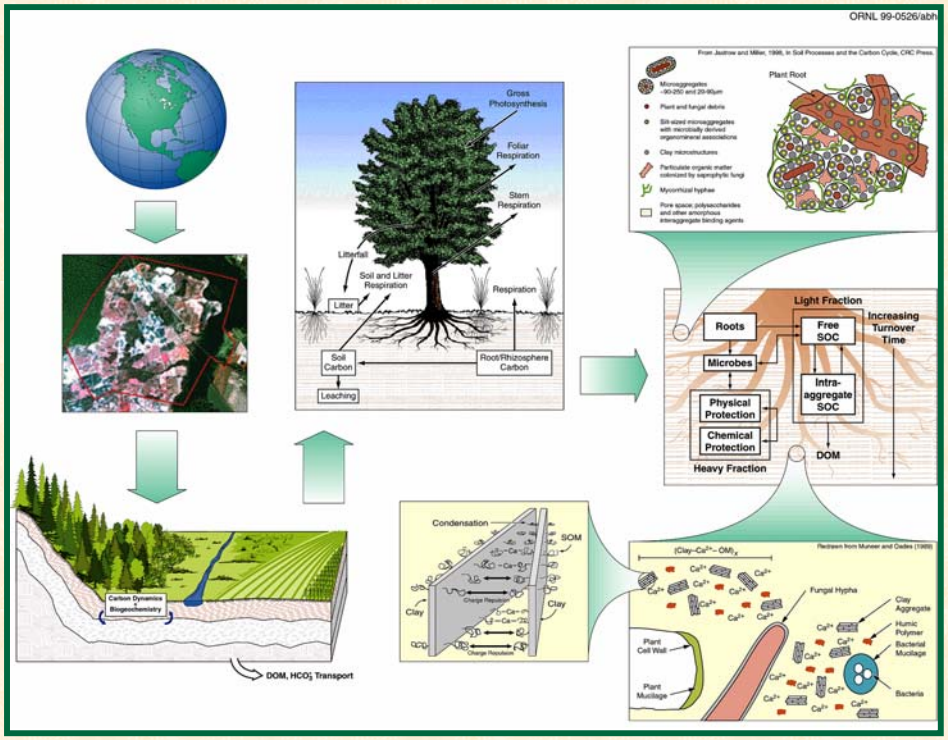
Raman Spectroscopy

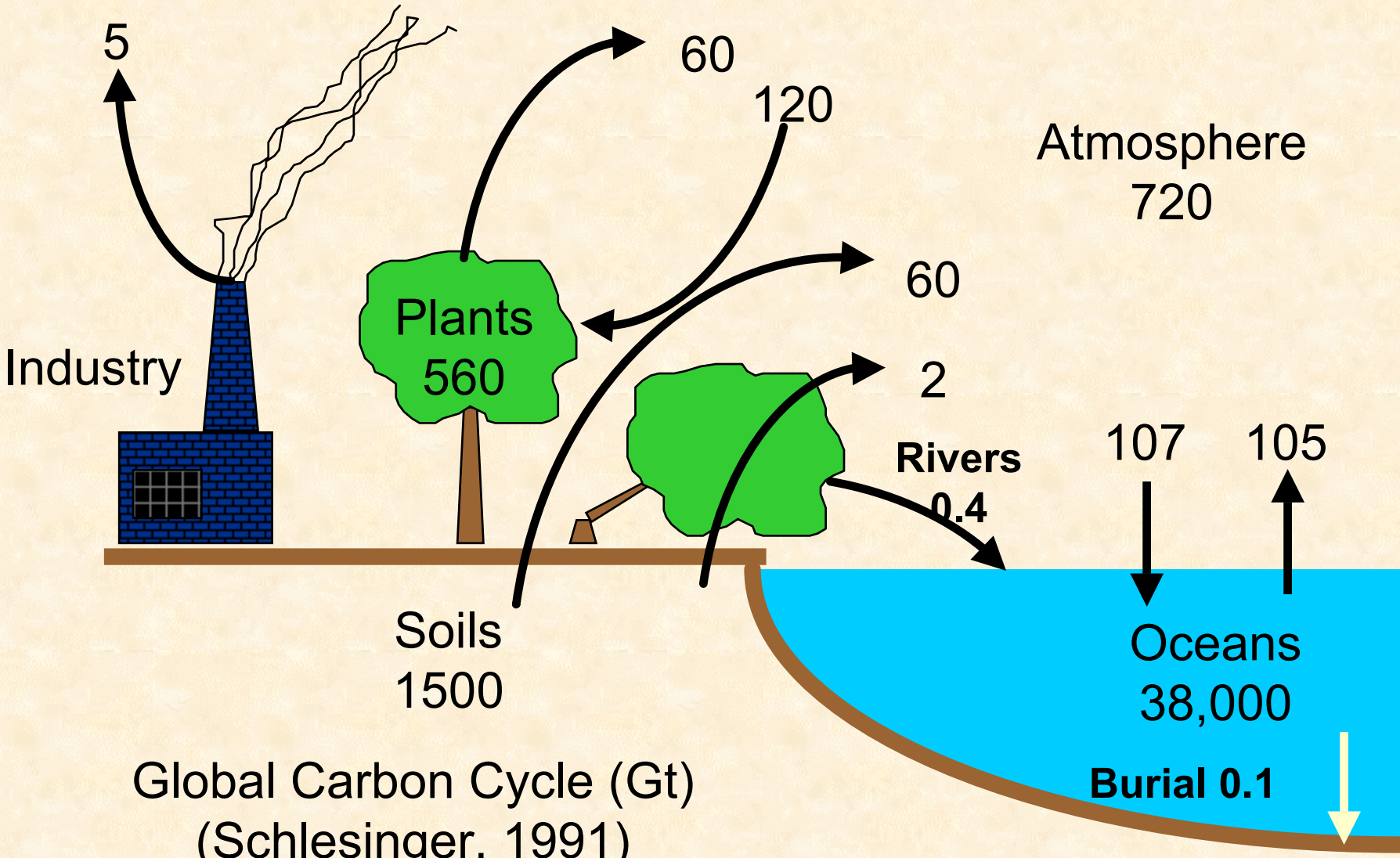
- Electro-tunable Surface Enhanced Raman Scattering (SERS) technique for detecting humic and fulvic acid in soils
- Working on a novel hybrid electro-SERS technique also for humic and fulvic acid



CSiTE Scientific Approach

- Understand carbon capture and sequestration mechanisms in terrestrial ecosystems across multiple scales from the molecular to the landscape
- Develop conceptual and simulation models for extrapolation of process understanding across spatial and temporal scales
- Estimate carbon sequestration potential at various scales
- Advance science of assessing environmental and economic consequences of sequestration



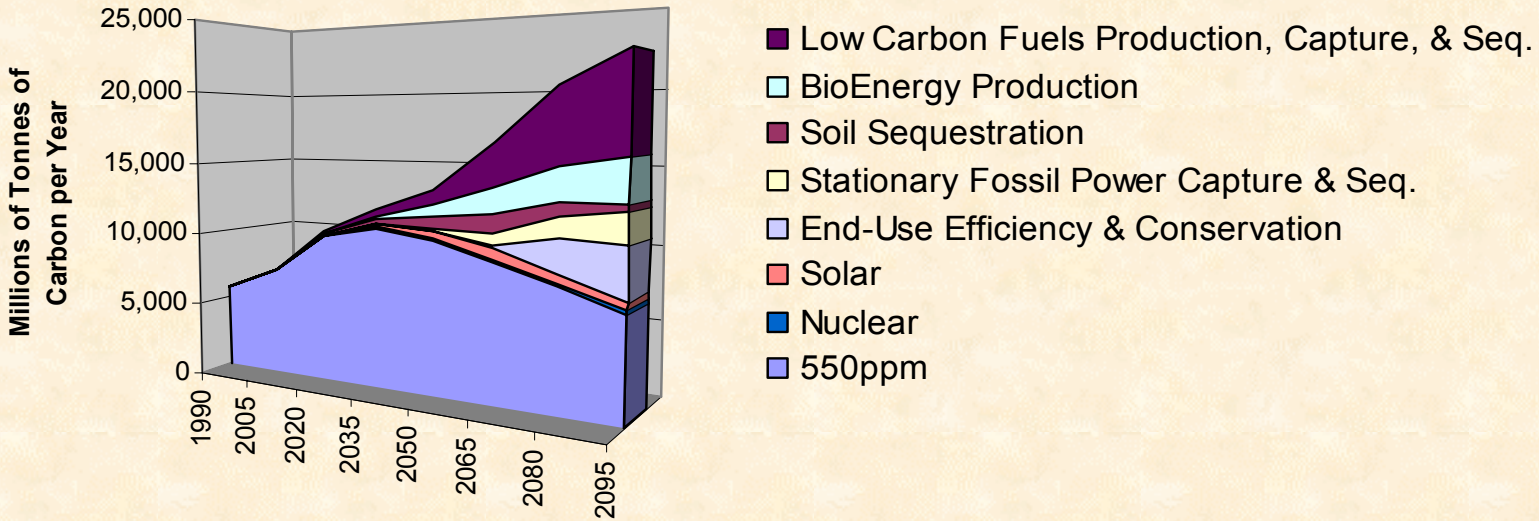


Global Carbon Cycle (Gt)
(Schlesinger, 1991)

Carbon Management

Gigaton Carbon Impact of Technology Systems

	Global	United States
Low-Carbon Fuels Production, Capture, & Sequestration	186	27
BioEnergy	90	15
Soil Sequestration	51	6
Stationary Fossil Power Capture & Sequestration	51	5
Energy Efficiency	42	14
Solar	34	0
Conservation ("Doing with Less")	17	12
Nuclear	13	0



Reforestation/Afforestation (Ballpark Figures)

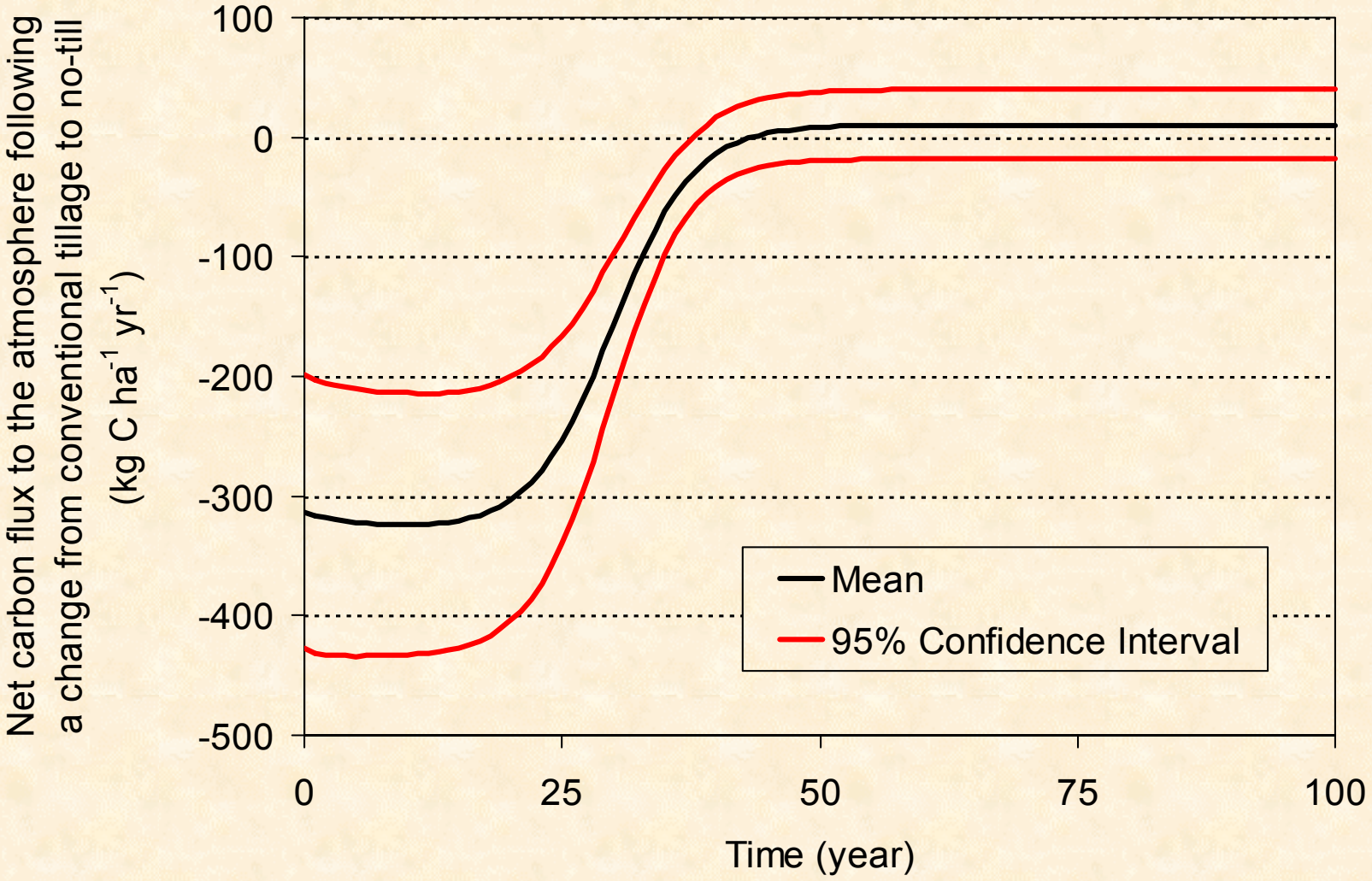
- Maybe $10 \pm 5 \times 10^{12}$ m^2 could be re/afforested
  - 3-10% global land area
  - Area of Brazil plus Colombia plus Paraguay
- Maybe 250 ± 150 g $C/m^2/y$ could be stored in wood, litter, and mineral soils
  - For the next 100 years?
- Thus, perhaps 2.5 ± 2 Pg C could be sequestered annually
  - In addition to present forest C sink activity

Courtesy of Jeff Amthor

Restore Agricultural Soil Carbon Pools *(Ballpark Figures)*

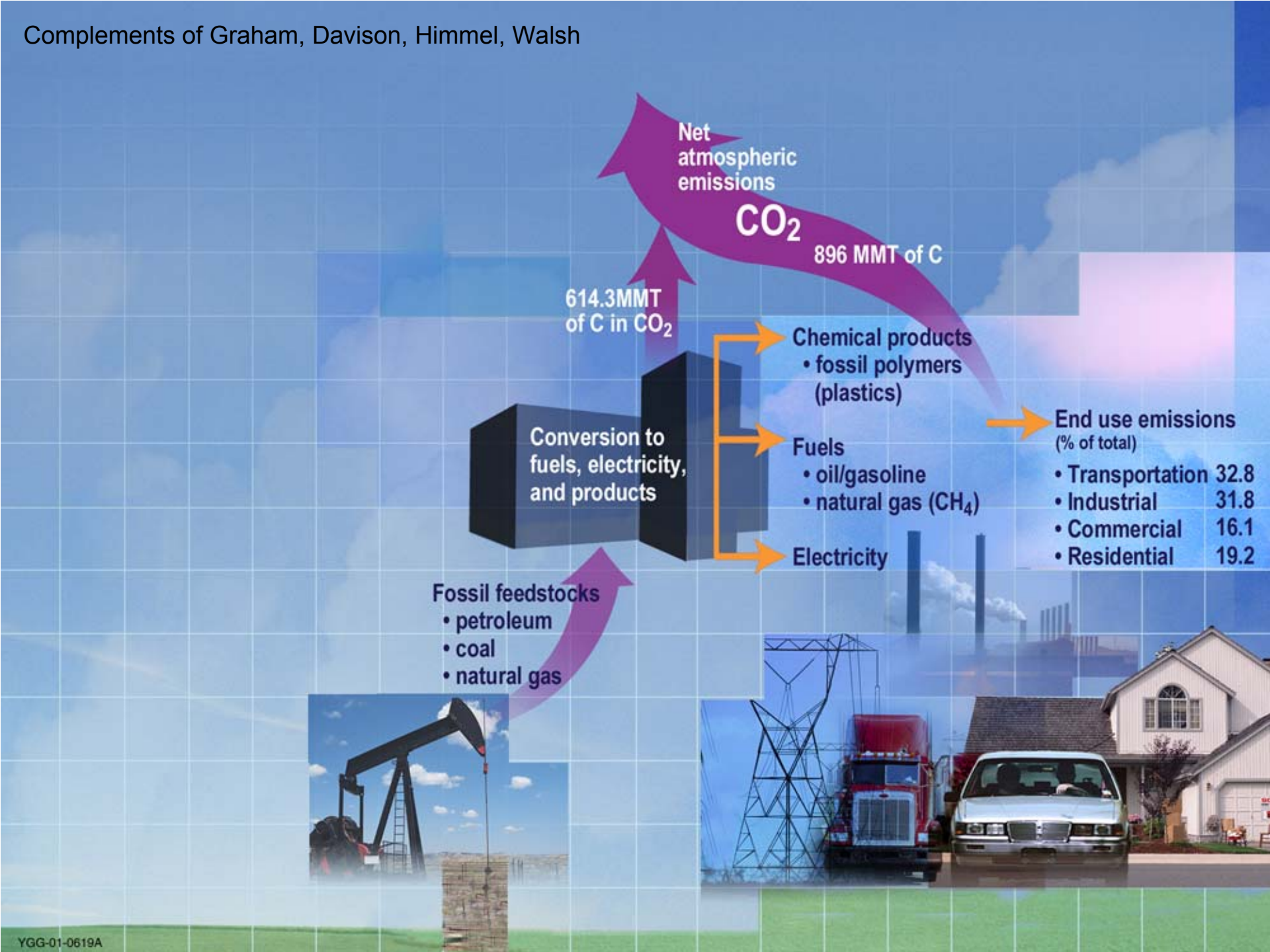
- Cropped soils presently contain 120 ± 30 Pg C
  - Contained 170 ± 40 Pg C before cultivation
  - Implies cumulative loss of 50 Pg C
- Recover C through crop management
  - Sequester 1.25 ± 0.25 Pg C/y
  - Maintain for 40 years?
- With innovative management might even exceed pre-cultivation C stocks

Courtesy of Jeff Amthor

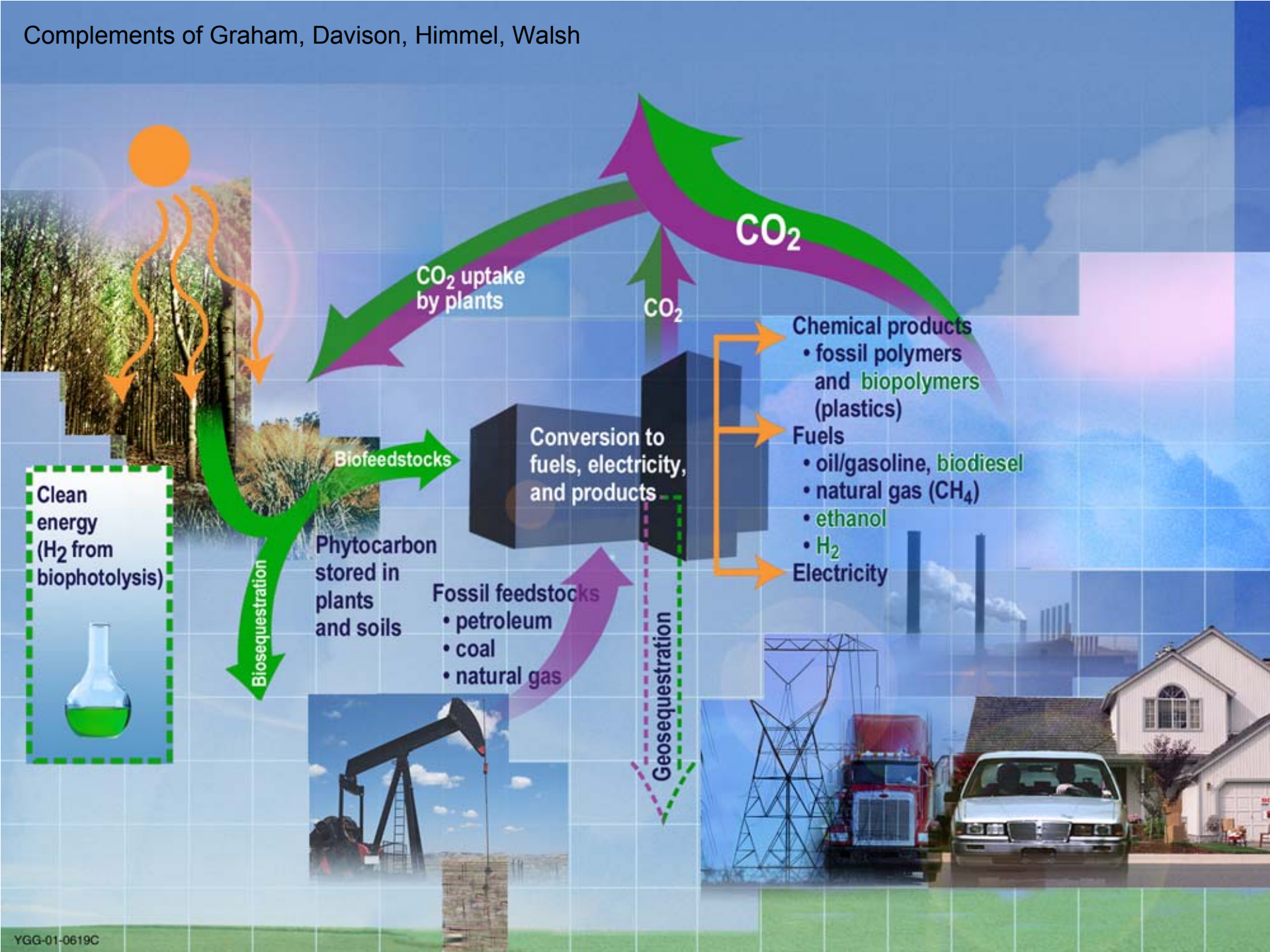


The net effect on greenhouse gas emissions following conversion from CT to NT for the average of U.S. crops. A mean value and 95% confidence interval have been estimated with a Monte Carlo simulation over the range of values described in the text for changes in soil organic carbon, crop yield, CO_2 and N_2O emissions, and land-use change.

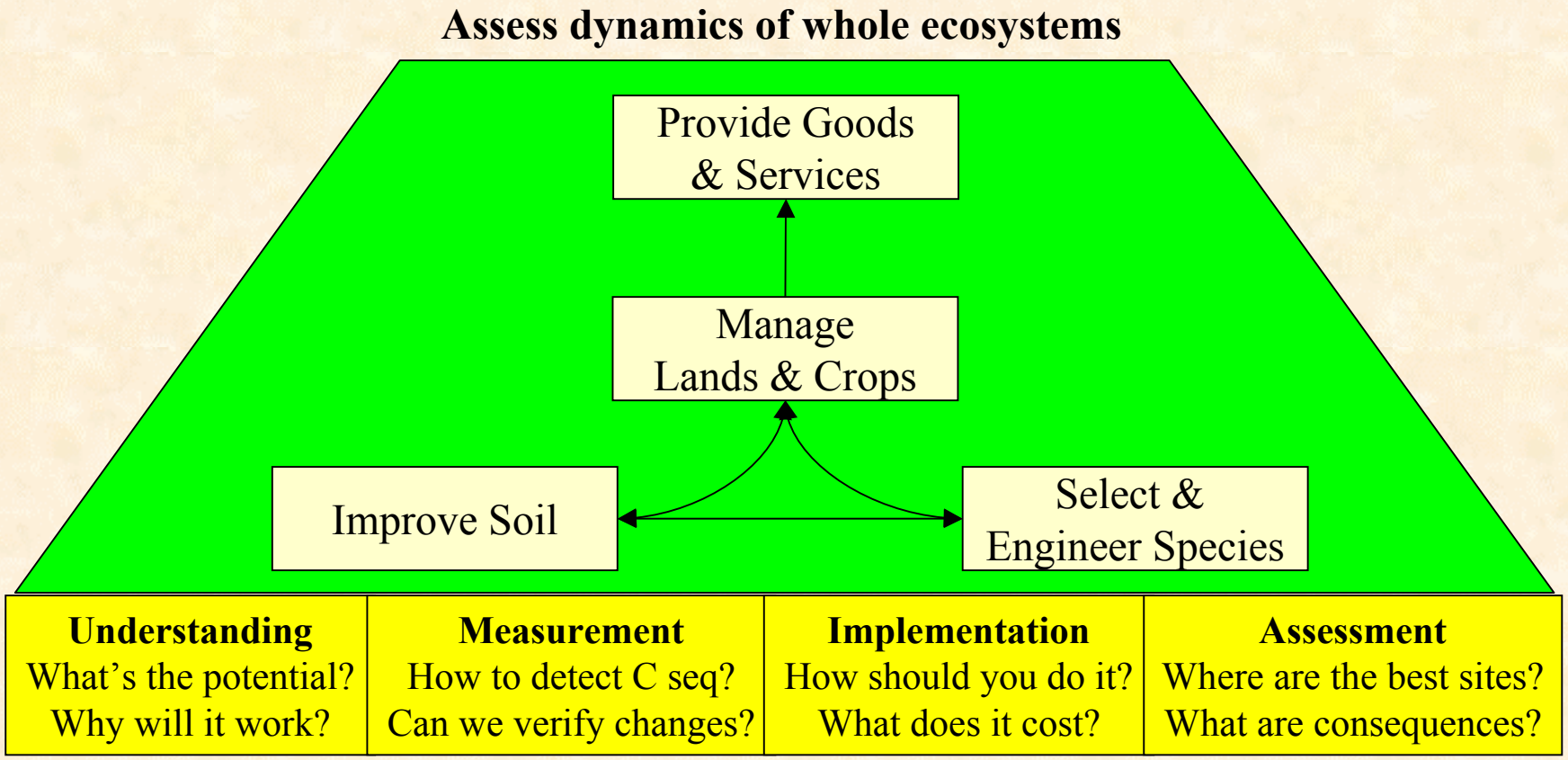
Complements of Graham, Davison, Himmel, Walsh



Complements of Graham, Davison, Himmel, Walsh



Terrestrial Technology Opportunities:
Sequestration, energy, and products



Fermilab Prairie Restorations

First year

Eleventh year

Second year

Initial years are dominated by species typical of old-field succession (annuals → biennials → weedy perennials).

Once litter buildup is sufficient to carry a fire, prairie grasses and forbs begin to take over.

Sampling and Analysis Methods

- Rowcrop field, 4 restored prairies, and virgin prairie remnant on related soil series
- Ten 0.5-m^2 circular quadrats per plot
- Clip aboveground plant biomass

- Pool three 10-cm soil cores (5-cm diam)
- Remove belowground biomass
- Pass through 2-mm sieve
- C and N determined with Carlo Erba NC2500 (no carbonates)

- **Initial samples 1985**
- **Prairies resampled 1999**

Estimated Residence Times of Organic Matter Stored in Various Measurable Pools of Agricultural Soils

(from Carter, 1996)

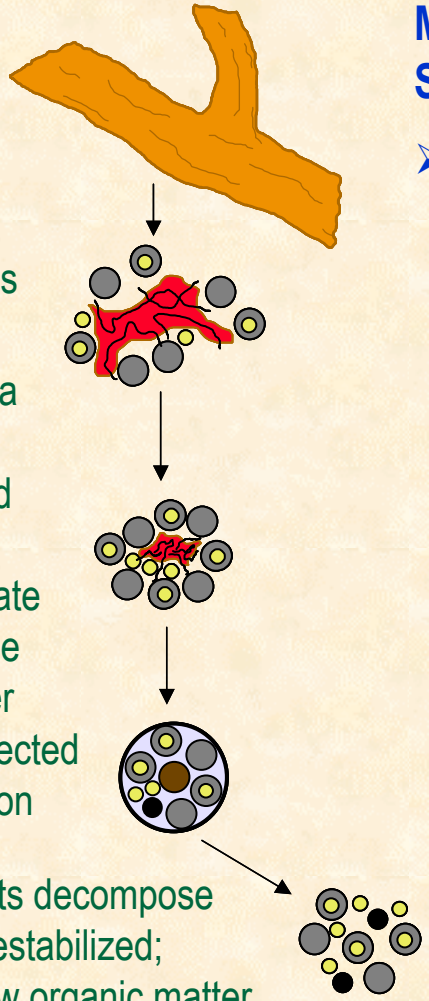
Type of organic matter	Proportion of total organic matter (%)	Residence time (yr)
Litter	—	1-3
Microbial biomass	2-5	0.1-0.4
Particulate [a]	18-40	5-20
Light fraction [b]	10-30	1-15
Inter-microaggregate [c]	20-35	5-50
Intra-microaggregate		
Physically sequestered	20-40	50-1000
Chemically sequestered	20-40	1000-3000

[a] Isolated by size (sieving)

[b] Isolated by density (flotation in heavy liquids)

[c] Within macroaggregates but external to microaggregates.

Conceptual Model of Microaggregate Turnover and Organic Matter Stabilization



Decomposing roots and detritus become encrusted with mineral particles forming microaggregates

Decomposition continues, but at a slower rate due to physical protection; aggregate is stabilized

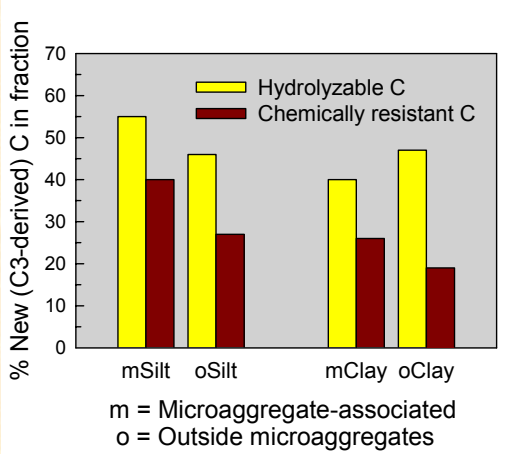
Slowed decomposition and intimate contact with soil minerals in stable aggregate enables organic matter to be humified or chemically protected by association with mineral fraction

Eventually, organic binding agents decompose sufficiently for aggregate to be destabilized; mineral fraction enriched with new organic matter

- Microaggregates ~ 50-250 μm
- Particulate organic matter colonized by saprophytic fungi
- Silt-sized aggregates with microbially derived organomineral associations
- Plant and fungal debris
- Fungal or microbial metabolites
- Biochemically recalcitrant organic matter
- Clay microstructures

CSiTE Scientists Focus on Measuring and Modeling Soil Fractions Tied to Organic Matter Stabilization Processes

- Soil fractionation procedures developed to isolate microaggregates from macroaggregate structure of soil

Stable C isotopes used to demonstrate:

- Microaggregates facilitate creation of chemically protected organomineral associations (more new C in microaggregate-associated silt and clay)
- Long residence time of chemically protected silt- and clay-associated C (only 19-49% new C after 55 y in Kansas grassland soils)