What is the Potential for Carbon Sequestration by the Terrestrial Biosphere?

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This paper highlights some of technical information about carbon sequestration (CS) in terrestrial ecosystems that was presented in various sessions of the First National Conference on Carbon Sequestration, Washington D.C., May 14-17, 2001. This summary was submitted after the conference and presents the viewpoint of DOE's Office of Science.

The Earth's mantle of vegetation naturally removes CO_2 from the atmosphere, and some of this carbon then becomes sequestered in biomass products and soil. As discussed at this National Conference on Carbon Sequestration, mechanisms of terrestrial biosphere carbon sequestration (TBCS) represent important options for sequestration of excess CO_2 from combustion of fossil fuels.

A number of studies suggest that the potential quantity of TBCS may be significant, and that economic aspects appear attractive; therefore we conclude the following points:

- Quantity of annual carbon sequestration by terrestrial ecosystems can be measured at a reasonable accuracy;
- Median measure of current NEP or sequestration by forested ecosystems is 3 metric tons per hectare per year;
- Current calculated global TBCS for forests is ~3Gt C per yr;
- Estimated future TBCS capacity is 200-250 Gt C using available knowledge and current technology and management practice at nominal estimated cost of $10-20 per metric ton of C;
- It seems reasonable to assume that advanced science, technology, and management can double the capacity at low additional costs.
- TBCS option offers potential for sequestering more than 50 percent of projected excess CO_2 that will have to be managed over the next century.

While present-day knowledge clearly establishes the fact of TBCS, it is also recognized that uncertainty surrounds estimates of the potential.
Extrapolation of contemporary measures and forward calculations, even when based on sound empirical information, often can be a risky proposition. As pointed out in the "TBCS calculation..." paragraph below, the contemporary global estimated quantity of CS is an approximation, and could in reality be somewhat larger or somewhat smaller than values estimated by this paper.
Clearly more research will improve understanding of rates, magnitudes and longevity of CS by ecosystems. Calculation of "...future potential..." of TBCS for the most part conservative instead of aggressive assumptions. The calculation of course also depends on extrapolation of current knowledge, and on assumptions about future technology, land and resource management and markets among other things. Since we are absent a crystal ball for knowing

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the future, the calculated future potentials should be regarded as informed estimates, and not yet hard numbers. Also, achieving TBCS depends on cost factors that can only be guessed - not only for the TBCS incidentally, but for all other CS options as well. The main point is that not only can TBCS play an important role in the Nation's future energy and carbon management programs, but there is increasing evidence that CS products contribute to improved environmental quality, and can help mediate non-energy caused environmental impacts.

Introduction

Important progress on mechanisms and quantification of TBCS was elegantly provided by the DOE Road Map report, Carbon Sequestration Research and Development (USDOE 1999). Readers are referred to Chapter 4 of this report (www.ornl.gov/carbon_sequestration/) for analysis and discussion of the terrestrial option. In this paper we will reiterate TBCS potentials and offer supporting scientific information that place actual and potential estimates on more firm scientific foundation. We also provide hypothetical future potentials of TBCS that might be achieved from further advances in scientific understanding of sequestration mechanisms, from development of new technologies, and from innovative management practices. We conclude the paper by estimating sequestration rates and estimated total quantities of sequestered carbon for representative ecosystems and for the global TBCS.

Terrestrial carbon fluxes account for more than half of the carbon transferred between the atmosphere and the earth's surface (about 120 Gt/yr), and current stores of carbon in terrestrial ecosystems are estimated at 2500 Gt C, with 75% of the stocks in the belowground soil carbon pool. Increasing attention is being focused on the role of managing and sequestering carbon in the biosphere as a means for addressing global climate change (IGBP 1998; USDOE 1999). Terrestrial ecosystems are widely recognized as a major biological scrubber for atmospheric CO_2 – and their ability to function as such can be increased significantly over the next 25 years through careful management. The potential for terrestrial carbon gains has been subject of much attention (Dixon et al., 1994; Masera et al. 1997; Moffat 1997; Cao and Woodward 1998; DeLucia et al. 1999). In contrast to other strategies for reducing net carbon emissions, terrestrial sequestration has the potential for rapid implementation. Increasing terrestrial carbon storage in soils is generally beneficial in that it is associated with improved soil quality and infiltration, yielding higher levels of land productivity. The carbon pools in terrestrial ecosystems are dynamic and these dynamics need to be accounted in carbon management and sequestration strategies. Terrestrial carbon sequestration is an important component of an overall carbon management plan, which should include direct reduction of emissions, because it is the method that can be most rapidly implemented, the potential storage is large, and there are ancillary positive benefits associated with increasing soil carbon concentrations.

Conference Highlights in Terrestrial Ecosystem Carbon Sequestration

Various aspects of TBCS were discussed at several terrestrial ecosystem sessions of the Conference. Jacobs (this proceedings), for example, pointed out that CS research is jump-started by past DOE (Office of Science-SC) supported research on the terrestrial carbon cycle, on ecosystem response to CO_2, and integrated assessment activities. In addition, SC has supported innovative studies in biotechnology and microbial and plant genetics – all offering new scientific advances. It is clear from presentations by Jacobs and others that TBCS R&D is really in its infancy, and that as new knowledge is gained, we can expect new strategies that will enhance TBCS. Scientific advances will lead to new measurement methods, enable better understanding of ecosystem carbon processes, result in improved models to assess future sequestration options, and develop engineering approaches for implementing improved strategies.

Presentations on terrestrial ecosystems at the NETL First National Conference on carbon sequestration generally fell into three categories:

1. Estimating the current potentials of sequestration in terrestrial systems, including how carbon dynamics and losses can be incorporated into assessment of more realistic carbon management and sequestration strategies.
2. Development of improved means for measuring, estimating, and managing carbon inventories.
3. Evaluation of strategies and policies related to terrestrial carbon management.

Some of the main points in each category are highlighted below:

1. Estimating the current potentials of sequestration in terrestrial systems

Several efforts are underway to improve estimates of the magnitude of the potential increase in terrestrial carbon storage. Estimates are variable, but the potential is generally thought to be large relative to the amount of annual US and global carbon emissions. Jacobs et al presented an overview of carbon activities. Garten presented a more site-specific estimation of carbon storage potential. Many of the presentations at the conference highlighted the importance of accounting for ecosystem dynamics related to carbon. For example, Breshears et al. highlighted the potential for fire and drought (and the increases in erosion rates that can be associated with both of these processes) to produce large rapid losses of carbon. The potential for these losses to occur needs to be factored into overall estimates and plans, and where feasible, management needs to mitigate that potential (e.g., fire management). Izaurralde also highlighted the role of soil carbon loss via erosion.

2. Development of improved means for measuring, estimating, and managing carbon inventories

Terrestrial carbon pools are highly spatially heterogeneous and dynamic, and these factors pose challenges in quantifying terrestrial carbon inventories and fluxes. Several of the presentations focused on new methods for measuring soil carbon (Ebinger et al. and Wullschleger). Improved methods are needed to more rapidly and accurately measure soil carbon, to measure soil carbon in situ in the field, and to more efficiently differentiate soil carbon components. Also of interest is determining the genetic constraints on plant growth within terrestrial and associated aquatic systems (e.g., Tuskan, Unkefer et al.). These factors need to be integrated with the ecosystem dynamics studied in #1 above.

3. Evaluation of strategies and policies related to terrestrial carbon management

Carbon management and sequestration strategies need to consider the implications of alternative estimation and accounting policies. Several different types of carbon assessment approaches were presented at the meeting (e.g. Paustian, King, McCarl, Sparrow, West). Important issues related to alternative methodologies include consideration of appropriate spatial and temporal resolution of carbon estimates and the costs and uncertainties associated with given carbon estimates.

Carbon Sequestration by the Terrestrial Biosphere

The terrestrial biosphere is a natural sink for the excess carbon dioxide (CO_2) that combustion of fossil fuels produces. Carbon accumulates in biomass and soils of all viable ecosystems due to net gains resulting from photosynthetic carbon uptake exceeding respiration loss. Growth and productivity of grasslands, forests, agricultural lands and other hugely diverse ecosystems intrinsically generate net carbon gain in the Earth' terrestrial biosphere. Another expression for the biological gain of carbon involving these ecosystem processes is Net Ecosystem Production. Accumulated and persistent gains (i.e., NEP) over time results in Terrestrial Biosphere Carbon Sequestration (TBCS).

NEP as the Measure of Ecosystem Carbon Sequestration

A rich history of carbon cycle research provides a reasonable understanding of ecosystem productivity and associated carbon budgets for the contemporary time frame. Data on primary productivity and carbon stocks are summarized in the DOE Road Map (Table 4.1, USDOE 1999), and relationships of ecosystem photosynthesis and respiration are discussed. However, as illustrated by these data, there is little or no quantitative information about ecosystem respiration so that calculations of NEP are often based on assumption or inference. Theoretically, NEP (net carbon gain or carbon sequestration) is represented by

$$NEP = GPP - (R_A + R_H)$$

where:
NEP = Net Ecosystem Production, or net C gain or C sequestered
GPP = Gross Primary Production, or C assimilated by canopy photosynthesis
$(R_A + R_H)$ = C loss through plant respiration (R_A) and organic matter decomposition (R_H)

Because of the general lack of data on ecosystem respiration there have been problems with using this approach to estimate carbon sequestration or TBCS.

Eddy Co-Variance Measurement of NEP

Recent research has provided new and direct measurement of NEP. The eddy-covariance method measures continuously net CO_2 exchange between the ecosystem and the atmosphere. Figure 1 illustrates implementation of the approach and direct measure of CO_2 flux at a forest site. Instruments installed on a tower extending from the surface through the canopy measure both movement of air parcels (i.e., eddys) and CO_2 concentration. The CO_2 flux measurement captures both photosynthetic uptake of CO_2 and the release of CO_2 by biomass and soil respiration. Net flux integrals are accumulated over desired time intervals (i.e., seconds, minutes, hours, etc), and the annual integration of rates of CO_2 exchange becomes net ecosystem exchange of CO_2. This annual quantity is equivalent to NEP or net carbon sequestration. Figure 2 shows daily net values, and annual integrals for several forests in the eastern USA. NEP ranges from 2 to 4 tonnes of carbon per year for these ecosystems. These data are typical of results obtained for 11 years from the Harvard Forest site, and for 5 years at the Howland and Oak Ridge sites. While year-to-year variation has been observed, the eddy covariance sums are usually within 25% of these reported values. At several sites, detailed measurements of biomass and soil carbon components have produced independent estimates of ecosystem NEP; the biometric-derived estimates compare favorably with the flux measurements. Thus, the new eddy-covariance technology is capable of directly measuring carbon sequestration of forest ecosystems. The technology has been deployed with grassland, crop and various other ecosystems, and has produced reliable data at a number of sites.

Flux Networks

There are a number of worldwide networks where net ecosystem exchange of CO_2 is being measured. Systematic measurements in the America's and Canada make up the AmeriFlux Network (Fig 3). The European is known as Carbo-Europe. An AsiaFlux network includes eastern Siberia, China, Japan, Korea S.E. Asia countries and Japan. In all there are about 145 sites comprising a global Flux Network that are producing net CO_2 exchange data, and much of the data will have unique value for estimating carbon sequestration of the terrestrial biosphere. More detailed description of sites and data files can be obtained at the web site (http://cdiac.esd.ornl.gov/programs/ameriflux).

Multi-year data from AmeriFlux and Carbo-Europe sites are shown in Figure 4. Net ecosystem exchange (NEE) of CO_2 is plotted against latitude for comparative purposes. In this case the negative NEE values represent net annual uptake of CO_2 by forest ecosystems from above 60 degrees N latitude to 30 degrees N latitude. Both data sets show increasing CO_2 uptake at lower latitudes, or at warmer temperatures and longer growing seasons. The range of NEE is from zero at high latitude to 750 $g/m^2/yr$, which translates into zero to 7.5 tonnes of carbon per hectare per year. Although there is an offset in NEE between the two data sets, which is explained by generally warmer conditions at equivalent latitudes in Europe (i.e., the Gulf Stream warming), the common rate of change (i.e., similar regression line slope) suggests that CO_2 uptake is regulated by similar intrinsic ecosystem processes. Thus, these data collections that span a wide range of ecosystem types are beginning to provide a scientific foundation for model calculation of carbon sequestration for larger landscape areas – based on knowledge of ecosystem properties and regional climate parameters.

TBCS Calculated from NEE and Forestry Data

Considering the full data set of Fig 4, a median NEE (i.e., NEP) value at roughly mid-latitude of the N. hemisphere is approximately 300 $gC/m_2/yr$ or about 3 tonnes per hectare per year. Since these NEE data are based on direct measurements, and since NEE = NEP, its possible to estimate TBCS of forested landscapes worldwide. Multiplying the 3 tonnes per hectare by the global area (10^{13} m^2) of deciduous forests (the mid-latitude data from Fig 4 largely represent deciduous forest ecosystems) yields an estimated annual carbon sequestration of 3Gt C/y. While this approximation is based on high precision NEE measurements, and global deciduous forest area is also known to a reasonable accuracy, the 3 Gt calculation clearly cannot be considered a definitive answer. However, while not all errors are known, and the estimate is "work-in-progress," the quantity still illustrates the potential of terrestrial ecosystems for sequestering excess CO_2. When the NEP for other non-deciduous forests and other types of ecosystems are considered, the current amount of carbon sequestered by terrestrial ecosystems will exceed the estimated 3 Gt C/yr.

NEP vs NBP and Carbon Sequestration

It has been pointed out in other analyses that ecosystem scale estimates of NEP do not necessarily represent net biosphere productivity (NBP) because other landscape scale processes like fire, insect infestations, and land use change may reverse or neutralize intrinsic rates of ecosystem carbon accumulation. Providing NBP estimates would call for another level of accounting, however. Land-use history, for example, is one factor that may affect NBP accounting. For example, it is generally recognized that large land areas of North America, Europe, Asia, and Australia are presently net carbon sinks because of previous century forestry and agricultural land-use practices that resulted in massive reductions in wood biomass and soil organic matter. Carbon sinks in these areas are attributed to recovery of biomass and soil following the loss of approximately 30 Gt C from prior management practices (Houghton and Hackler 2001). Over the second part of the 20th century these regions have become carbon sinks as the result of forest regrowth and reversion of formerly forested land after agricultural abandonment. The decline in soil organic matter in agricultural soil has also been halted and is gradually being increased by rising agricultural productivity and reduced tillage intensity. These synchronous recoveries lead to significant NBP gains of the large regional and continental areas. For this circumstance, improved management of recovering land, and smart management of land area not previously impacted will likely produce CS gains that exceed last century carbon losses.

Thus, it is important to recognize that many landscape scale processes that often involve human intervention can be managed with the intent of protecting or preserving sequestered carbon, thereby causing NBP to exceed current measures of NEP. The point is that landscape scale considerations are likely to sustain or possibly enhance the intrinsic quantity of sequestered carbon calculated from eddy covariance measurements.

What is the Future Potential TBCS?

There are two aspects to this question. First what TBCS could be achieved with existing knowledge and practices either right now or in the near future? Second, with a focused R&D program, what enhancements might be possible?

There are seven near-term strategies (see below), that if implemented could lead to TBCS of up to 10 Gt C/y. These rates cannot be maintained indefinitely. However, it is likely that they could be generated for 25-50 years or so. If forests were managed for sustainable harvesting with the wood put into long-lived products, or the creation of bioproducts or biofuel, the forest rates could be extended even longer. Let’s assume a conservative estimate of 5 Gt C/y for a total carbon storage value on the order of 250 Gt C for a 50 year time period.

1. Reverse current land use change that emits CO_2. Globally, it is estimated that approximately 1.5 Gt C/year are released to the atmosphere from changing land use. This potential could be realized through improved management and development practices that promote the protection of lands with high carbon value.
2. As described above, 3 Gt C/year or more will continue to be sequestered if currently forested lands are properly managed.
3. Reforestation (or afforestation) of a small portion of available global lands (6×10^{12} m^2 ~5% global land area) could eventually generate sequestration of ~2 Gt C/year (assuming NEP ~300 g $C/m^2/y$ as above). This value is uncertain, but provides an order-of-magnitude possible potential (Amthor and Jacobs 2000)

4. Through agricultural practices, the world has "lost" perhaps 50 Gt C from soil. Over the next 50 y, it might be possible to recapture and store this soil C by improved agricultural practices (e.g., low-till) at a rate of 1 Gt C/y (Amthor and Jacobs 2000).
5. Remediation of degraded lands is estimated to provide a sequestration potential of 1 Gt C/year (USDOE 1999).
6. Management of grasslands and rangelands has been estimated at 0.5 to 1 Gt C/y (USDOE 1999).
7. Coupling the use of biomass for products, fuel, and power with soil C sequestration could lead to rates on the order of 1 Gt C/y (USDOE 1999).

The second aspect addresses whether the above values could be enhanced through research and development. There is no perfect precedent for such assessments, so we look to the agricultural sector for some possible analogies. From 1950 through 1999, USDA (2000) reports crop productivity increases from about 70 to 250% depending on crop type, for an average of 145%. English and Chuang (1997) provide estimates for projected continued increases in productivity that range from 90 to 157%, with an average of 114%. Assuming that R&D increases potential rates of TBCS only 50% over the next 50 years, and furthermore that such increases can be realized only on options 3-7 in the above paragraph, would lead to sequestration rates of an additional ~3 Gt C/y. Over a 50 y period, this would lead to another 150 Gt C sequestered.

If these potentials can be achieved, the TBCS options offers total sequestration over the next 100 years of perhaps 250 to 400 Gt C. This amount offers a significant percentage of the ~500 Gt C the world is expected to have to sequester to help mitigate possible climate change impacts by 2100 (Bajura 2001, this conference).

TBCS at What Cost?

There are few operational experiences where an actual cost of TBCS has been evaluated. *A priori*, it is likely that TBCS could be implemented in multiple strategies where costs could range from near zero to modest payments for optimization and management. The concept of ecosystems functioning as "natural biological scrubber" is introduced by the Road Map (USDOE 1999), and if this approach is implemented with park and protected forests, for example, carbon is sequestered at essential zero cost. In such circumstances, the annual carbon increment enhances ecosystem quality (e.g., improved biodiversity, soil productivity, moisture retention, etc), where if value is assigned to these properties and credited to a carbon increment, then terrestrial sequestration would offer negative cost or a net environmental benefit. This scenario would occupy one end of the cost spectrum.

Perhaps on the other end of the cost spectrum, actual payment to optimize nominal rate sequestration AND to secure long-term stability of sequestered carbon would be on the order of $10-20/t C. Current projects being led by The Nature Conservancy (Coda 2001, this conference) have costs that range from $10 to $20 /t C. Monitoring and verification are estimated at roughly 20% of these costs. Through R&D, these costs will surely be significantly reduced. Achieving enhanced sequestration may require additional investment in management, technology and research, but total cost would not be expected to be significantly more than that for nominal rate sequestration. Investments in R&D may result in enhanced sequestration for no cost increase beyond the current inexpensive rates.

It is also possible to postulate intermediate strategies across the cost spectrum that could take advantage of various natural mechanisms and market conditions. The main point, however, is that terrestrial options typically have a low-cost threshold because applications logically build on the natural, intrinsic biological CO_2 scrubbing tendency of ecosystems, and in many instances, there is no requirement for expensive capture, transport and engineered disposal technology.

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Ameriflux Approach

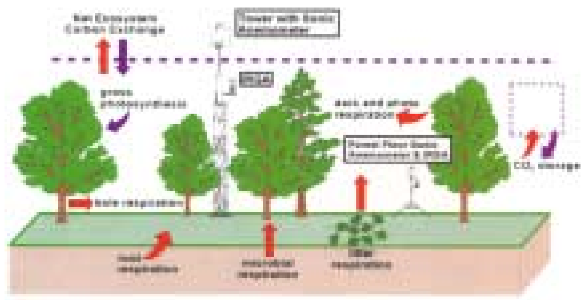

Figure 1: Approach and direct measurement of CO_2 flux at a forest site. Eddy co-variance instruments mounted on the tower measure net exchange of CO_2 (NEE) of the forest ecosystem. NEE represents the net of carbon gain by photosynthesis and loss by the various components of respiration.

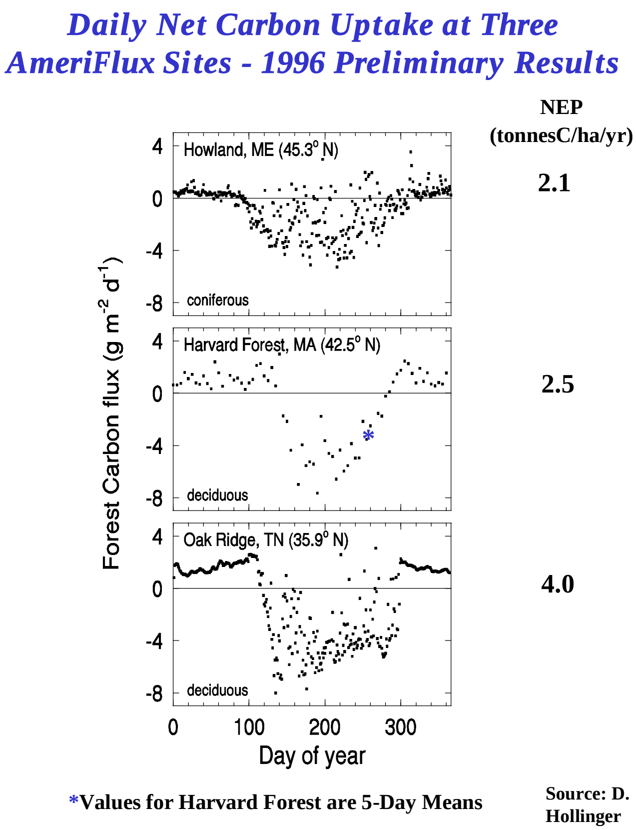

Figure 2: Daily NEE values for three AmeriFlux sites (except for Harvard Forest, which are 5-day averages), and annual NEP calculation. Negative net quantity shown on ordinate is CO_2 exchange with respect to the atmosphere; values above the zero line represent daily respiration loss from the forest, and below the line are daily photosynthetic gains. The annual integral of all measurements gives annual NEE (i.e., NEP or CS) of the forests. (Data used by permission of D. Hollinger, AmeriFlux Science Team Leader)

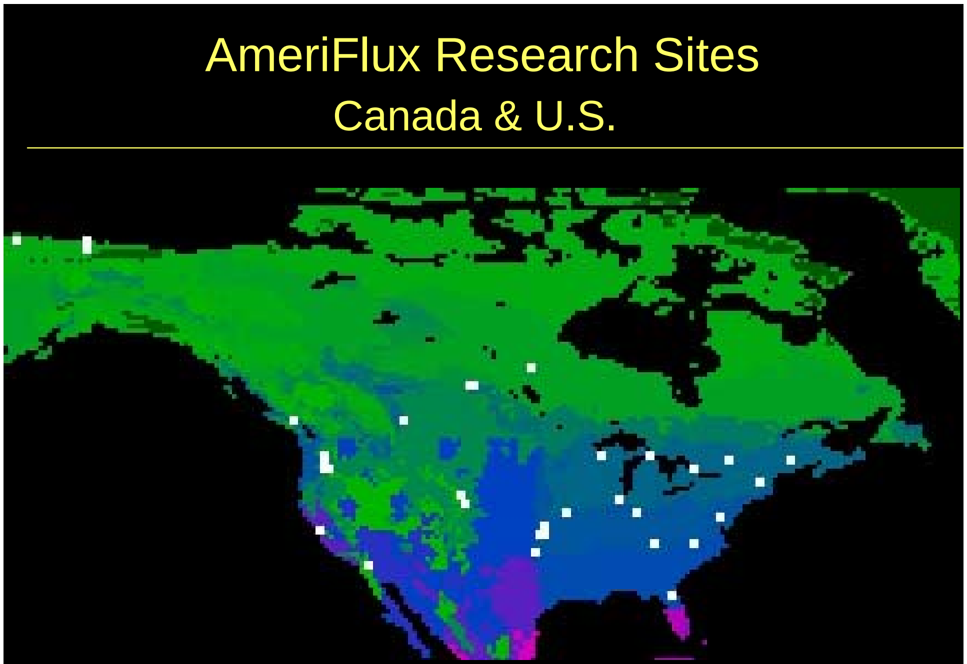

Figure 3: AmeriFlux Network: Sites where systematic NEE data have been obtained in North and America and Canada.

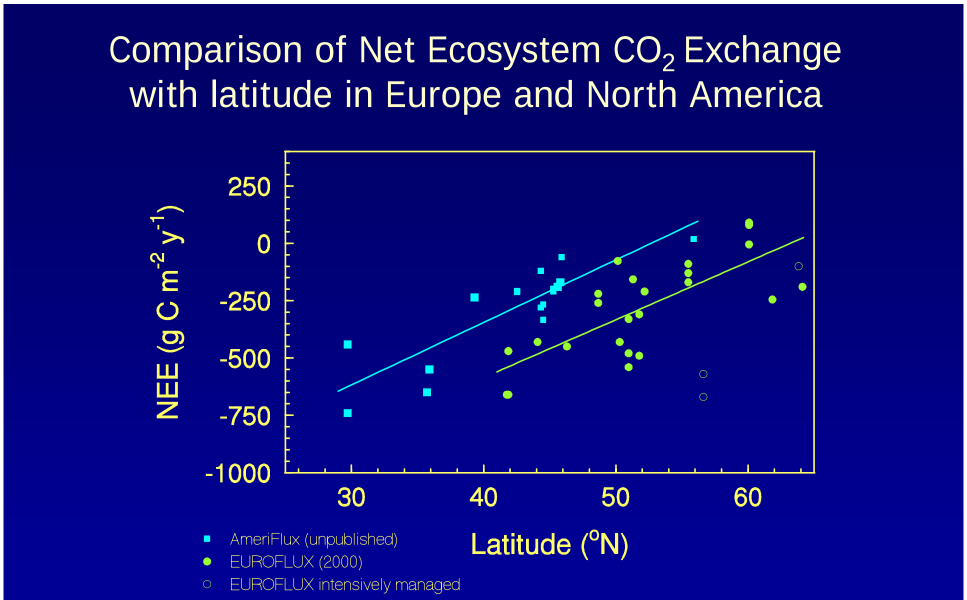

Figure 4: Comparison of NEE of CO_2 data from AmeriFlux and Carbo-Europe (NEE convention is same as in Fig 2). NEE plotted as a function of latitude illustrates greater NEP or CS in warmer regions of both N. America and Europe. (Data used by permission of D. Hollinger, AmeriFlux Science Team Leader)