Soil Carbon Sequestration: Will it happen? Will we know it?

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A brief review of the issues…

- In 1977, Freeman Dyson asked the question: can we control the carbon dioxide in the atmosphere?
  - Via tree planting (4.5 Pg C yr^{-1})
- Soils as carbon sinks emerged later
  - II IPCC Assessment (0.4 – 0.8 Pg C yr^{-1} for 50 – 100 years) (Cole et al., 1997)
  - But Kyoto Accord did not include soils as sinks
    - Not permanent
    - Difficult to measure
- Significant R&D progress achieved during last decade
- IV IPCC Assessment (Smith et al., 2008)
  - Assigns small role to soils as sink
  - But significant role to agriculture to mitigate GHG emissions (5.5 – 6.0 Pg CO_2-eq yr^{-1})

Objectives

- Review soil carbon sequestration
  - Mechanisms
  - Rates and uncertainties
  - Climate change impacts on soil carbon pools
  - Coupled cycling of carbon and nitrogen
- Describe advances in monitoring and verification
  - Models, accounting, remote sensing
  - Integrated approaches
- Soil carbon sequestration for mitigation of and adaptation to climate change

An equation of soil (organic) C change (ΔSOC, Mg ha^{-1} yr^{-1})

$$\boxed{\Delta SOC = \underbrace{\overbrace{\overbrace{C_P - C_{Ra}}^{\textbf{NPP}} - C_{Rh}}^{\textbf{NEP (NEE)}} - C_E - C_L}_{\textbf{NECB}}}$$

Carbon additions (e.g. manure) or subtractions (e.g. harvest) should be included when pertinent

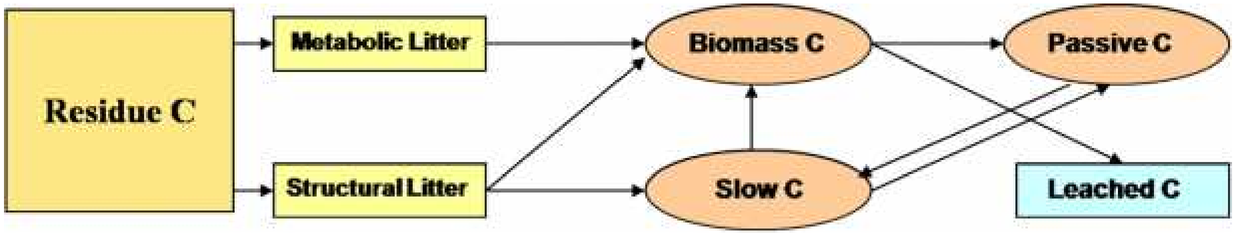
Current understanding of mechanisms leading to carbon stabilization in soil

- Biochemical alteration
  - Biotic and abiotic processes transform organic matter into chemical forms with increased resistance to decomposition
- Physicochemical protection
  - Biochemical attack of organic matter is inhibited by organomineral interactions at very small spatial scales

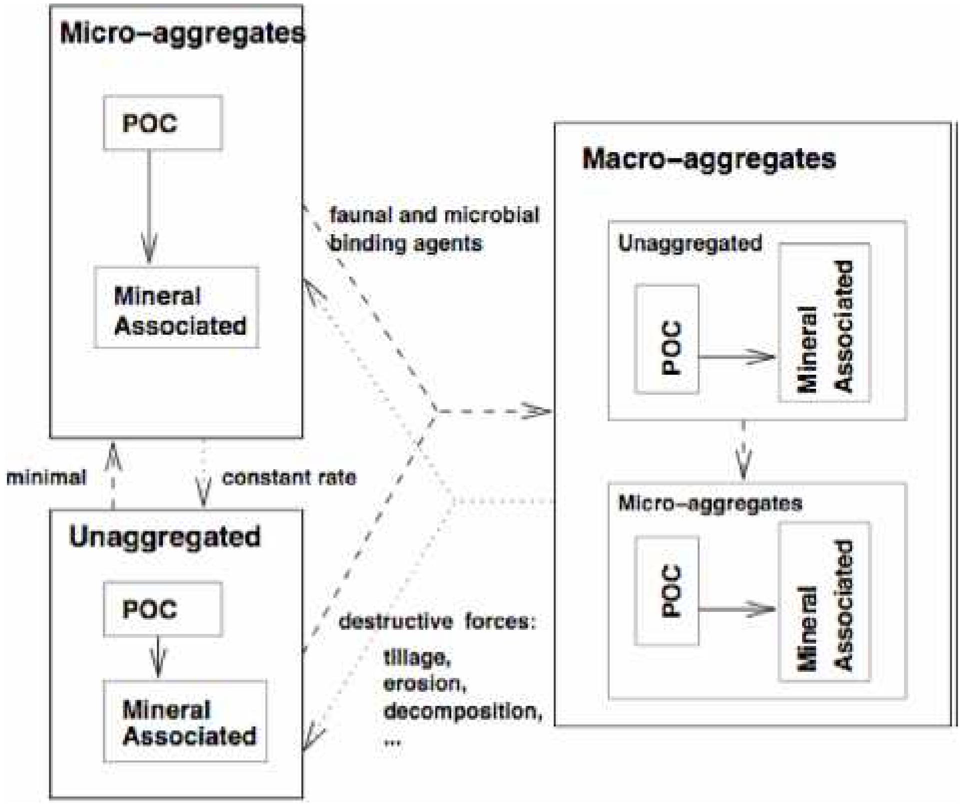
- Soil structure and its dynamics control these processes and reflect the degree of organic carbon stabilization in soil

Jastrow et al. (2007)

This new understanding is helping with the formulation of new soil organic models



Conceptual pools soil C models



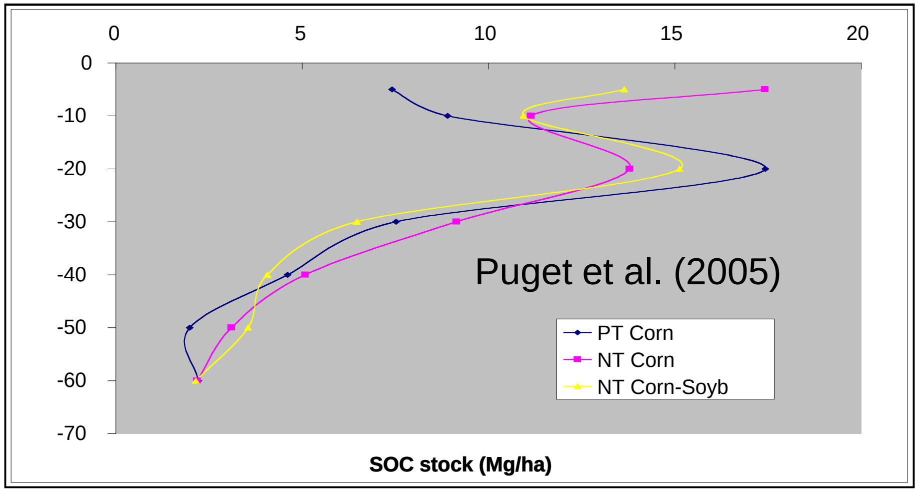
Physical fraction pool soil C models

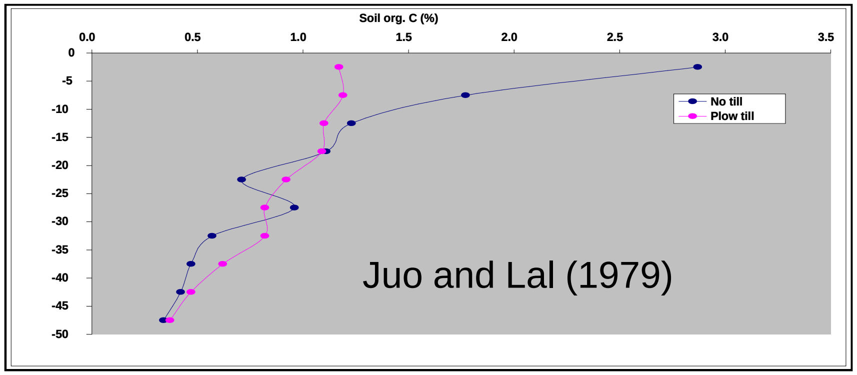
Six et al. (unpubl.)

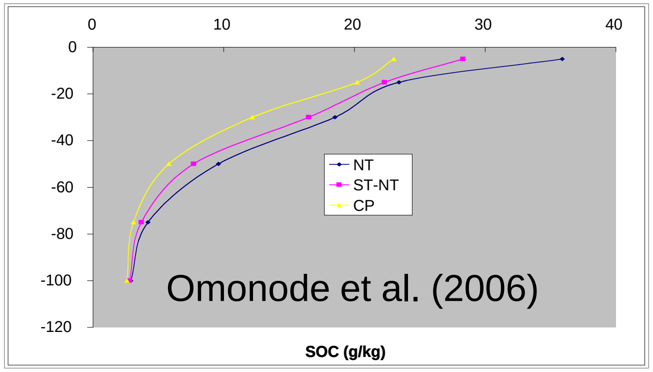
What practices for sequestration? What rates?

- There are many: cropping intensity, crop rotations, fallow reduction, improved grazing, nutrient management, and…
- No till, a practice made synonymous of soil C sequestration
  - Global rates by West and Post (2002): 0.57 ± 0.14 Mg C ha^{-1} yr^{-1}
  - Canadian rates by VandenBygaart et al. (2003)
    - Western Canada: 0.32 ± 0.15 Mg C ha^{-1} yr^{-1}
    - Eastern Canada: -0.01 ± 0.27 Mg C ha^{-1} yr^{-1}
- Recent controversy
  - Baker et al. (2006)
    - No-till does not lead to soil C sequestration
    - Too shallow depth of sampling
  - Blanco-Canqui and Lal (2008)
    - Field sampling of no till and plow till soils in OH, KY, and PA
    - Soil C increased in some soils but only in upper layers, not whole soil profile

Examples of tillage effects at depth…





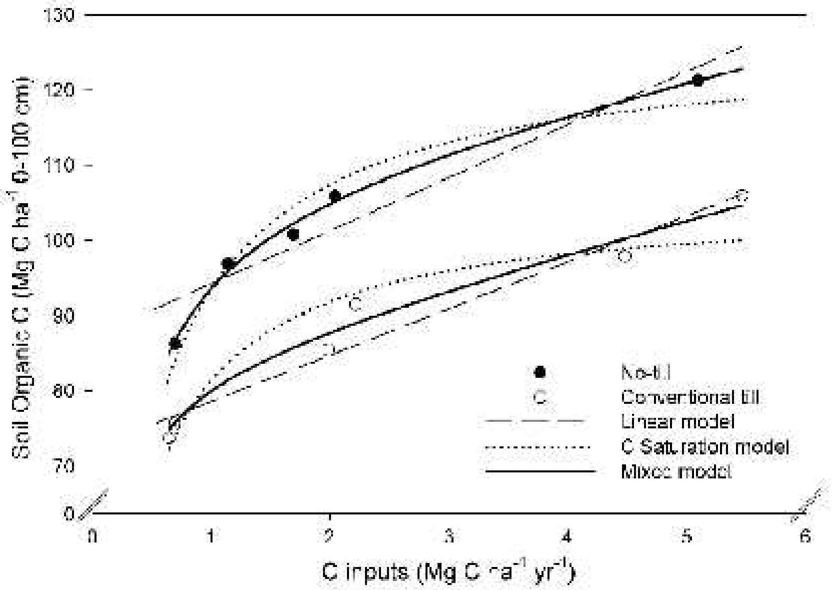


…and isotopic evidence

- In Puget et al. (2005), δ^{13}C evidence supports a greater retention of C from corn residues in no till (13%) than in plow till (8%)
- Six and Jastrow (2002) synthesized δ^{13}C evidence that the mean residence time of whole soil carbon in no till (80 ± 19 years) is greater than in conventional till (52 ± 11 years)

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)



Modeled vs observed C saturation in conventional and no till as a function of C inputs in Sanborn Plots

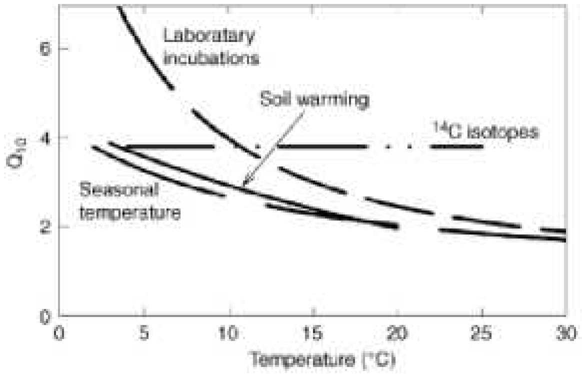
Stewart et al. (2007)

Will climate change affect the soil carbon balance in upcoming decades?

- Climate change will likely affect the soil carbon balance

$$\Delta SOC = C_P - C_{Ra} - C_{Rh} - C_E - C_L$$

- But a key issue, still unresolved, is the ultimate effect of global warming on the soil carbon balance (Kirschbaum, 1995, 2006)

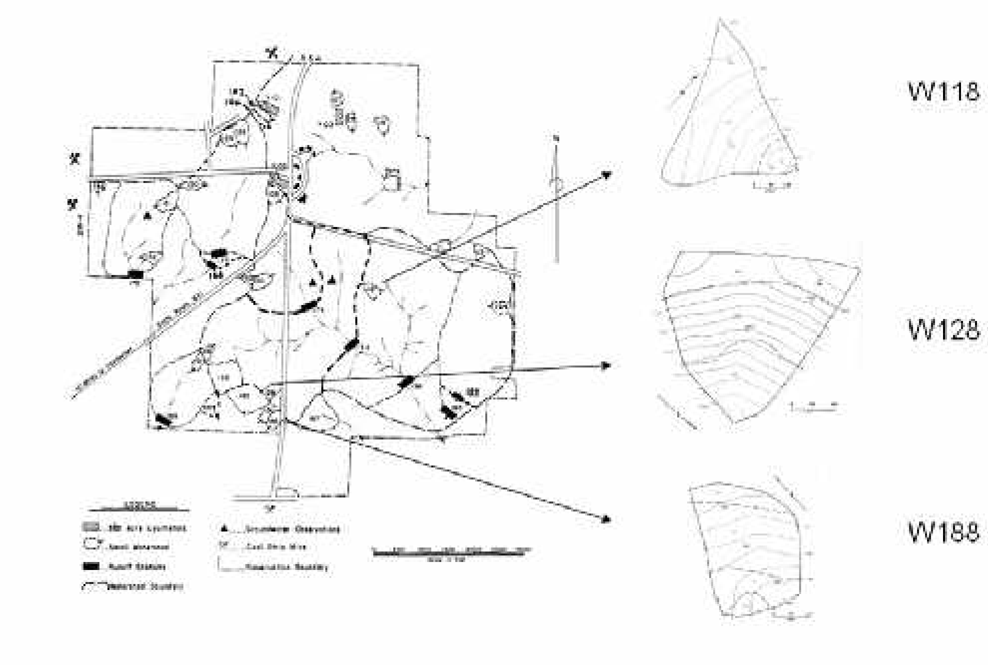


Temperature dependence of soil-carbon efflux rates estimates with differents methodologies (Kirschbaum, 2006)

What is the role of erosion in the soil carbon balance?

Annual C fluxes of three Ohio watersheds

	Plant C	Manure C	Respi-red C	Sedim-ent C in runoff	Soluble C in runoff	Lea-ched C
	---------- kg C ha^{-1} y^{-1} ----------					
W118	5702	228	5419	39	34	27
W128	5807	69	5979	82	46	22
W188	5868	34	5300	131	48	31



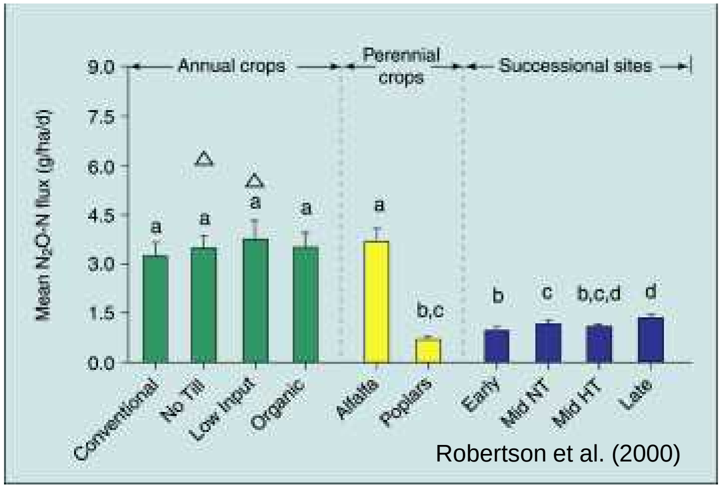
North Appalachian Experimental Watershed (Coshocton, OH)

Simulated soil C erosion (30 – 212 kg C ha^{-1} yr^{-1}) compared in magnitude to soil C sequestration rates (225 kg C ha^{-1} yr^{-1})

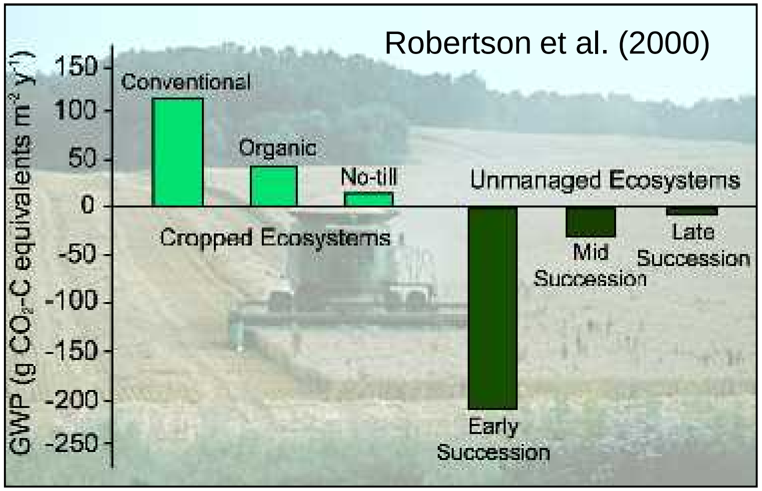
Izaurralde et al. (2007)

Soil carbon sequestration and full carbon accounting

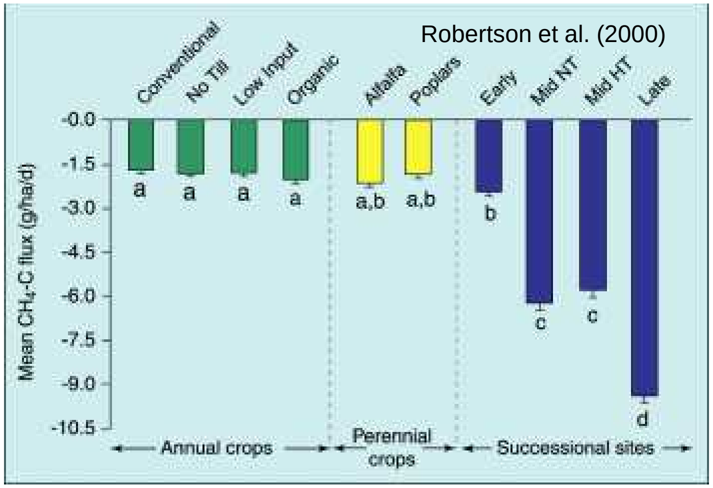
- Comprehensive approaches are needed to evaluate the mitigative power of agricultural practices (Robertson et al. 2000)
- N_2O emissions under no till may vary by region (Western vs. eastern Canada) Helgason et al. (2005)
- And even within a region for a same practice (Rochette, 2008)



Robertson et al. (2000)

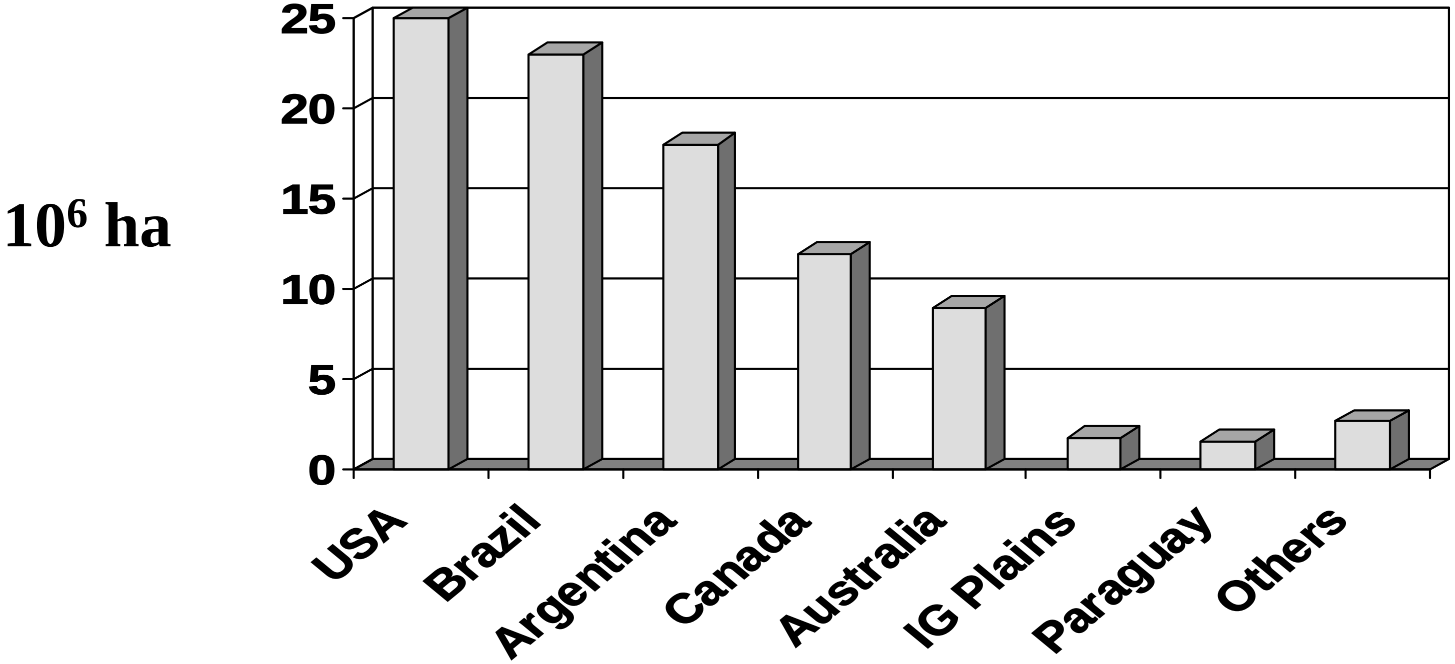


Robertson et al. (2000)



Robertson et al. (2000)

Soil carbon sequestration under no till, is it happening?



Adoption of no till reached ~100 Mha in 2005

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

Detecting and scaling changes in soil C by direct methods, simulation modeling, and remote sensing interpretation

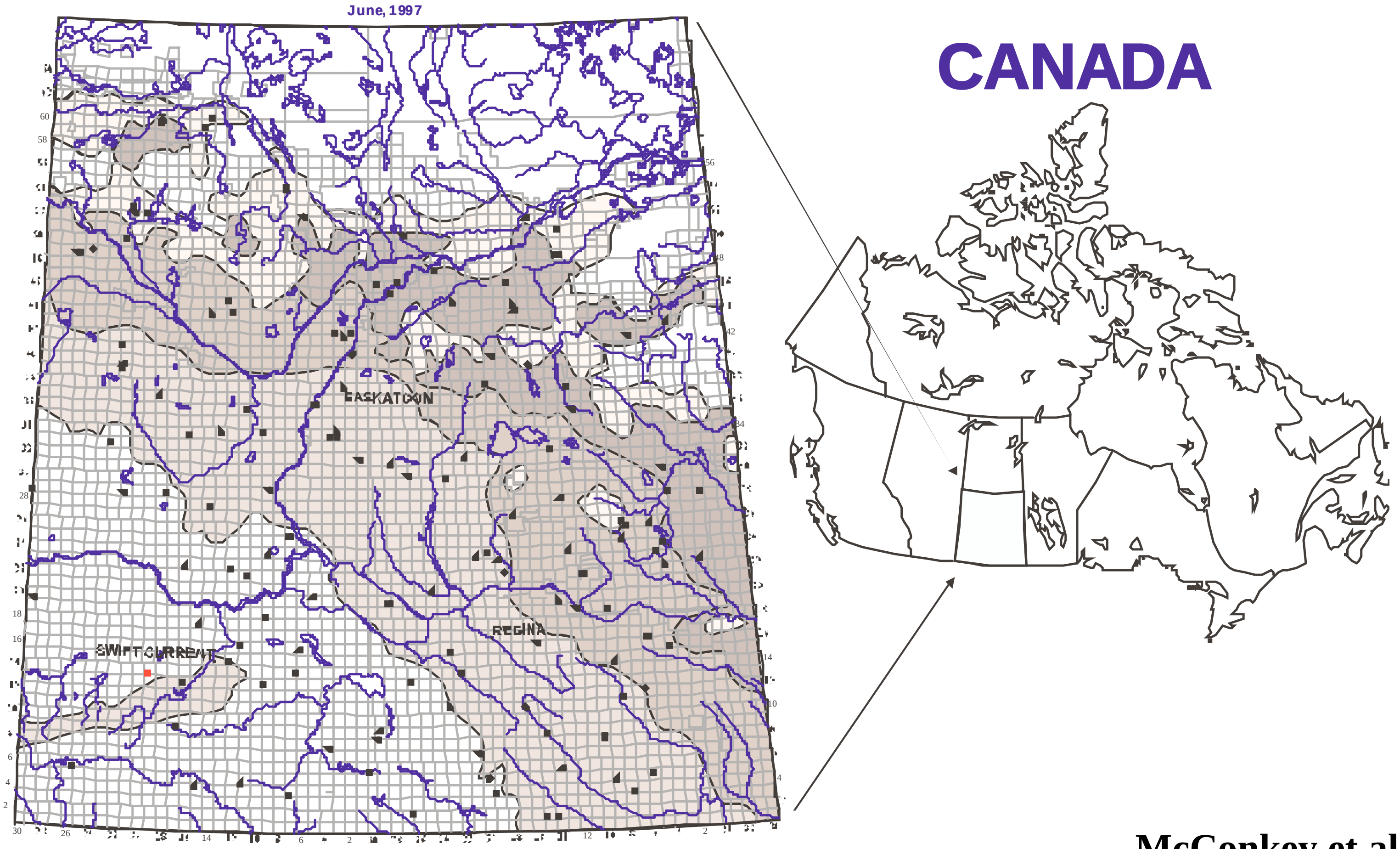
- Base data
  - Land units
  - Databases
- Sampling design and data
  - Statistical power
  - Baselines
- Sampling and processing
  - Depth and depth increments
  - Bulk density
- Reporting results
  - Equivalent soil mass
- Ancillary measurements
  - Crop and biomass yields
  - Inputs and management
  - Environmental conditions
- Modeling and remote sensing
  - Models and model complexity
  - Remote sensing
    - Crop identification
    - Crop residue cover

Izaurralde and Rice (2006)

The Canadian Prairie Soil Carbon Balance Project documented at field scale changes in soil C under no till in a 3-yr period

Saskatchewan

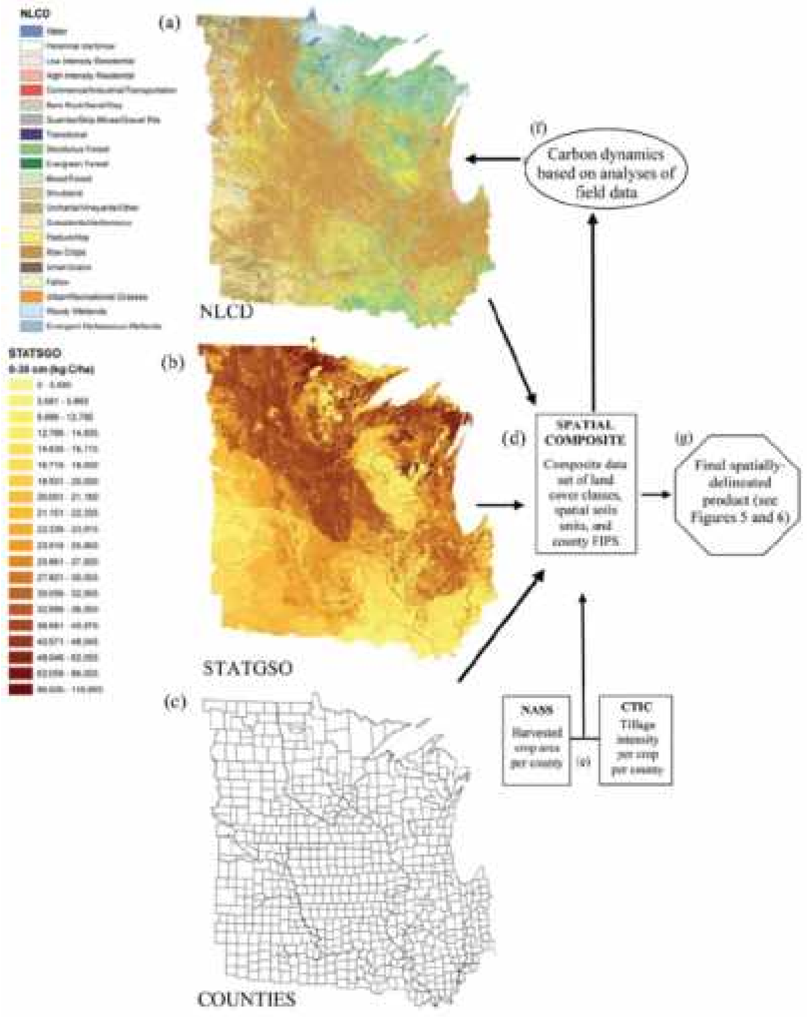
Verification Sites



McConkey et al. (2001)

Regional accounting framework to estimate soil C changes

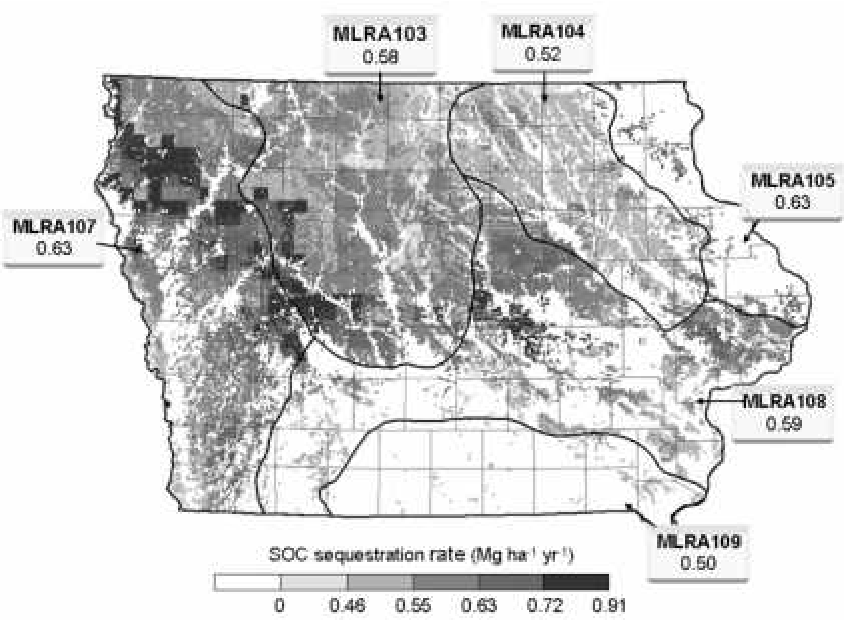
- Approach integrated inventory and remote sensing data on 670 counties in the Midwest
- Changes in soil carbon during 1991 – 2000 varied between 34 and 45 Tg C as a result of changes in tillage practices



West et al. (2008)

Ecosystem models have been used to estimate soil carbon sequestration at regional scales

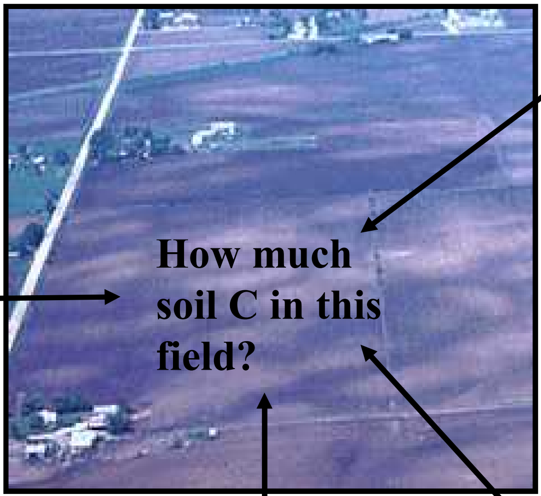
- EPIC model was instrumented with weather, soil, inventory, and remote sensing data in Iowa
- EPIC explained
  - 87% of yield variation
  - 75% of measured soil C
- EPIC simulated an increase of 28 Tg during 1980 – 2019



Causarano et al. (2008)

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



How much soil C in this field?

Inelastic Neutron Scattering (INS)

Mid / Near Infrared Spectroscopy (MIR / NIR)

Laser Induced Breakdown Spectroscopy (LIBS)

Izaurralde et al. (2006)

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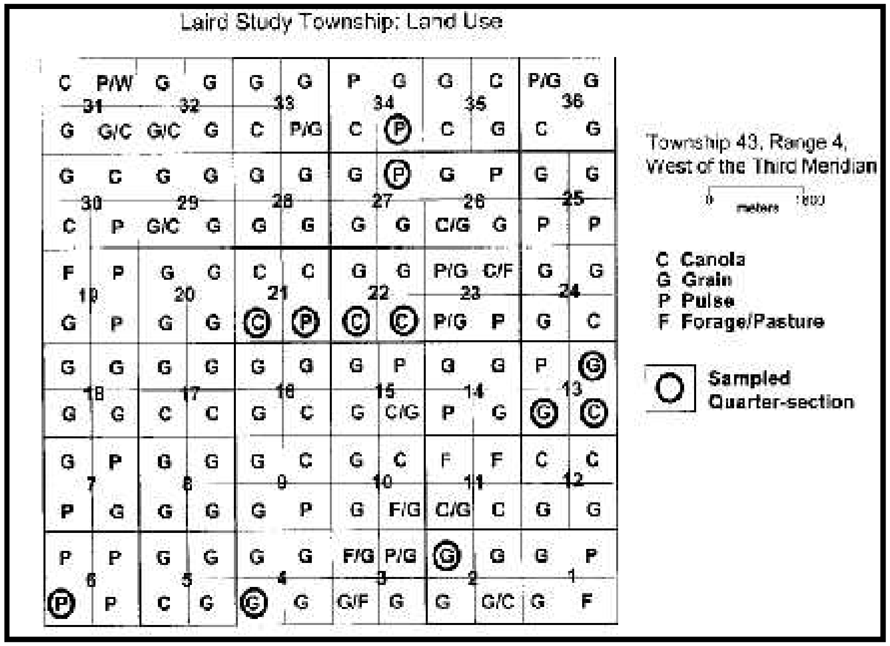
Upscaling N_2O fluxes from fields (40 ha) to township scale (9200 ha)

- N_2O fluxes measured by chamber methods during the 2002 spring thaw at 12 sites in a township near Laird, Saskatchewan (Canada)
  - Canola, pea, and wheat residues
  - Cattle manure
- Largest cumulative emission (330 g N_2O ha^{-1}) measured on cattle manure cover
- N_2O emissions did not correlate with either WFPS or soil temperature
- Upscaling on ha-scale basis was done by multiplying the cumulative emission of N_2O times the area of each crop type in the township
- The stratification by crop type was useful at identifying emission differences among the sites (wheat > canola = peas)
- For this relatively homogenous region, however, the area-weighted mean for cumulative emissions differed little from the non-area-weighted mean

Pennock et al. (2005) Can. J. Soil Sci. 85:113-125



Soil carbon sequestration as a mitigative and adaptive tool to address climate change

- Soil carbon sequestration will happen in the context of food, fiber, and energy production
- Increased levels of soil organic matter improve soil quality
  - Enhanced productivity
  - Nutrient storage
  - Soil tilth
  - Infiltration and water-holding capacity
  - pH buffering capacity
  - An example: $\uparrow$ SOM $\rightarrow$ $\uparrow$ Porosity $\rightarrow$ $\downarrow$ N_2O flux

Post et al. (2009)

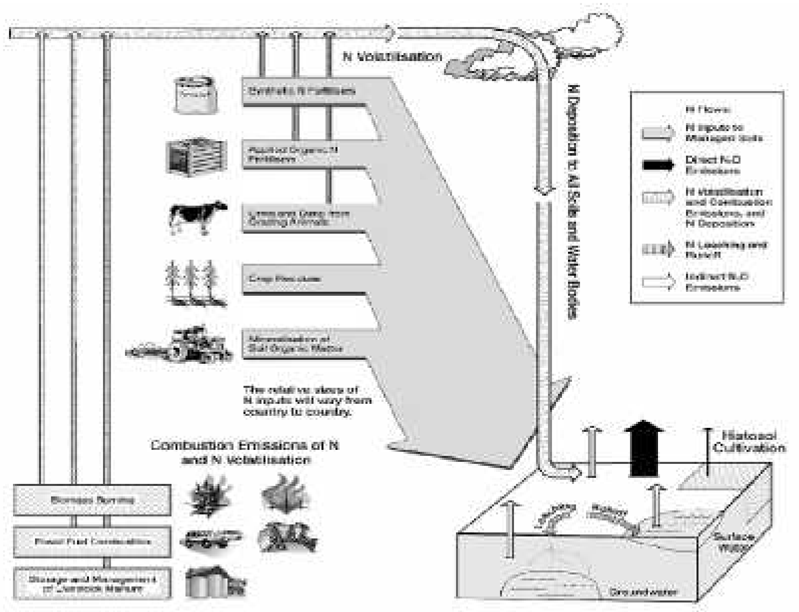
Conclusions

- Soil carbon sequestration, will it happen?
  - There is every reason to believe that soil carbon sequestration should happen
  - Soils should have a prominent role both in mitigation of and adaptation to climate change
- Soil carbon sequestration, will we know it?
  - Integrated approaches and new technologies give us reason to believe that we will be able to monitor and verify with acceptable accuracy soil carbon sequestration at local and regional scales

Additional slides on N_2O measurements and modeling

2006 IPCC Guidelines for National Greenhouse Gas Inventories; Vol. 4, Ch. 11
(http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.htm)

- Mostly for country or regional scale
- Three methodologies:
  - Tier 1: basic, direct N_2O emissions from managed soils estimated as:
    - $N_2O_{Dir}{-}N = N_2O{-}N_{Ninp} + N_2O{-}N_{OS} + N_2O{-}N_{PRP}$
    - For N inputs, calculation includes fertilizer N, organic amendments, crop residues, N mineralization
  - Tier 2: more detailed emission factors and data (e.g., organic N)
  - Tier 3: modeling or measurement approaches (e.g., DNDC, DayCent)

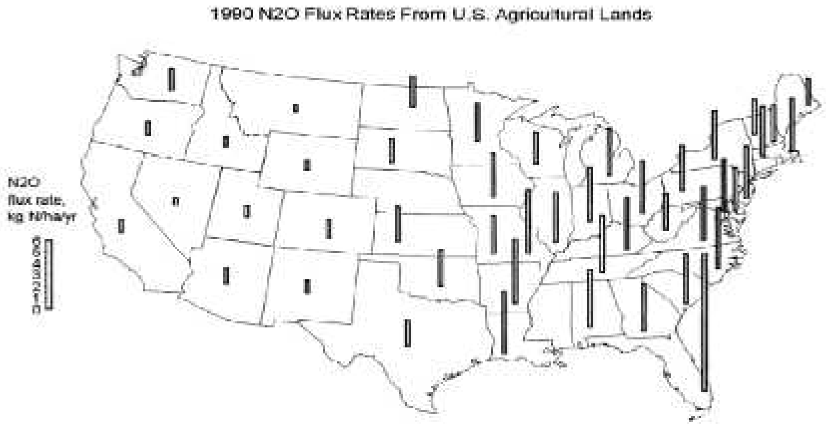


Sources and pathways of N that result in direct and indirect N_2O emissions from soils and waters

DNDC, a biogeochemical model to simulate soil carbon dynamics and trace gases in agriculture

Li et al. (1992a,b) J. Geophys. Res. 97

- Denitrification in DNDC occurs under oxygen-deficient conditions (e.g., wet soils following rain events)
- Nitrates are converted to NO_2^- and then to N_2O and N_2
- Nitrous oxide production and denitrification are functions of carbon decomposition, soil pH, soil water content, and soil temperature
- Li et al. (1996) produced generalized estimates of N_2O flxues across U.S. agricultural lands

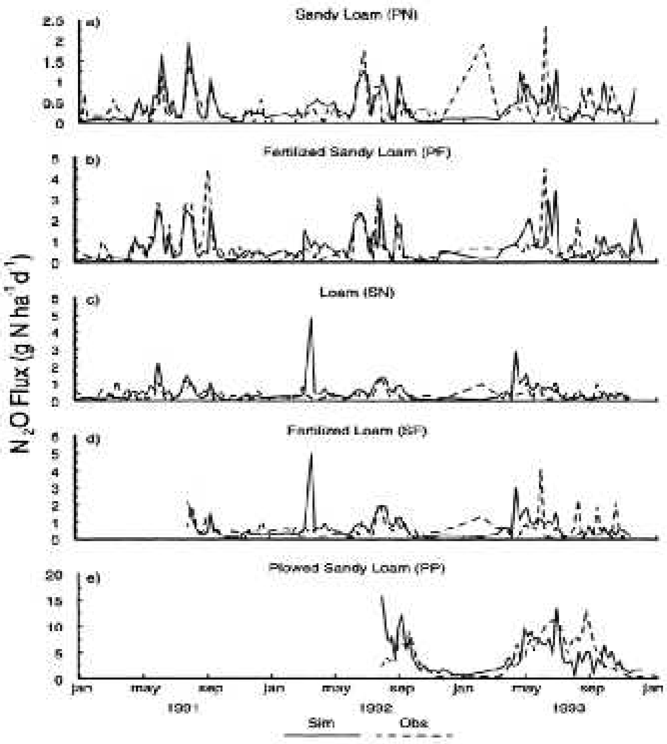


Li et al. (1996) Global Biogeochem. Cycles 10:297-306

Modeling N_2O and N_2 production generated from denitrification and nitrification process

Parton et al. (1996) Global Biogeochem. Cycles 10:401-412

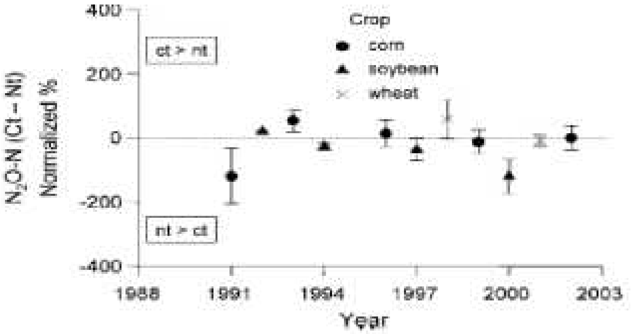
- Daily time step process-based model developed on the basis of the Century model
- Models nitrification as a function of soil pH, soil water content, soil temperature, and soil NH_4^+ level
- N_2O formation during nitrification is a direct function of nitrification rate
- N_2O and N_2 formation during denitrification is modeled as a function of heterotrophic respiration, soil NO_3^- level, and water-filled pore space (WFPS)



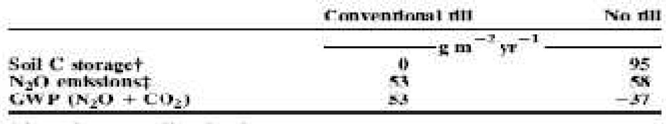
Do no till cropping systems emit more N2O than conventional till systems?

Grandy et al. (2006) J. Environ. Qual. 35:1487-1495

- No till systems are perceived to emit more N_2O than conventional till systems
- Grandy et al. (2006) measured N_2O and yields in corn-soybean-wheat rotations during 1989-2002 in SW Michigan
- Conclusions
  - No till increased soil C
  - No till improved aggregation
  - N_2O fluxes were higher in no till in 2 out of the 10 years, but on average there was no difference
  - Yields were not different



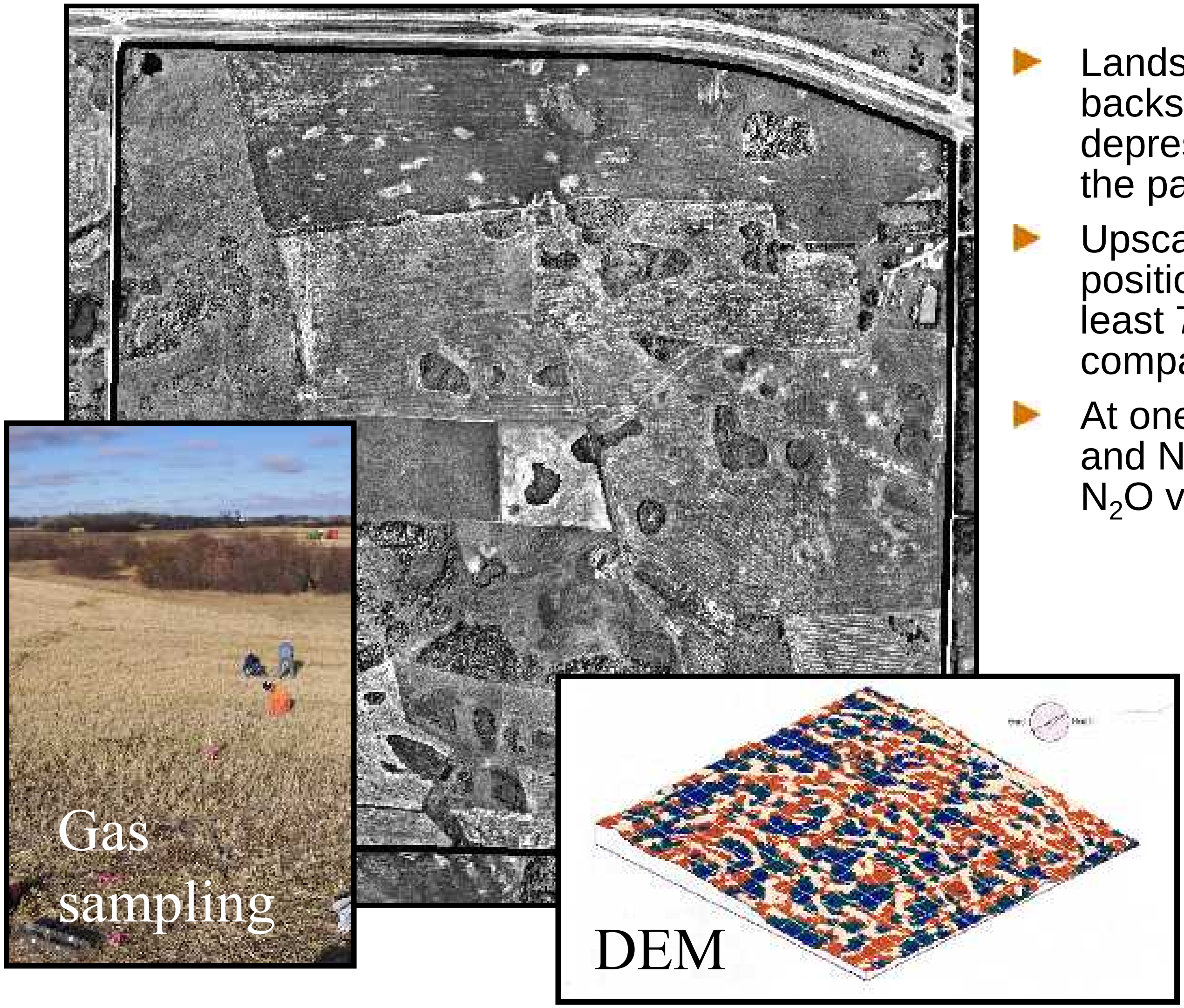
Global Warming Potentials



	CO₂ equivalents	
	Conventional till	No till
	g m^{-2} yr^{-1}	
Soil C storage†	0	95
N_2O emissions‡	53	58
GWP (N_2O + CO_2)	53	−37

Upscaling N_2O fluxes from hillslope to field scale

Izaurralde et al. 2004. Soil Sci. Soc. Am. J. 68:1285-1294



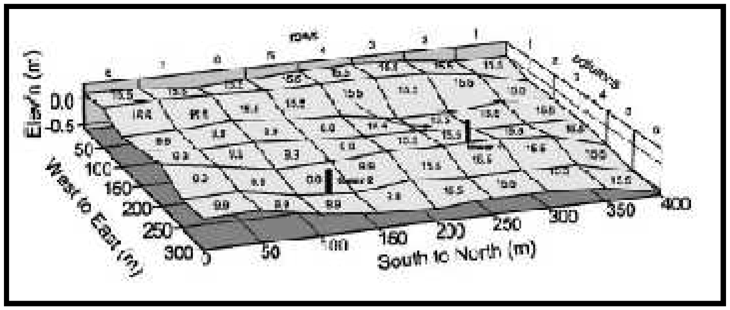
- Landscape position (shoulder, backslope, footslope, and depression) affected N_2O fluxes but the pattern varied seasonally
- Upscaling N_2O fluxes by landscape position increased estimates by at least 7%, in 5 out of 6 occasions, compared to arithmetic averaging
- At one site, water-filled pore space and N rate explained >70% of the N_2O variability

Izaurralde et al. (2004) Soil Sci. Soc. Am. J. 68:1285-1294

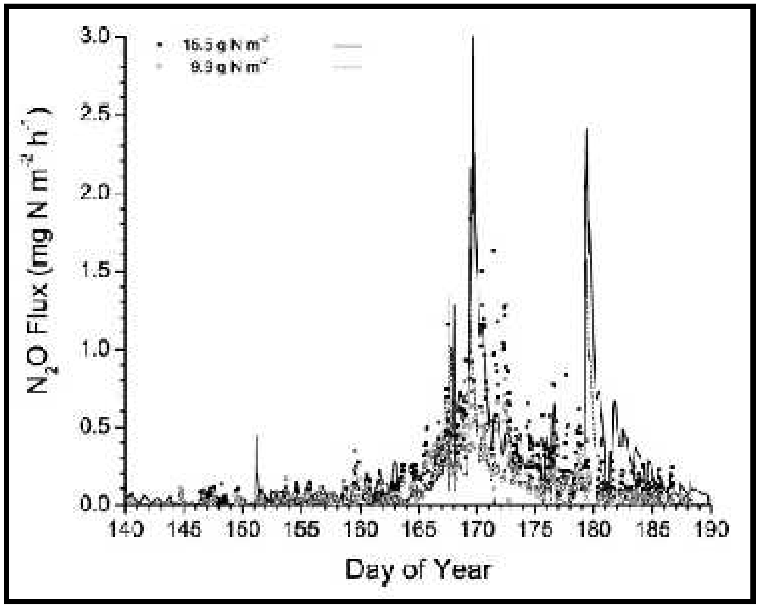
Measuring and modeling N_2O fluxes at the field scale

Grant and Pattey. (2003) Soil Biol. Biochem. 35:225-243

- The model *ecosys* was run in 3D mode to simulate N_2O fluxes from a fertilized field with topographic variations
- Modeled data were compared with field scale measurements made using eddy covariance towers and a tunable diode laser trace gas analyzer
- Large spatial and temporal variability of N_2O emissions were modeled and measured
- Spatial and temporal aggregation of emissions to regional scales should not be based upon modeled or measured values of individual sites at time steps of a day or more
- Aggregation should rather be based upon diurnal values from typical landscapes within a region in which variation of surface topography and soil type is accurately represented



N application and TDL towers



Observed (symbols) and modeled (lines) N_2O fluxes