The Impact of CO_2 Fertilization, Changing Land Use, and N-deposition on Soil Carbon Storage

by Kevin Geyer Harrison

Submitted in partial fulfillment of the
requirements for the degree
of Doctor of Philosophy
in the Graduate School of Arts and Sciences

COLUMBIA UNIVERSITY
1994

ABSTRACT

The Impact of CO_2 Fertilization, Changing Land Use and N-deposition on Soil Carbon Storage

Kevin Geyer Harrison

Fossil fuel combustion and changing land use have increased atmospheric and oceanic carbon inventories less dramatically than expected. This discrepancy has been termed the "missing sink." CO_2 fertilization and N-deposition processes could be sequestering some of this missing carbon. An improved understanding of disturbance and recovery carbon dynamics associated with changing land use may reduce this discrepancy by lowering biospheric release estimates. This research explores how these perturbations alter soil carbon inventories.

Soil carbon responds to perturbations to a greater or lesser extent, depending on the turnover time of the soil organic material. Using radiocarbon measurements and a simple model, I have modelled soil organic material's turnover times, which range from decades to millennia, as a binary system having active and passive components.

CO_2 fertilization, the plant net primary productivity increase observed at elevated CO_2 levels, increases soil carbon inventories. This research introduces a "greening" model to estimate this increase, using a CO_2 fertilization factor, active soil carbon inventory, and turnover time.

This research also uses radiocarbon measurements to examine how cultivation reduces the inventory of active soil carbon. Further, the relationships between carbon loss and vegetation type, farming technique, and the clay content of soil have been examined to identify patterns that can be used to develop strategies for mitigating future carbon loss.

Formerly cultivated lands that are undergoing secondary succession can sequester atmospheric carbon. This research extends previous work in this area. One coniferous site in this study had a higher soil carbon inventory than its native deciduous counterpart.

Anthropogenic nitrogen deposition, like CO_2 fertilization, may also increase soil carbon storage. This research sets limits on the amount of carbon sequestered by nitrogen deposition by determining the amount and fate of anthropogenic nitrogen.

In summary, CO_2 fertilization and N-deposition can potentially sequester a major portion of the so-called missing sink. This research identifies ways to limit biospheric carbon loss and enhance carbon recovery on formerly disturbed lands.

Table of Contents

List of Tables

List of Figures

Acknowledgements:

While I worked toward my Ph. D. at Lamont, numerous people shared their time and expertise selflessly, and, mentioned or unmentioned, I thank them all.

Wally Broecker heads the list. Scientists acquainted with him consider him a character, perhaps a prerequisite to being a world class geochemist. Working with Wally has proven to be extremely challenging, but equally rewarding. He provided an incredibly stimulating environment that often left my head spinning. He always presented problems, but not without attendant help and encouragement. Wally allowed me to have differing opinions, if I could defend them.

Through a multitude of carefully considered questions, Inez Fung insured that I could explain every aspect of my research. Every time I met with Inez she would bring up recent advances in global change geochemistry and make me relate them to my thesis research. She brought many obscure but valuable references to my attention.

Jim Simpson added considerable perspective to this research, often pointing out seemingly insignificant aspects the proved important. He encouraged me to develop and follow up on my new research ideas.

Sue Trumbore provided considerable advice at all stages. Rick Fairbanks, Flip Froelich and Tyler Volk, all members of my examining committee, did an exemplary job helping me through the defense process.

I collaborated with many scientists outside Lamont, including those at Duke University, Kansas State University, the Soil Science Institute in Firenze, Italy, and the University of Saskatchewan. Eric Haney and Peter Harrell helped select the Duke Experimental Forest field sites and did considerable work in constructing the 2 meter deep soil pits. Professors Bill Schlesinger, Dan Richter and Norm Christenson hosted my visit to Duke, helped select the field sites and shared their expertise in many discussions that helped clarify my research objectives. Jeff Schoenau hosted my visit to the University of Saskatchewan, provided soil samples and supporting data, and made valuable suggestions for further research. Michel Ransom hosted my visit to Kansas State University, and with Bill Wehmueller, helped me select fields sites and use the soil probe truck. I thank Edoardo A. C. Costantini (Istituto Sperimentale per Lo Studio) for helping in Italy by providing soil samples on short notice. Thankfully, his English was far better than my Italian.

Many people at Lamont aided in the completion of my thesis. Nancy Mager ensured smooth and rapid communication between the various committee members and investigators associated with this project. In the graduate office, Mia Leo, Betty Hiscock and Missy Pinckert provided invaluable assistance in negotiating the maze of requirements at Lamont and Columbia. In particular, Mia helped me through some inevitable rough spots. Guy Mathieu instructed me in the art of making graphite radiocarbon targets for accelerator mass spectrometry. Rick Mortlock, Marty Fleischer, Pat Malone and Linda Baker all helped get me running solo on the Carlo Erba Carbon Nitrogen Analyzer. Patty Catanzaro transformed my sketches into true graphics.

The students at Lamont offered considerable help. Rachel Oxburgh helped greatly with the modelling. Steve Chillrud lent his expertise in many analyses, helped me interpret the more perplexing results and offered much encouragement toward completing my research.

I especially thank Beth Ann Zambella for her understanding, encouragement, able library research and hard work transforming my peripatetic thoughts into comprehensible manuscripts. Her love and inspiration helped overcome the multitude of challenges I encountered.

The Department of Energy and a NASA Global Change Fellowship funded this research.

Chapter 1: Soil Carbon and Atmospheric CO_2 Concentrations

Abstract:

This research strives to assess the impact of CO_2 fertilization, changing land use and nitrogen deposition on soil carbon storage. This research tests the hypothesis that soil sequesters a significant portion of the so-called missing sink. To test this hypothesis, I have developed a greening model that uses CO_2 growth enhancement results and radiocarbon-based estimates of soil carbon turnover times. I have explored the effects of land use changes on soil radiocarbon and carbon content at sites in North Carolina, Lombardy, Saskatchewan and Kansas. Natural N-fixation appears to promote enhanced soil recovery at an abandoned site and limits carbon losses at a cultivated site. I have also explored how N-deposition may increase carbon storage on land and in the ocean.

Introduction:

This thesis explores the impact of CO_2 fertilization, changing land use and N-deposition on soil carbon and nitrogen storage. Schlesinger (1991) estimates that soil carbon reservoirs hold about 1500 GtC, which is almost three times the amount of carbon in the pre-industrial atmosphere and nearly three times the amount of carbon residing in terrestrial vegetation. CO_2 fertilization is the observation that plants increase their net primary production when exposed to elevated carbon dioxide levels. I examine the possibility that CO_2 fertilization may be working to increase the size of the soil carbon reservoir. To study how perturbations such as CO_2 fertilization influence soil carbon, the residence time of soil carbon must be known. The mean residence time is a barometer for how quickly a pool can respond to perturbations. Those with short turnover times respond the fastest. Hence, a pool of carbon that turns over every thousand years will not

show a big increase due to perturbations, such as increased net primary productivity. The carbon pool's turnover times and inventories for the terrestrial biosphere are listed in table 1.1. In chapter 2, I show how soil radiocarbon measurements can be used to estimate soil carbon turnover times and inventories. Once I have determined the turnover times and inventory of active soil carbon, I will estimate the amount of carbon sequestered by the terrestrial biosphere with a CO_2 fertilization or greening model.

Disturbances, such as deforestation and cultivation, have affected soil radiocarbon, carbon and nitrogen inventories (chapters 3 and 4). Once farmers and lumberjacks abandon the disturbed land, carbon inventories usually begin to increase. Chapter 5 explores the dynamics of soil carbon recovery. Kauppi et al. (1992) have postulated that N-deposition has significantly increased terrestrial biosphere biomass. Chapter 6 sets limits on the amount of carbon sequestered because of anthropogenic N-deposition.

Global Carbon Budget:

The size of the imbalance between CO_2 sources (fossil fuel combustion and changing land use) and CO_2 sinks (increasing atmospheric and oceanic inventories) alarms scientists and policy makers. Sundquist (1993) estimates this imbalance is 1.8 ± 1.4 Gt C/year for the 1980's (see table 1.2). Until scientists reduce these uncertainties, creating a strategy to reduce the rate of atmospheric carbon dioxide buildup is difficult. The largest uncertainty in the global carbon budget is the terrestrial biosphere.

Previous researchers have estimated biospheric carbon release using a bookkeeping technique (Houghton & Skole, 1990). The bookkeeping technique uses land use records, estimates of native and disturbed carbon inventories, lifetimes of harvested products, rates and extents of recovery to estimate biospheric release. The fractional loss of terrestrial biospheric carbon for native ecosystems can be measured as a function of time. Similarly, the recovery of abandoned cultivated lands can be measured as a function of time. These losses and gains can be extrapolated to the world using land-use records. The accuracy of these methods depends on the quality of the available economic records (Skole and Tucker, 1993) and the assumptions of biospheric carbon inventories prior to the disturbance. Furthermore, this technique cannot account for processes such as CO_2 fertilization and N-deposition that could be stimulating carbon storage in the terrestrial biosphere.

Scientists have developed three isotopic techniques to estimate biospheric carbon release that are independent of the bookkeeping technique. Siegenthaler & Oeschger (1987) have estimated that biospheric carbon releases ranged from 0-18 GtC from 1958 to 1978 (i. e. 0 to 0.9 GtC/year), which is significantly less than the 32 GtC (1.8 Gt C/year) estimated by Houghton & Skole (1990). Siegenthaler & Oeschger estimate net biospheric release by using a deconvolution technique: they infer a carbon loss from the biosphere using an ocean uptake model and atmospheric measurements of C-13 and CO_2. Keeling & Shertz (1992) have developed a new interferometric technique to measure oxygen, and they use seasonal variations and temporal trends in atmospheric oxygen concentrations to estimate biospheric carbon release. While the results of this technique are intriguing, it will be years before geochemists reduce uncertainties enough to allow meaningful comparisons with other techniques. Quay et al. (1992) have developed a strategy for estimating biospheric release using stable carbon isotopes. The current dearth of oceanic C-13 data will limit the use of this technique because the uncertainties is the data do not further constrain the global carbon budget.

Why do the bookkeeping and isotopic techniques give markedly different estimates of biospheric losses? One possibility is greening of the terrestrial biosphere provides the most likely candidate for reducing these differences. Greening can be defined as increasing the carbon storage in the terrestrial biosphere by anthropogenic alterations. Increasing levels of atmospheric carbon dioxide and anthropogenic N-deposition provide possible solutions. Unlike the isotopic and bookkeeping techniques, which imply greening indirectly, I have estimated the amount of carbon sequestered by CO_2 fertilization and N-deposition more directly. Before perturbations to the terrestrial biosphere can be put in the proper context, one needs to know the turnover time and inventory of active soil carbon. The residence (also turnover & replacement) time can be defined as the time it takes for the carbon input (or loss) from a pool to equal the total amount of carbon in the pool. Carbon pools having the shortest residence times will show the fastest response to perturbations.

Skole and Turner (1993) discuss some of the difficulties in measuring the area of land that undergoes change and offer a way of improving future bookkeeping estimates. For example, studies of the amount of Amazon forest present made by three different groups came up with vastly different answers. The FAO-UNEP group found 3, 562, 800 km^2, the IBGE group found 3, 793, 664 km^2, and Fearnside and coworkers found 4, 195, 660 km^2 of forest. The area of forest found by high resolution satellite was 5, 032, 920 km^2.

When the uncertainties in land use area are combined with carbon inventory uncertainties to estimate carbon fluxes from particular regions, the differences can grow larger. R. A. Houghton (1993) points out differences in estimated carbon accumulation rates: Sedjo (1992) estimated that the former Soviet Union is sequestering 0.416 GtC/yr, while Melillo et al's. (1988) estimate is 0.154 GtC/yr.

The soil humus reservoir of 1500 GtC translates to an average inventory of 1 g C/cm^2 or 100, 000 kg C/hectare. Were this carbon mixed uniformly to a depth of 20 cm, it would overage 0.05 g C/cm^3. Harrison et al. (1993) estimate that after exclusion of peats and what they call passive organic soil carbon, the total drops to 500 GtC, which corresponds to a mean 0.35 g C/cm^2 and 1.5% carbon in a homogenized 20 cm-long soil column.

Soil Carbon Turnover:

Chapter 2 describes a strategy for estimating carbon turnover times using soil radiocarbon measurements. The radiocarbon age of pre-bomb soil suggests that surface soil carbon turns over every 850 years. But the observed increase in soil radiocarbon after bombs released radiocarbon to the atmosphere (1950-1964; see figure 1.1) suggests that there is a component of soil carbon that has a fast turnover time. Clearly, soil carbon contains a continuum of compounds whose turnover times range from a few years to a few millennia. I model soil carbon as a binary system: active and passive. Currently, the available bulk soil radiocarbon data do not warrant using more than two components, but clearly indicate the inadequacy of using a single component. Active carbon has a residence time short enough to respond to anthropogenic perturbations. Passive soil carbon's residence time is so long that it will not show a significant response on the decadal time scale.

Because the radiocarbon age of deep soil often exceeds thousands of years, I have assumed that deep soil (at depths greater than 0.5 to 1.0 meters, where soil radiocarbon values approach a minimum value) contains only passive soil carbon (see figure 1.2). Therefore, radiocarbon measurements of deep soil carbon can be used to estimate passive soil carbon turnover times.

The proportion of active to passive carbon in surface soil can be determined using the passive turnover time and the average pre-bomb surface value. The active soil carbon turnover time can be estimated by comparing the observed increases in post-bomb soil radiocarbon with hypothetical turnover times generated by models.

Greening:

Having determined the active soil carbon turnover time and inventories, a CO_2 fertilization or greening model (see figure 1.3) can predict the amount of carbon sequestered by the terrestrial biosphere (see chapter 2). Increasing levels of atmospheric carbon dioxide can increase plant net primary productivity (Strain & Cure, 1985 and see figure 1.4). Bazazz and Fajer (1992) suggest that elevated carbon dioxide levels increase water use efficiency and decrease photo-respiration, leading to increased productivity for chamber experiments. Native ecosystems, which face species competition and nutrient limitations may show a reduced response to CO_2 fertilization. We use these chamber results for lack of more realistic measurements.

Changing Land Use:

In contrast to CO_2 fertilization, cultivation reduces soil carbon inventories by 25% (Schlesinger, 1986; Post & Mann, 1990; see also figure 1.5). Hence, I expect disturbed surface soils to have lower radiocarbon values than native soils. Figure 1.6 supports this assertion: while there is considerable scatter, the cultivated soil radiocarbon values all lie below the native soil radiocarbon values. Cultivation appears to have reduced the inventory of fast cycling carbon. Chapter 3 explores this hypothesis, which compares model predictions with data for native and cultivated surface soils worldwide.

This research explores the dynamics of carbon and nitrogen loss associated with changing land use by looking at paired native and cultivated sites by sampling forested and grassland sites in different climates in North Carolina, Saskatchewan, Kansas and Lombardy, Italy (chapter 4). The North Carolina site includes a native temperate deciduous forest and a flat cultivated site that has been continuously row cropped for tobacco since 1949. Farmers planted the sloped Saskatchewan boreal site using a fallow/cereal crop rotation. The Saskatchewan grassland site is also on a slope. Researchers selected the Lombardy grassland site because of its high clay content, to test the hypothesis that carbon lost from surface soil could be redeposited in deeper soil, like a chromatographic column (Meints & Peterson, 1977). The Kansas site was chosen to see how N_2 fixing crops have affected soil carbon and nitrogen inventories.

After farmers and lumberjacks have disturbed and abandoned land, it begins to reestablish its vegetative cover. The dynamics of this recovery and impact on carbon and nitrogen inventories are not well known (Schlesinger, 1986). Even so, recovery forms an important and perhaps untested component for the bookkeeping approach. The role of N-fixing vegetation in enhancing soil carbon recovery is studied. Perhaps, adding usable nitrogen can increase the carbon inventory in soil. The recovering Kansas grassland site was selected because it is unlikely that any nitrogen fixing scrub would be planted on an abandoned cultivated site; these are often seeded with brome grass. This site contrasts with a North Carolina site where N_2 fixing scrub could have bolstered soil N levels after abandonment. Archived soils from a South Carolina site show how the dynamics of soil carbon recovery can be explored using radiocarbon measurements.

Soil Carbon Variability:

Measurements of soil properties, such as carbon and nitrogen contents, will likely show more variability than similar properties measured in the open ocean and in the remote atmosphere because mixing of soil is very slow compared to mixing the more fluid atmosphere and hydrosphere. To begin to address soil heterogeneity, I took replicates at most sites: North Carolina (6), South Carolina (8), Saskatchewan (5), and Lombardy (5). Replicates were not collected in Kansas because good land use history could not be obtained and not taken for the North Carolina cultivated site because the site was not adjacent to the native and recovering sites.

In planning this study, I based my sampling on the work of Anderson (1991). He found carbon inventory variability to average 11% for native soils and 16% for cultivated soils (see table 1.3). These results seem counterintuitive because one expects plowing to

homogenize soil. Perhaps, plowing mixes heterogeneously and suppresses natural mixing processes.

At the North Carolina native site (see tables 1.4 and 1.5), the standard deviation for five sites was 10% for the carbon inventory and 8% for the nitrogen inventory. The recovering site showed even greater variations. The North Carolina recovering standard deviation was 11% for the carbon inventory and 16% for the nitrogen inventory. The samples from Saskatchewan, Lombardy, and South Carolina were homogenized before analysis.

Nitrogen Deposition:

Like the CO_2 fertilization discussed in chapter 2, N-deposition has the potential to sequester carbon on land and in the ocean. If we assume that all the deposited nitrogen (ammonia and nitrate) is anthropogenic (0.1 Gt N/year; Duce et al., 1991), then 0.7 to 15 GtC could be sequestered, depending on the C/N ratios for the resulting organic compounds. The C/N ratios in this thesis are reported by mass. The C/N ratios are about 7 for marine humus (plankton and plankton debris), 15 for bulk soil and about 150 for trees (Schlesinger, 1991). Chapter 6 explores the amount of anthropogenic N produced annually, the ecosystems it gets deposited on and the fraction of N that remains in the ecosystem. Researchers have determined that most of the retained nitrogen gets incorporated into soil organic material (Aber, 1992). Nitrogen lost from the land ends up in the ocean or similar aquatic environments, which also receive N via direct deposition.

Summary:

In assessing the role of soil carbon in mediating atmospheric carbon dioxide levels, geochemists need to know the turnover time and inventory of active soil carbon.

This work develops a strategy for estimating soil carbon turnover rates using radiocarbon measurements. The turnover times and inventory sizes of the terrestrial biosphere can be used in a greening model to compare the carbon sequestration due to CO_2 fertilization with the so-called missing sink. This thesis explores the dynamics of carbon loss and recovery caused by changing land use (see table 1.6), takes a brief look at engineering managed land to reduce carbon losses associated with disturbance and to enhance soil carbon recovery of cultivated lands., and assesses the role of anthropogenic N-deposition in increasing biospheric carbon.

Table 1.1: Terrestrial Biosphere: inventories and turnover times.

Carbon pool	inventory size (GtC)	residence time (years)
soil(<1 meter)	1500[a]	?
litter*	60[b]-240[c]	1.2[b]
long-lived vegetation	500[b]	25[d]-63[b]
short-lived vegetation	90[b]	1.5[b]

*stem, branch and twig litter.

Schlesinger (1991) estimates 1500 Gt C of carbon are stored in soils. However, soil contains a continuum of compounds whose turnover time ranges from a few years to a few millennia. Warneck (1988) has estimated the turnover time and residence times of the litter and vegetations pools in the terrestrial biosphere.

[a] Schlesinger, 1991

[b] Warneck, 1988

[c] Potter (In Press)

[d] Emanuel et al., 1984

Table 1.2: The Global Carbon Budget for the 1980's.

Reservoir	Average flux GtC*/year
Sources	
Fossil fuel combustion	5.4 ± 0.5
Deforestation & land use	1.6 ± 1.0
Total	7.0 ± 1.2
Sinks	
Atmosphere increase	3.2 ± 0.1
Oceans (modeled uptake)	2.0 ± 0.8
Total	5.2 ± 0.8
Imbalance (sources - sinks)	1.8 ± 1.4

(Sundquist, 1993)

*GtC equals 10^{15} grams of carbon.

Table 1.3: Soil variability in Canadian (Saskatchewan) soils (Anderson, 1991).

Zone (g/cm2)	Native organic C (g/cm2)	Cultivated organic C
Brown (21)	1.054±0.129	1.085±0.178
Dark Brown (23)	1.010±0.117	0.578±0.96
Black (22)	1.150±0.112	1.017±0.159

Table 1.4: Soil C, N & C/N (by mass) data at Duke Experimental Forest (Durham, NC).

	Native			Recovering		
depth(cm)	%C	%N	C/N	%C	%N	C/N
0-2.5	3.42	0.15	23	8.52	0.54	16 (site a)
2.5-5	2.26	0.12	19	4.05	0.19	21
5-10	1.94	0.11	18	1.76	0.10	18
10-15	0.94	0.06	16	1.14	0.07	16
15-20	0.50	0.04	12	0.99	0.06	16
20-30	0.74	0.04	18	0.62	0.06	10
30-40	0.31	0.03	10	0.34	0.04	8
40-50	0.65	0.04	16	0.64	0.04	16
0-2.5	6.00	0.25	24	7.87	0.34	23 (site b)
2.5-5	2.61	0.14	19	2.04	0.11	19
5-10	1.08	0.11	10	1.15	0.06	19
10-15	1.32	0.06	22	1.08	0.06	18
15-20	0.63	0.04	16	0.82	0.05	16
20-30	1.11	0.05	22	0.60	0.04	15
30-40	0.20	0.02	10	0.33	0.03	11
40-50	0.28	0.03	9	0.28	0.03	9
0-2.5	3.33	0.16	21	8.52	0.38	22 (site c)
2.5-5	2.61	0.14	19	1.78	0.10	18
5-10	1.98	0.10	20	1.66	0.07	24
10-15	1.38	0.07	20	1.21	0.07	17
15-20	0.80	0.05	16	1.02	0.06	17
20-30	1.30	0.06	22	0.48	0.10	5
30-40	0.26	0.03	9	0.63	0.04	16
40-50	0.38	0.03	13	0.42	0.04	10
0-2.5	6.89	0.29	24	7.48	0.35	21 (site d)
2.5-5	2.60	0.14	19	2.11	0.10	21
5-10	1.61	0.11	15	2.07	0.08	26
10-15	1.11	0.06	18	0.70	0.04	17
15-20	1.64	0.07	23	1.36	0.06	23
20-30	0.93	0.05	19	0.92	0.05	18
30-40	0.33	0.03	11	0.42	0.04	10
40-50	0.46	0.05	9	0.34	0.01	34
0-2.5	7.66	0.37	21	5.76	0.27	21 (site e)
2.5-5	2.96	0.16	18	1.83	0.11	17
5-10	2.23	0.11	20	1.66	0.08	21
10-15	1.02	0.06	17	0.98	0.06	16
15-20	0.85	0.05	17	0.77	0.05	15
20-30	0.62	0.05	12	0.48	0.04	12
30-40	0.46	0.04	11	0.43	0.04	11
40-50	0.35	0.00	0	0.34	0.03	11

Table 1.5: Soil Carbon and Nitrogen Inventory Variability at the Duke Experimental Forest. (Durham, North Carolina). Depths are from 0 to 50 cm.

Native site	organic carbon(g/cm2)	organic nitrogen(g/cm2)	
a	0.601	0.035	
b	0.656	0.038	
c	0.687	0.038	
d	0.783	0.045	
e	0.765	0.042	
average	0.698±0.068	0.040±0.003	C/N=18
Recovering site	organic carbon(g/cm2)	organic nitrogen(g/cm2)	
a	0.834	0.055	
b	0.650	0.037	
c	0.754	0.050	
d	0.766	0.038	
e	0.605	0.037	
average	0.722±0.083	0.043±0.007	C/N=17

Table 1.6: Changing land use sampling locations and characteristics.

location	ecosystem	land use: native	disturbed	recovering
North Carolina	forest	X	X	X
South Carolina	forest			X
Saskatchewan	forest	X	X	
Saskatchewan	grass	X	X	
Lombardy	grass	X	X	
Kansas	grass	X	X	X

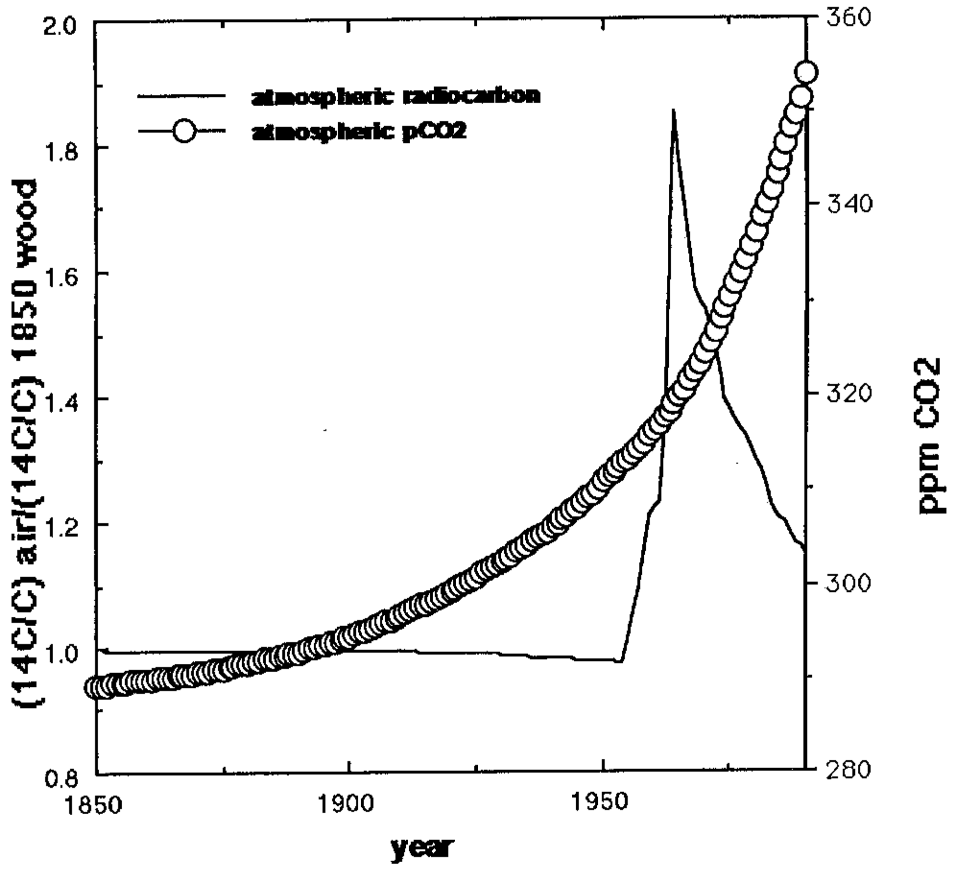


Figure 1.1. Increase of radiocarbon and CO_2 in the atmosphere plotted as a function of time. Atmospheric carbon dioxide concentrations increased substantially. The radiocarbon content of the atmosphere decreased slightly until the test of nuclear weapons almost doubled atmospheric radiocarbon. Fossil fuel combustion released large amounts of radiocarbon-free carbon dioxide to the atmosphere, which diluted the radiocarbon concentration of the atmosphere until nuclear bombs started increasing it in the 1950's. In 1964, a test ban treaty reduced radiocarbon input into the atmosphere, resulting in decreasing atmospheric radiocarbon levels.

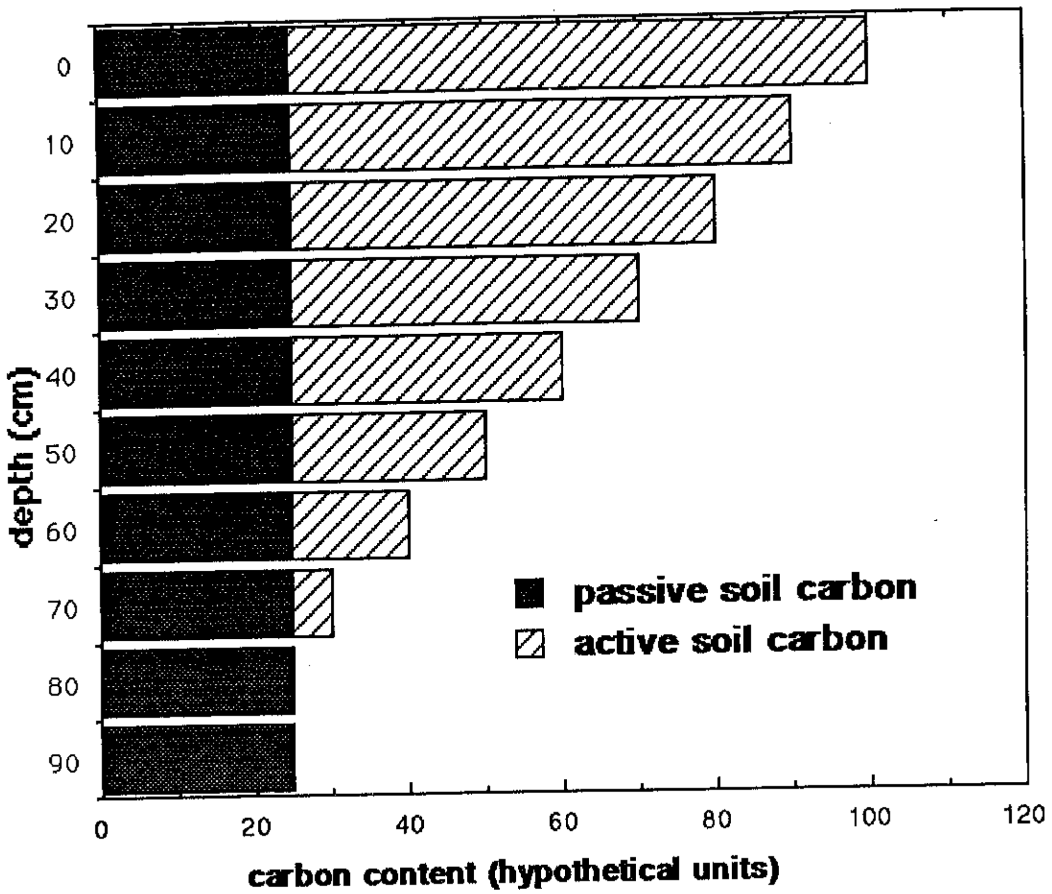


Figure 1.2. Hypothetical mixture of fast and slow cycling carbon in a soil column. The surface soil contains a mixture of 3 parts fast for every 1 part slow. This ratio diminishes with depth until only the slow cycling component is left. The passive soil carbon inventory does not remain constant with depth, but the variations are small in the upper meter of soil. This mixture was only used to generate this conceptual diagram and should not be confused with data.

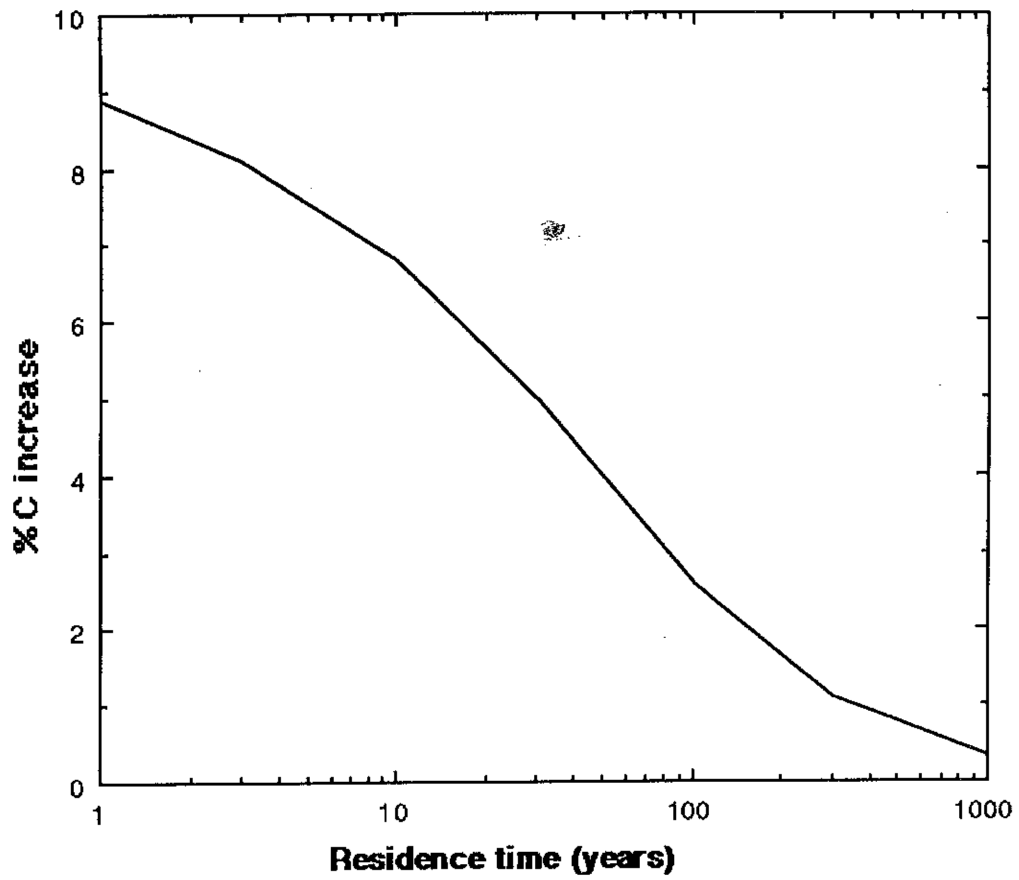


Figure 1.3. Model showing the percentage increase in carbon reservoir as a function of residence time. Model is for a 25% increase in atmospheric carbon dioxide levels, using a CO_2 fertilization factor of 0.35 (i. e., net primary productivity increases 35% for a doubling of atmospheric carbon dioxide). Carbon pools having short residence times show the greatest increase, while carbon pools having a turnover time of longer than 1000 years show almost no increase.

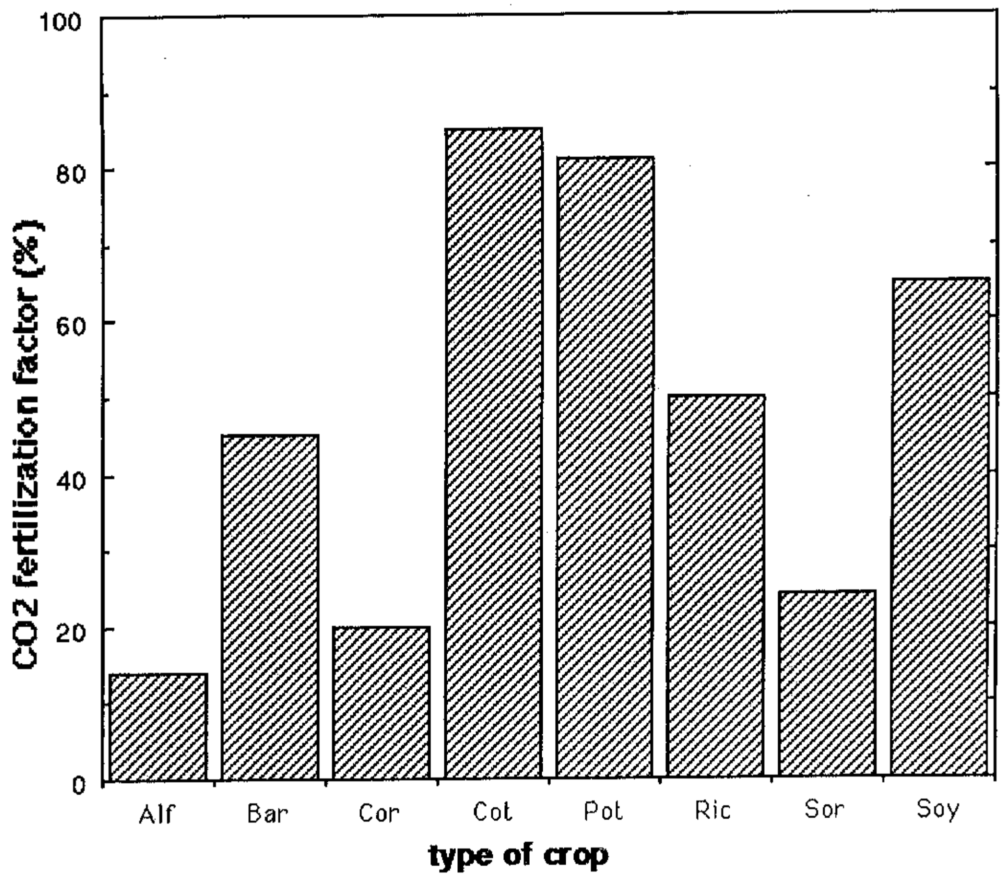
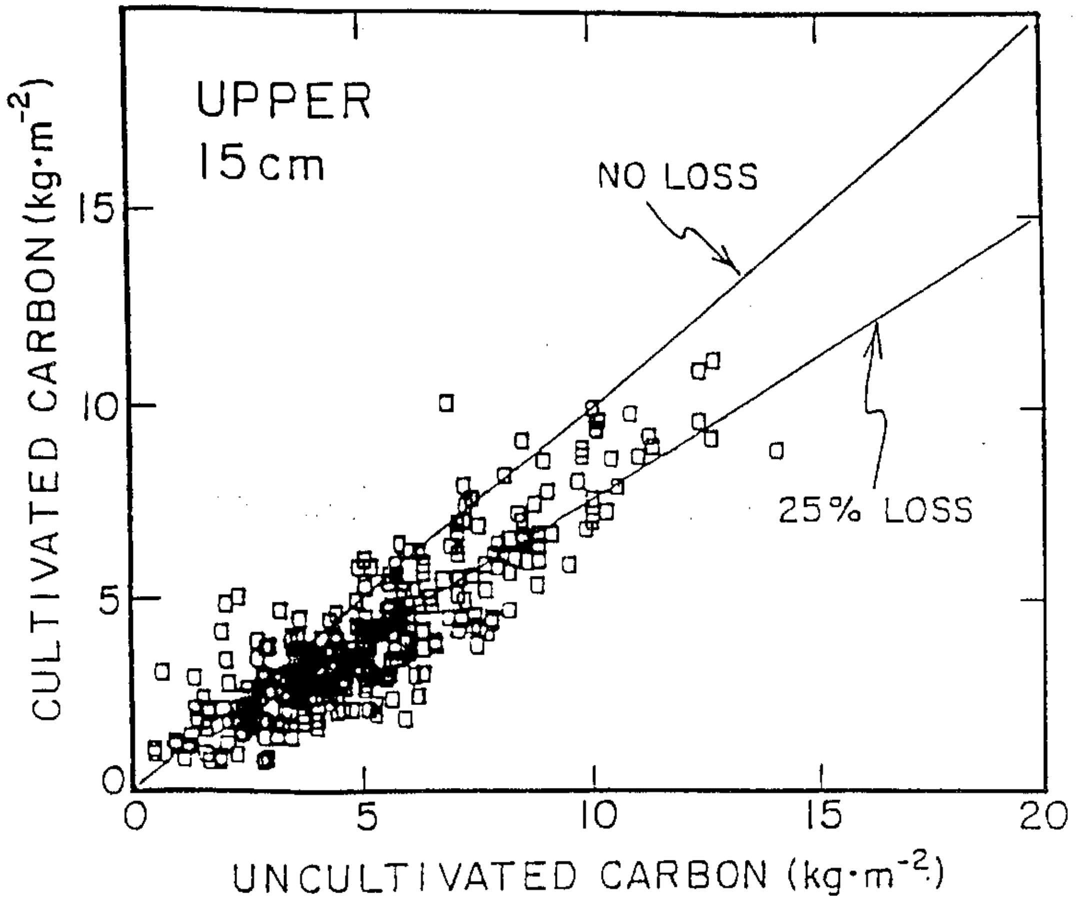


Figure 1.4. Strain and Cure's (1985) results for increases in plant growth in a greenhouse with a doubled CO_2 concentration.



Post & Mann (1990)Figure 1.5. Post and Mann (1990) plotted carbon content for paired native and cultivated soils. Although there is considerable scatter, cultivated soils on average have about 25% less carbon than their native counterparts. This values agrees with the work of Schlesinger (1986), who states that farming reduces the input of crop residues into the soil and that decomposition is accelerated by the higher temperatures and moisture content of cultivated soil.

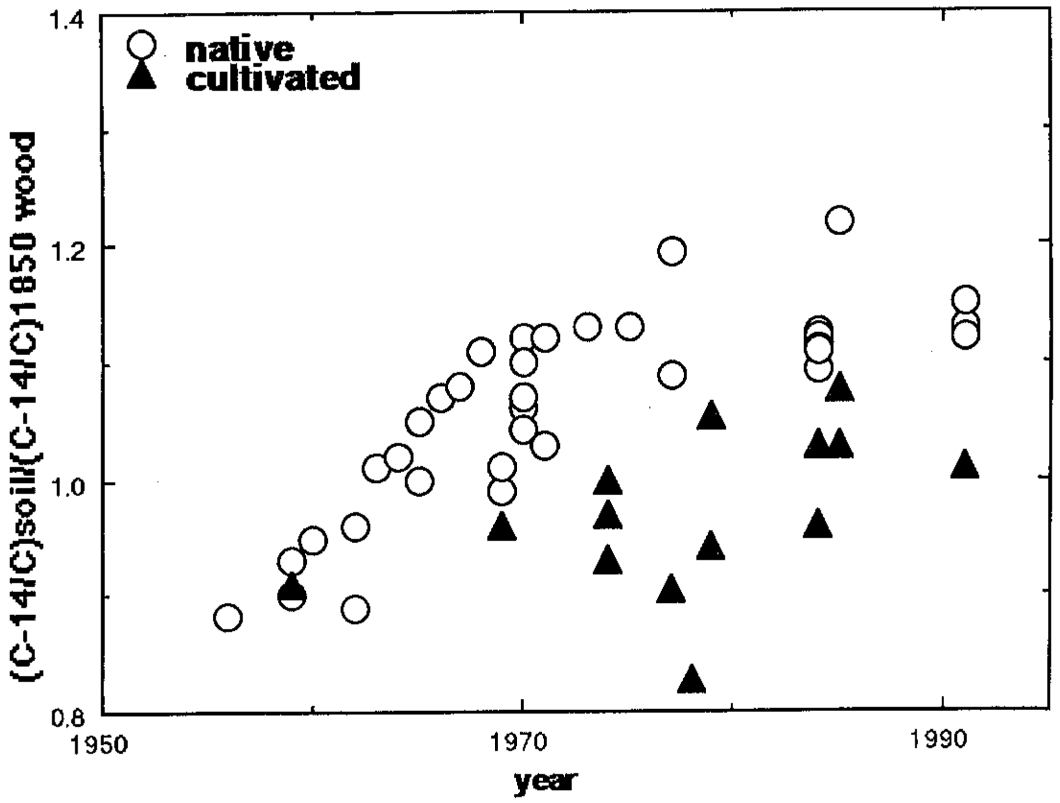


Figure 1.6. Plot of radiocarbon content in surface soils (<15cm) as a function of time. The native soils (open circles) have consistently higher values than the cultivated soils (dark triangles). The native soil radiocarbon values tend to increase from a pre-bomb average of 90% modern to 115% modern in the 1990's.

GLOBAL BIOGEOCHEMICAL CYCLES, VOL. 7, NO. 1, PAGES 69-80, MARCH 1993

A STRATEGY FOR ESTIMATING THE IMPACT OF CO_2 FERTILIZATION ON SOIL CARBON STORAGE

Kevin Harrison and Wallace Broecker

Department of Geochemistry, Lamont-Doherty Geological Observatory, Columbia University Palisades, New York

Georges Bonani

ETH-Zürich, Institut für Mittelenergiephysik, Zürich, Switzerland

Abstract. As soils are a likely candidate for the so-called missing carbon sink, we explore the possible impact of CO_2 fertilization on the global humus inventory. For any given greening-induced enhancement of plant growth, the increase in soil carbon inventory will depend on the spectrum of turnover times with respect to oxidation. Here we develop estimates of carbon turnover rates based on soil radiocarbon measurements.

INTRODUCTION

The so-called missing carbon sink is the difference between the amount of carbon released by fossil fuel burning and deforestation and the amount of excess carbon which has appeared in the atmosphere and ocean reservoirs (Figure 1 and Table 1). When combined with the atmospheric increase, most estimates of oceanic CO_2 uptake [Keeling, 1973; Oeschger et al., 1975; Broecker et al., 1979; Bacastow and Bjorkstrom, 1981; Peng, 1986; Maier-Reimer and Hasselmann, 1987; Keeling et al., 1989a, b; Toggweiler et al., 1989a, b] fall short of matching fossil fuel CO_2 released during the same time interval. Thus the missing sink is generally thought to be at least as large as the deforestation source (Table 1). If Houghton and Skole's [1990] estimate of biospheric release over the period 1958 to 1978 is used, about 37 GtC (or 1.8 GtC/year for the 1980s) are unaccounted for [Houghton et al., 1990, 1992]. This bookkeeping does not include processes such as CO_2 fertilization and N deposition, which could stimulate terrestrial carbon storage.

One promising candidate for the missing sink is greening of the terrestrial biosphere through CO_2 fertilization of plant growth. Today's atmosphere contains 25% more CO_2 than did the atmosphere in 1800 [Neftal et al., 1985; Bacastow and Keeling, 1981]. The average growth enhancement factor (i.e., percent increase in plant growth rate divided by percent increase in atmospheric CO_2 content) found in short term chamber experiments is 0.35 [Esser, 1987; Kohlmaier et al., 1989; Bazzaz and Fajer, 1992]. If the results of these experiments are applicable to the natural environment, then between 1850 and today, the rate of plant growth should have increased by 9%. The use of limited, short-term chamber experiments to estimate real-world response is highly controversial, but it is all we have. For example, the experiments neglect the natural limitations imposed by space, water and nitrogen availability. Indeed, the long-term experimental results of Norby et al. [1992] demonstrate no significant increase in plant biomass for yellow-poplar trees grown for years in enriched CO_2 environments; however, these authors do report increased root turnover and increased carbon dioxide flux out of the soil. Perhaps, soil carbon increased. At least for some regions, N is no longer limiting because of anthropogenic deposition of NH_3 and NO_3 [Kauppi et al., 1992]. Duce et al. [1991] estimate that 0.050 Gt of oxidized N and 0.054 Gt of reduced N are deposited on land and in the oceans annually. At least 60 % of this total flux is

Paper number 92GB02938.
0886-6236/93/92GB-02938 $10.00

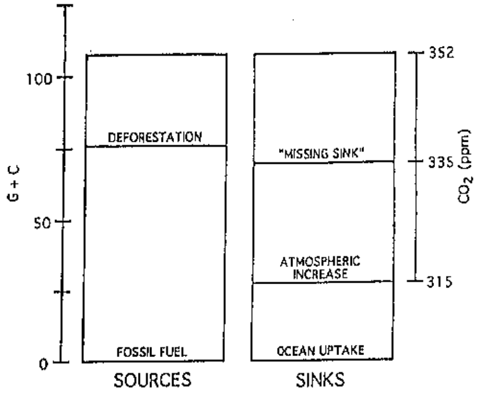


Fig. 1. Missing carbon sink, 1958-1978. Sources (fossil fuel and deforestation) and sinks (ocean uptake, atmospheric increase and "missing") for atmospheric carbon dioxide from 1958 to 1978. The left axis units are GtC(10^{15} gC) and the right axis units are ppm CO_2. The fossil fuel and deforestation exceed ocean uptake and the atmospheric increase by 37 GtC. Hence the atmosphere increased from 315 ppm in 1958 to only 335 ppm in 1978. Were the carbon in the missing sink to have remained airborne, the CO_2 content in 1978 would have been 352.

anthropogenic: Peterson and Melillo [1985] conservatively estimate that fossil fuel combustion releases 0.02 Gt N per year and that fertilizer production releases 0.04 Gt N per year. Even if a relatively low carbon/nitrogen ratio of 10 is adopted, utilization of this nitrogen by the global ecosystem would sequester 0.6 GtC per year.

MODELING APPROACH

Our model builds on the work of earlier researchers. Parton et al. [1987, 1988] have developed the Century model and Jenkinson [1990] the Rothemsted model for studying soil organic matter inventories. The structure of the two models is similar. For example, both estimate the flux of plant residue into three soil compartments: active, slow, and passive. Other soil organic dynamic modelling has been done by O'Brien and Stout [1978] and Hsieh [1992].

The Century model calculates the climate change response of soil organic matter inventories for a grassland ecosystem. Sanford et al. [1991] have even applied this model to nongrassland ecosystems. The parameters showing the greatest sensitivity are the turnover times for the slow and passive soil pools. These terms have been estimated indirectly from long-term incubation experiments and Martel and Paul's [1974] soil radiocarbon measurements. Parameters include temperature, moisture, soil texture, plant lignin content, and N input. Parton et al.[1987, 1988] adopt a fast-cycling pool with a 20- to 50-year response time and a slow-cycling pool with an 800 to 1200 year response time, and estimate that over half of soil organic carbon is slow cycling.

TABLE 1. Global Carbon Budget

	1958-1978		Annually for 1980s	
	GtC	Reference	GtC	References
		Sources		
Fossil fuel	76	Marland and Rotty [1984]	5.4±0.5	Houghton [1990, 1992]
Deforestation	32	Houghton and Skole [1990]	1.6±1.0	Houghton [1990, 1992]
Total additions	108		7.0	
		Sinks		
Atmosphere increase	43	Bolin [1986]	3.2±0.1	Houghton [1990,1992]
Oceanic uptake	28	Broeker et al. [1979]	2.0±0.8	Houghton [1990,1992]
Total storage	71		5.2	
Missing sink	37	(by difference)	1.8±0.4	Houghton [1990,1992]

The Rothamsted model's structure is similar to the Century model and is equally sensitive to the turnover time estimates for the slow and passive soil pools. Jenkinson [1990] estimates his turnover times by using data from carbon inventory changes in long-term agricultural experiments. He uses a fast-cycling pool with a 20-year response time and a slow-cycling pool turnover time approaching infinity. He estimates that the top 23 cm of one soil plot consists of 10% slow- and 90% fast- cycling carbon.

O'Brien and Stout [1978] have devised a sophisticated model to interpret their soil radiocarbon measurements in New Zealand that includes carbon input, rate of decomposition and diffusivity through soil using radiocarbon data as a constraint. They assign a 50-year turnover time to their fast cycling pool and a near infinite turnover time to their slow-cycling pool. Hsieh [1992] presents a similar model for agricultural systems. He assumes that the fast cycling carbon pool has been depleted by cultivation. He estimates turnover times for the slow-cycling pool ranging from 853 to 3000 years and guesses that the fast pool residence time could be less that 20 years. Schlesinger [1991] has estimated a fast-cycling pool turnover time of about 28 years using a mass balance approach.

Here we present a strategy for estimating turnover times more directly using radiocarbon measurements. To explore the dynamics of CO_2 fertilization's influence on soil carbon storage, we have developed a simple model. We assume that the carbon inventory for the world's soils was at steady state in the year 1850 (i.e., the input flux via litter and roots equaled the output flux via bacterial decomposition). We perturb the system by increasing the level of atmospheric CO_2 (following observed time history from 1850 to the present, see Figure 8) and assume a CO_2 fertilization factor of 0.35 for the carbon flux into the soil box (this fertilization factor has never been directly measured for soil and is controversial even for vegetation). This, in turn, causes the inventory of soil carbon to rise. However, as the carbon inventory increases, so does the rate of soil respiration. We assume that microbes oxidize a fixed fraction of the soil organic carbon to CO_2 each year. We further assume that the change in global temperature over this interval has been too small to increase respiration rates.

Considering an instantaneous doubling of atmospheric carbon dioxide illustrates why carbon accumulates. For example, take a 500 GtC reservoir with a 25 year residence time and 20 GtC/year steady state exchange flux. A stepwise doubling of CO_2 from 290 ppm to 580 ppm instantly increases the input flux to 27 GtC/year, the new steady state exchange flux. This increased input gradually increases the size of the carbon reservoir, which in turn gradually increases the output (the decay constant times the reservoir size), until it equals the input. At the new steady state, the reservoir size would be (1+ 0.35) (500), or 675 GtC. The e-folding time for the transient leading to this new steady state would be 25 years.

Clearly, no single residence time can characterize the complex of organic compounds in soils. Nor can the most appropriate residence time for any one soil be applied to others. Even the determination of the portion of the soil carbon falling into broad residence time bands currently lies beyond our grasp. As outlined below, we simplify the problem by dividing soil organics into that portion which has a mean residence time too long to significantly respond to a perturbation with an e-folding time of 30 years (the mean age of fossil fuel CO_2 molecules), and into that portion with residence times short enough to show a significant response. We use radiocarbon data to assign a single average residence time to each of these reservoirs.

Perturbations, like CO_2 fertilization, have the greatest impact on carbon pools having short residence times, and the least influence on carbon pools having long residence times. For example, the carbon pool having a residence time of a few years increases its carbon inventory by 9% (Figure 2). In contrast, pools with residence times greater than 1000 years experience almost no change. A carbon pool having a 25-year residence time will show an increase of 6%.

Tracer experiments provide a way to estimate soil-carbon residence times. Two global carbon tracer experiments include diluting and enhancing the C-14 content of the atmosphere. We define R as the measured C-14/C ratio of the sample divided by the C-14/C ratio of 1850 wood. R(atmosphere) decreased by 2.5% between 1850 and 1950 as the result of burning fossil fuel. This dilution's impact would be difficult to detect. However, nuclear bombs increased R(atmosphere) from 1950 to 1963, to almost 1.9. In 1963, nuclear tests were banned and since then R(atmosphere) has decreased exponentially. This near-doubling of R(atmosphere) should be reflected in the fast-cycling pools in soil (Figure 3). The 3-year pool follows the atmospheric signal, although its maximum occurs later and has a smaller amplitude. Longer residence-time pools have ever smaller maxima occurring at ever later times.

EXPERIMENTAL RESULTS

We have made radiocarbon measurements on native sites from four locations: Lodi, Italy; Duke

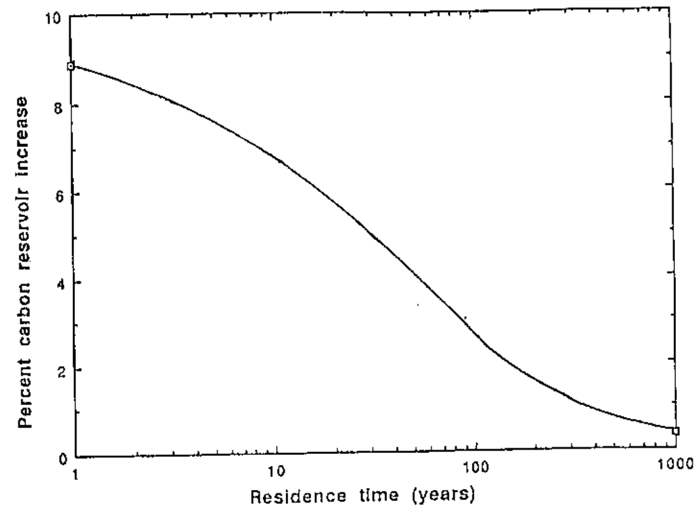


Fig. 2. Soil carbon residence time versus percent carbon reservoir increase, 1850 to 1985. This plot shows how residence time influences the percentage increase in the carbon inventory for a 0.35 CO_2 fertilization factor. The shortest-cycling time carbon pools have the greatest increase.

Experimental Forest near Durham, North Carolina; the Konza Prairie in Manhattan, Kansas; and two sites near Saskatoon, Saskatchewan, Canada (see Table 2 and Schoenau [1988]). We have followed the procedure described by Trumbore [1988] for measuring radiocarbon in bulk soil. In short, our sample treatment includes hand picking of visible plant and root debris and floating in water of charcoal and smaller plant debris. Carbonates have been removed with dilute acid. The remaining organic carbon has been oxidized to carbon dioxide and subsequently reduced to form graphite targets for accelerator mass spectrometry.

In addition to our results, we summarize literature values. The locations of the sampling sites are plotted in Figure 4. Although our literature search has been reasonably comprehensive, data are scant.

When the native soil radiocarbon values are plotted against time (Figure 5), a trend becomes apparent. The limited number of prenuclear soils show values below atmospheric averaging 0.90 (Table 2). The values rise during the 1960s and flatten thereafter at a value averaging 1.15.

INTERPRETING SURFACE RADIOCARBON MEASUREMENTS USING MODEL RESULTS

A one-reservoir model fails to explain the observed surface R(soil) increase from prebomb to present-day values (Figure 5). For example, the average pre-1963 R(soil) value (Table 2) is 0.90 (850 years). Our model predicts that carbon having a turnover time of 850 years will show little bomb C-14 buildup. Hence we have modeled the soil carbon system with two components, one slow and one fast.

Our strategy is to find the amount and residence time for these fractions to fit the mean surface soil observations. We have found the best fit by iteration, and have assigned a mean residence time of 3700 years to the slow fraction (25% of the total) and 25 years to the fast fraction (75% of the total). In this way, we achieve a fair fit to both the prebomb average and the postbomb surface data points (Figure 7).

We arrive at this breakdown as follows: We assume that deep in the soil zone the fast-cycling component is gone. Hence the R measured deep in the soils provides an estimate of the slow-cycling component;s turnover time. This approach avoids problems in using physical and chemical fractionation methods. The available deep soil radiocarbon values, listed in Table 3, average 0.63, which corresponds to a 3700-year residence time. For the fast-cycling pool, we find by iteration that a 25-year residence time gives the best fit. Specifically, we show how bomb radiocarbon would build up in soil carbon pools having 3700-, 100-, 25- and 10-year residence times (Figure 6). We add 25% of the slow pool to 75% of the fast pool to replicate the 0.90 prebomb R(soil) value. We superimpose the experimental observations over our model prediction to find that a 25-year residence time for the fast pool provides the best fit to the data (Figure 7).

A better fit could presumably be achieved by

TABLE 2. Surface Soil Radiocarbon Data for Noncultivated Soils

Sampling Date	R(soil)	Location	Vegetation/ Soil Type	Precipitation mm/yr	Temperature degrees C	Reference
1927	0.82	Leningrad, Russia	spodosol	325	7	f
1959	0.90	Amazon basin	ulti[illegible]	1500	30	f
1956	0.88	New Zealand	silt loam	1250	1250	a
1959	0.93	Amador County, Calif.	temperate forest	250	12	n
1960	0.95	Judgeford, New Zealand	silt loam	1250	15	l
1962	0.89	Saskatchewan, Canada	mollisol	325	7	e
1962	0.96	"	"	"	"	e
1963	1.01	Judgeford, New Zealand	silt loam	1250	15	l
1964	1.02	"	"	"	"	l
1965	1.00	"	"	"	"	l
1965	1.05	"	"	"	"	l
1966	1.07	"	"	"	"	l
1967	1.08	"	"	"	"	l
1968	1.11	"	"	"	"	l
1969	1.01	Saskatchewan, Canada	mollisol	325	7	d
1969	0.99	"	"	"	"	d
1970	1.12	"	"	"	"	i
1970	1.07	"	"	"	"	i
1970	1.04	"	"	"	"	i
1970	1.06	"	"	"	"	i
1971	1.12	"	"	"	"	j
1971	1.03	"	"	"	"	j
1971	1.03	"	"	"	"	j
1971	1.12	"	"	"	"	l
1973	1.13	"	"	"	"	l
1977	1.09	"	"	"	"	g
1977	1.19	"	"	"	"	g
1984	1.13	Wohldorf, Germany	hapludalf	650	8	b
1984	1.12	Ohlendorf, Germany	"	"	"	b
1984	1.12	Timmendorf, Germany	"	"	"	b
1984	1.11	Akka, Israel	polloxevert	620	18	b
1984	1.11	Qedema, Israel	"	"	"	b
1984	1.12	Patancheru, India	rhodustalf	1300	27	b
1984	1.09	Lodi, Italy	grassland	860	13	m
1985	1.22	Saskatchewan, Canada	grassland	325	7	m
1991	1.15	Konza Prairie, Kansas	grassland	732	13	m
1991	1.12	Durham, N. C.	deciduous	1100	15	m

We define prebomb as being earlier than 1963 and used estimated temperatures and precipitation. References: a[O'Brien, 1986]; b[Scharpenseel et al., 1989]; Martel and Paul, 1974b]; e[Campbell et al., 1967]; f[Trumbore et al., 1990]; g[O'Brien, 1984]; i[Goh et al., 1977]; l[O'Brien and Stout, 1978]; m (this study, radiocarbon analyzed by AMS at ETH) and n(S. Trumbore, manuscript, 1992). In Kansas, we sampled the Konza Prairie, an NSF LTER site.

TABLE 3. Deep Soil Radiocarbon Values for Cultivated and Noncultivated Systems

Soil Type	Depth,cm	R(soil)	Location	References
Mollisol	65-105	0.49	China	Becker-Heidmann et al. [1988]
Mollisol*	40-50	0.76	New Zealand	O'Brien [1986]
Vertisol	60-140	0.60	Israel	Scharpenseel and Becker-Heidmann [1989]
Udic	60-140	0.60	Patancheru, India	Becker-Heidmann [1989]
Mollisol	85-110	0.62	Hildesheim, Germany	Tsutsuki et al. [1987]
Mollisol	80-100	0.71	Hildesheim, Germany	Tsutsuki et al. [1987]

*Under house.

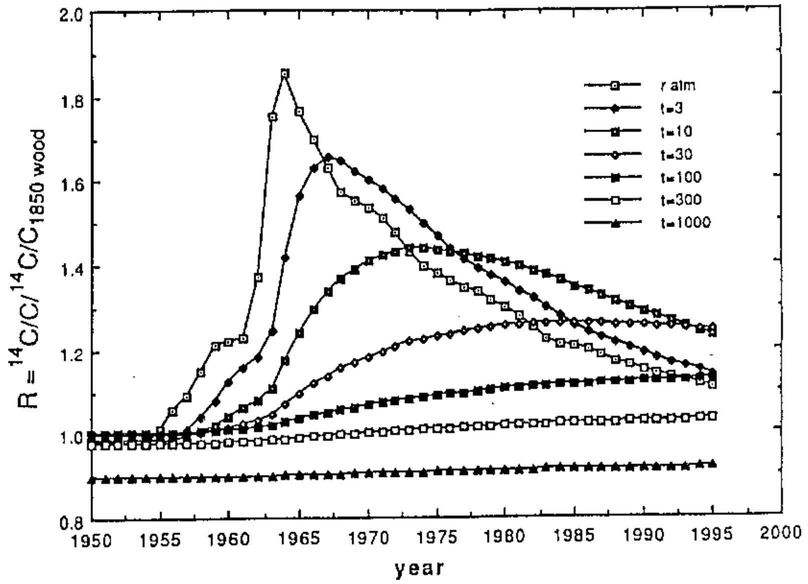


Fig. 3. Radiocarbon spectrum plot. Carbon 14 ratio is plotted against time, from 1950 to 1995. The ratio ranges from 0.8 to almost 1.9. The atmospheric ratio shows the greatest increase, which stems from nuclear testing in the atmosphere. This bomb spike is propagated through the soil carbon having different residence times. The shortest soil carbon residence time plotted, 3 years, shows the greatest perturbation. However, even in this short residence time, the atmospheric signal is significantly attenuated. The longest residence time of 1000 years shows the least change. We neglect the delay in going from the vegetation pool to the soil carbon pool, which takes a few years, because this time is samll when comparted to the 25 year turnover time for the fast cycling carbon pool.

TABLE 4. Carbon Inventory Increases

Carbon Pool	Inventory Size, GtC	Residence Time, Years	Increase 1850-1992, %	Carbon Stored: 1850-1992, GtC	1958-1978, GtC	Ann,1980s, GtC
Fast soil	500	25	6	31	7	0.5
Litter*	60	1.2	9	6	1	0.1
Long-lived vegetation	500	63	4	21	4.5	0.3
Short-lived vegetation	90	1.5	9	9	2	0.2
Total				67	14.5	1.1
Missing sink				105	23†-37	1.8

*Stem, branch, leaf, and twig litter.

†The missing sink decreases to 23 GtC from 1958 to 1978 if Siegenthaler and Oeschger's [1987] estimates of biospheric carbon release are used.

dividing the fast turnover reservoir into several subparts, each with its own residence time. We show one such example in Figure 7. A combination of subparts, one with a 10-year and the other with a 100-year turnover time, does not make a significant improvement. Our conclusion is that further subdivision of the fast reservoir is not warranted until a far larger data set is available.

Sensitivity Test

The surface soil contains a mixture of fast-cycling soil carbon and slow-cycling soil carbon. Our best estimate is that in surface soil, the soil carbon consists of a mixture of 75% fast-cycling component and 25% slow-cycling component. However, the fast-cycling component decreases with depth (Figure 9).

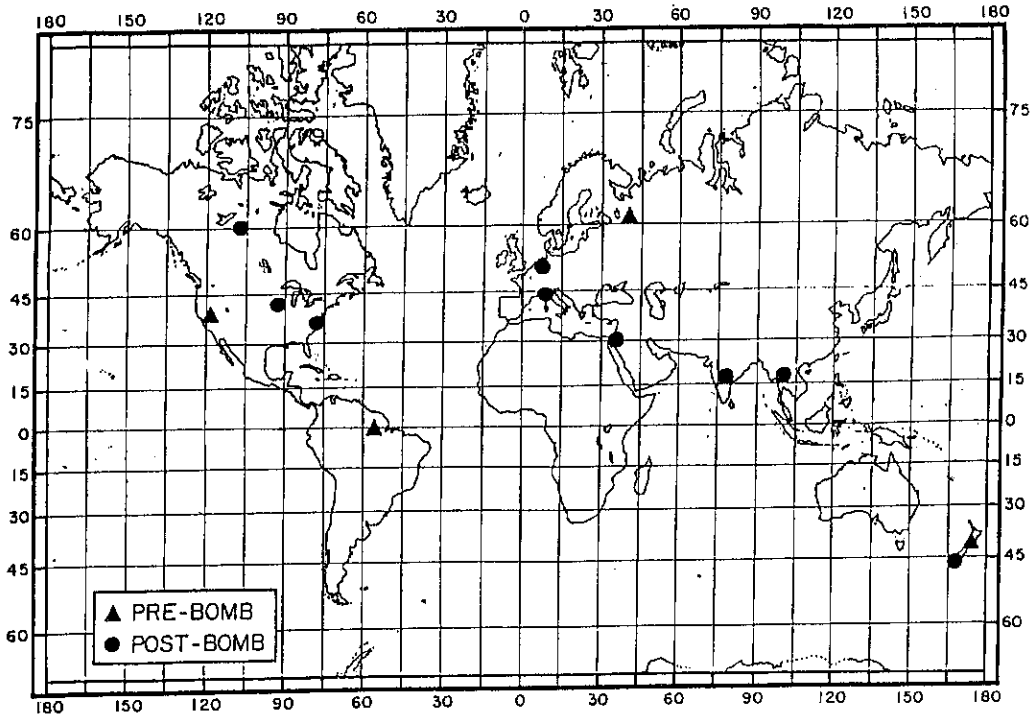


Fig. 4. Radiocarbon sampling site locations. The open triangles correspond to sites sampled before 1963, and the solid circles correspond to sites sampled in 1963 and later.

We can look at two extremes for the fast-cycling and slow-cycling pools. To estimate the maximum amount of fast carbon, we assume that the slow-cycling component has no radiocarbon. To replicate the prebomb value of 0.91, we would need 91% fast-cycling component in the surface soil, which is only a modest increase above our best guess of 75% fast for the surface soil. More realistic estimates of the slow-cycling portion can be obtained from Table 3. The lowest value is 0.49 (82% fast), and the highest value is 0.76 (63% fast).

Another area of uncertainty comes from our estimate that prebomb R(soil) was 0.91. It is this value in conjunction with the R(soil) for deep carbon that determines the proportions of fast-cycling soil and slow-cycling soil. These values range from a low of 0.82 (51% fast) to a high of 0.96 (89% fast).

We have estimated the turnover time of the fast cycling pool to be 25 years, which corresponds to a 6.15% fertilization rate from 1850 to 1992. A 20-year turnover time would produce a 6.29% fertilization and a 30-year turnover time a 5.76% fertilization. These differences are not significant. In our model, we assume that the pools are discrete. We use a CO_2 fertilization factor of 0.35 throughout the model runs, which can cause a maximum error of about 9% in the amount of additional carbon sequestered.

While our approach is crude, it does provide a template for future research. If a larger set of measurements on deep soil, prebomb soils, and bomb-era soils were available, we could make estimates of soil residence times for specific ecosystems. In particular, measurements on soil samples collected in the early 1970s, when R(soil) values diverge for the differing residence times (Figure 3), are needed.

ESTIMATING THE GLOBAL INVENTORY OF FAST CYCLING CARBON

Identifying the residence times and reservoir sizes of organic carbon pools is an important step toward understanding how terrestrial ecosystems respond to perturbations, such as CO_2 fertilization. To calculate the global inventory of fast-cycling carbon, we need to know the fraction of global soil containing rapid turnover carbon. Using soil radiocarbon and carbon content profiles, we estimate that 50% of the soil column contains fast-cycling carbon (the surface soil

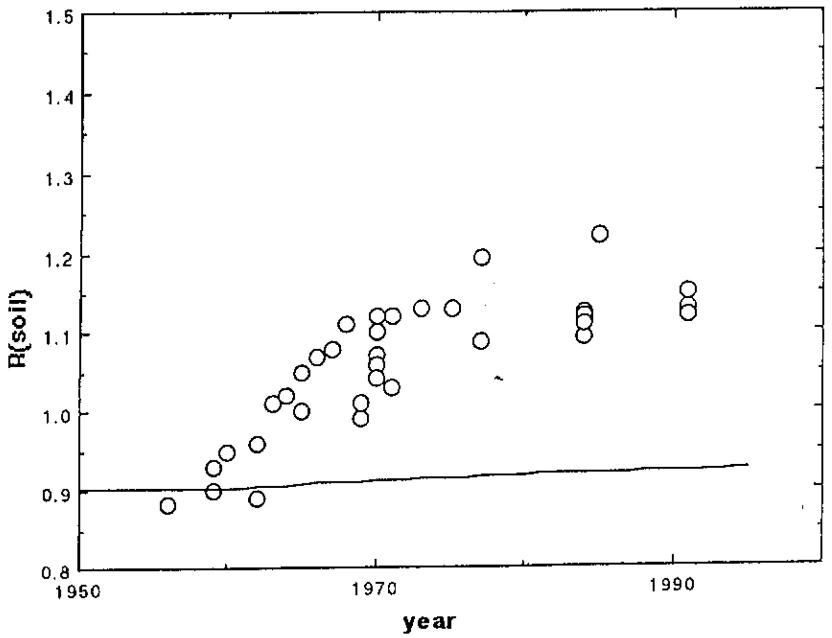


Fig. 5. R(soil) vs time. Measured R(soil) carbon values for noncultivated soils are plotted against time from 1950 to 1991. The values tend to increase during the 1960s and then level off. Model results for a theoretical carbon pool having an 850-year residence time are shown by the line. If soil carbon consisted of components having this single residence time, one would expect the observations to fall around this line.

contains 75% fast cycling component, but this ratio diminishes with depth, see Figure 9). Hence the complete soil carbon inventory for the entire soil column (deep to surface) has a lower proportion of fast cycling carbon than just the surface soil. Schlesinger [1991] estimates that 1500 GtC are sequestered globally in soil. We subtract 500 GtC from this global total to remove ecosystems with small amounts of fast-cycling carbon, such as boreal, tundra, and alpine ecosystems. Hence we estimate the global fast-cycling carbon pool to be 500 GtC (1000 GtC times 0.5, Figure 9).

USING CARBON RESIDENCE TIMES TO ASSESS THE IMPACT OF CO$_2$ FERTILIZATION

On the basis of the fast-cycling pool's size and residence time, we can estimate the amount of additional carbon that has been sequestered because of CO$_2$ fertilization. Using a 25-year residence time and applying a 0.35 greening factor, this translates into a 31 GtC sequestration since 1850.

This approach ignores storage in stem, branch, twig and leaf litter. In our study, this component has been physically removed from the soil. This pool stores about 60 Gtc and has an average residence time of 1.2 years [Warneck, 1988]. Hence 6 GtC from fine roots and litter have been sequestered because of CO$_2$ fertilization since 1850.

We have also failed to consider the increase in vegetation biomass. If we use a 1.5-year residence time for short-lived vegetation having a 90 GtC inventory and a 63-year residence time for a long-lived 500 GtC pool [Warneck, 1988], we estimate that the short-lived pool sequesters 9 GtC and the long-lived pool sequesters 21 GtC since 1850. If we combine the amount of carbon sequestered due to CO$_2$ fertilization in soil, litter and vegetation, we calculate that about 67 GtC have been stored from 1850 to 1992 and 1.1 GtC annually for the 1980s (Table 4). Therefore, about 60% of the annual missing sink of 1.8 GtC/year [Hougton et al., 1990, 1992] might be explained by CO$_2$ fertilization.

CONCLUSION

We have developed a model that estimates soil carbon residence times from soil radiocarbon measurements. We use these residence times to predict the extent of soil carbon's response to CO$_2$ fertilization. We hope this approach will serve as a strategy for future research.

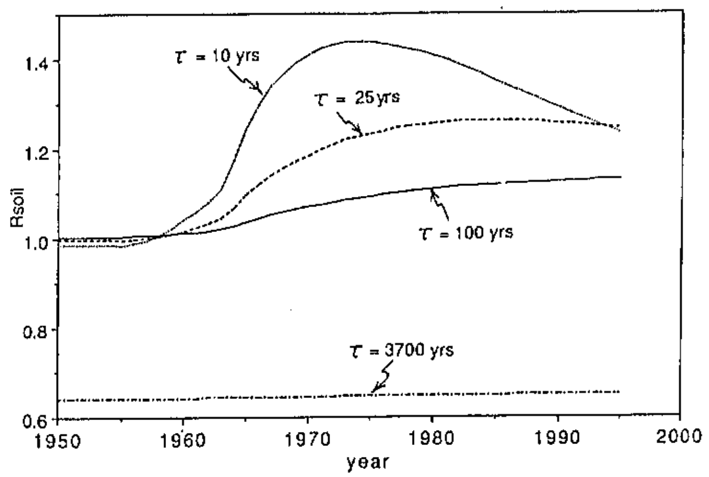


Fig. 6. R(soil) having residence times of 3700, 100, 25, and 10 years versus time. Soil radiocarbon values can be modeled as a system consisting of slow and fast components. We use an average deep R(soil) of 0.63 (3700 years) to estimate the residence time of the slow-cycling component. We believe the fast-cycling component's reservoir is made up of components with residence times ranging from 10 to 100 years.

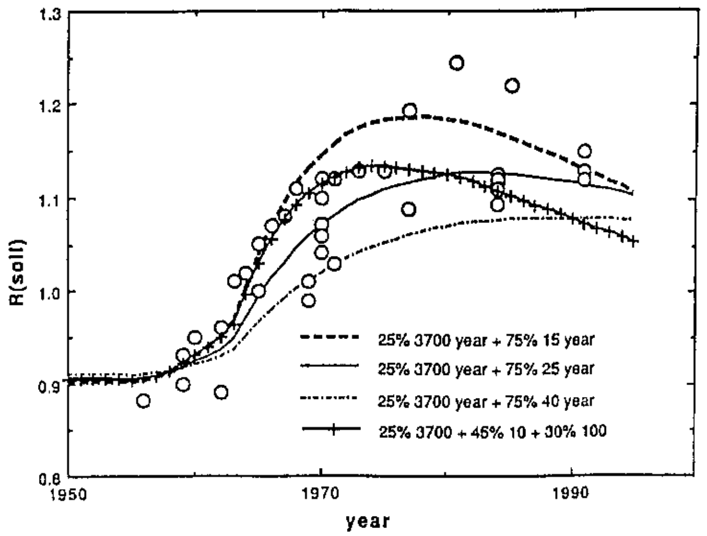


Fig. 7. R(soil) model predictions and R(soil) observations versus time. We combine 75% of the fast-cycling components with 25% of the slow-cycling components to reproduce prebomb values. The prebomb values for the fast-cycling pools converge because their turnover time is much less than the mean life of radiocarbon. However, these curves diverge when bomb radiocarbon is released to the atmosphere. R(soil) carbon for noncultivated soils is also plotted (open circles). We have superimposed our soil carbon modeling results for 15-, 25-, and 40-year residence times over this data. The 15- and 40-year cycling times almost bracket the experimental data, with the 25-year cycling time providing the best fit. We compare the result of the model calculation for our standard two-component mixture (25% 3700-year and 75% 25-year) with that for a three-component mixture consisting of 25% 3700-year, 45% 10-year, and 30% 100-year.

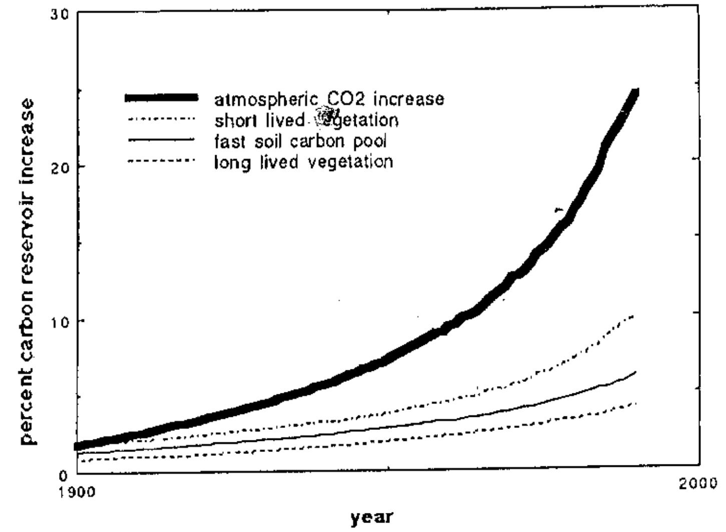


Fig. 8. Percent carbon reservoir increase for various carbon pools. We plot the percent reservoir increase from 1900 to 1990 for atmospheric CO_2 observations, short-lived vegetation, fast soil, and long-lived vegetation.

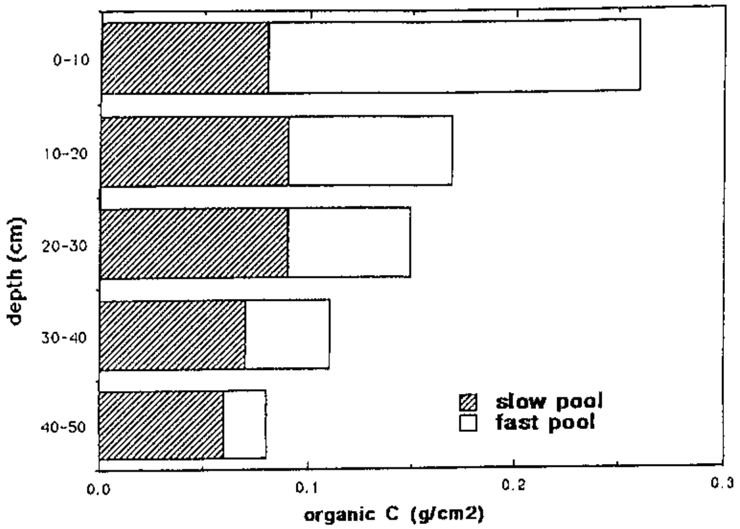


Fig. 9. Slow- and fast- cycling carbon versus depth. Both bulk soil carbon content and R(soil) decrease with increasing depth. Specifically, O'Brien [1985] found that R(soil) decreases from 1.08 (0-10 cm), 0.94 (10-20 cm), 0.91 (20-30 cm), 0.89 (30-40 cm) to 0.81 (40-50cm). We use an R(soil)value of 0.63 for the slow pool and 1.28 for the fast pool. The fast-cycling pool decreases rapidly with depth, but the slow-cycling pool decreases only slightly with increasing depth. About 50% of the integrated soil column is fast-cycling carbon.

Acknowledgments. We thank BethAnn Zambella for her understanding, encouragement, skilful editorial assistance, able library research and masterful wordsmithing. Jim Simpson and Inez Fung helped this project evolve with their insightful questions, patient discussions and modelling insights. Eric Haney and Peter Harrell helped select the Duke Experimental Forest field sites and did considerable work in constructing the 2-m-deep soil pits. Bill Schlesinger, Dan Richter, and Norm Christenson hosted my visit to Duke, helped select field sites and shared their expertise in many discussions that helped clarify our research objectives. Jeff Schoenau hosted my visit to the University of Saskatchewan, provided soil samples and supporting data, and made valuable suggestions for further research. Michel Ransom hosted the visit to Kansas State University, and in conjunction with Bill Wehmueller, helped us select field sites and use the soil probe truck. We thank Edoardo A. C. Costantini (Istituto Sperimentale per lo Studio) for helping us in Italy by providing soil samples on short notice. Nancy Mager helped make numerous text, budget and figure revisions and ensured smooth and rapid communication between the various investigators associated with this project. Rachel Oxburgh helped considerably with the modeling. Elaine Mathews and Katy Prentice provided a seemingly endless supply of answers and references to the multitude of questions raised by our research. In Kansas, we sampled the Konza Prairie, an NSF LTER site. DOE and a NASA Global Change Fellowship funded this research. Three anonymous reviewers helped improve our manuscript considerably with their helpful comments and suggestions. We thank them all. This is LDGO contribution 5031.

REFERENCES

Bacastow, R., and A. Bjorkstrom, Comparison of ocean models for the carbon cycle, in *Carbon Cycle Modelling, Scope 16*, edited by B. Bolin, pp. 29-79, John Wiley, New York, 1981.

Bacastow, R., and C. D. Keeling, Atmospheric carbon dioxide concentration and the airborne fraction, in *Carbon Cycle Modelling, Scope 16,* edited by B. Bolin, pp. 103-112, John Wiley, New York, 1981.

Bazzaz, F. A., and E. D, Fajer, Plant life in a CO2-rich world, *Sci.Am., 266,* (1), 1992, 68-74.

Becker-Heidmann, P., L. W. Liu, H. W. Scharpenseel, Radiocarbon dating of organic matter fractions of a Chinese mollisol, *Z. Pflanzenernahr. Bodenkd., 151*, 37-39, 1988.

Becker-Heidmann, P., and H. W. Scharpenseel, Carbon isotope dynamics in some tropical soils, *Radiocarbon, 31*, (3), 672-679, 1989.

Broecker, W. S., T. Takahashi, H. J. Simpson, and T. H. Peng, Fate of fossil fuel carbon dioxide and the global carbon budget, *Science, 206*, 409-418, 1979.

Campbell, C. A., E. A. Paul, D. A. Rennie, and K. J. McCallum, Applicability of the carbon-dating method of analysis to soild humus studies, *Soil Sci., 104*, (3), 217-223, 1967.

Duce, R. A., èt al., Atmospheric input of trace species to the world oceans, *Global Biogeochem. Cycles, 5,* (3), 193-259, 1991.

Esser, G., Sensitivity of global carbon pools and fluxes to human and potential climate impacts, *Tellus, ser. B, 39*, 245-260, 1987.

Goh, K. M, T. A. Rafter, J. D. Stout and T. W. Walker, Accumulation of soil organic matter and its carbon isotope content in a chronosequence of soils developed on aeolian sand in New Zealand, *J. Soil Sci., 27*, 89-100, 1976.

Goh, K. M., J. D. Stout and T. A. Rafter, Radiocarbon enrichment of soil organic fractions in New Zealand soils, *Soil Sci., 123,* (6), 385-390, 1977.

Houghton, J. T., G. J. Jenkins and J. J. Ephraums (Eds.), *Climate Change, The IPCC Scientific Assessment,* Cambridge University Press, New York, 1990.

Houghton, J. T., B. A. Callander, and S. K. Varney (Eds.), *Climate Change 1992, The Supplementary Report to the IPCC Scientific Assessment*, Cambridge University Press, New York, 1992, pp. 24.

Houghton, R. A., and D. L. Skole, *The Long-Term Flux of Carbon Between Terrestrial Ecosystems and the Atmosphere as a Result of Changes in Land Use,* Carbon Dioxide Information Analysis Center, Oak Ridge, Tenn., 1990.

Hsieh, Y-P., Pool size and mean age of stable soil organic carbon in cropland, *Soil Sci. Soc. Am. J., 56,* 460-464, 1992.

Jenkinson, D. S., The turnover of organic carbon and nitrogen in soil, *Philos. Trans. R. Soc. London, Ser. B, 329,* 361-368, 1990.

Kauppi, P. E., K. Mielikainen, and K. Kuusela, Biomass and carbon budget of European forests, 1971-1990, *Science, 256*, 70-74, 1992.

Keeling, C. D., The carbon dioxide cycle: reservoir models to depict the exchange of atmospheric carbon dioxide with the oceans and land plants, in *Chemistry of the Lower Atmosphere,* edited by S. Rasool, pp. 251-329, Plenum, New York, 1973.

Keeling, C. D., R. B. Bacastow, A. F. Carter, S. C. Piper, T. P. Whorf, M. Heimann, W.G. Mook and H. Roeloffzen, A three-dimensional model of atmospheric CO_2 transport, 1, Analysis of Observational Data, in *Aspects of Climate Variability in the Pacific and Western Americas, Geophysical Monograph 55,* edited by D. H. Peterson, pp. 165-236, AGU, Washington, D.C., 1989a.

Keeling, C. D., S. C. Piper, and M. Heimann, A three-dimensional model of atmospheric CO_2 transport based on observed winds, 4, Mean annual gradients and interannual variations, in *Aspects of Climate Variability in the Pacific and the Western Americas, Geophysical Monograph 55,* edited by D. H. Peterson, pp. 305-363, AGU, Washington, D.C., 1989b.

Kohlmaier, G. H., E-O. Sire, A. Janecek, C. D. Keeling, S. C. Piper and R. Revelle, Modelling the seasonal contribution of a CO2 fertilization effect on the terrestrial vegetation to the amplitude increase in atmospheric CO2 at Mauna Loa Observatory, *Tellus, Ser. B, 41*, 487-510, 1989.

Maier-Reimer, E., and K. Hasselmann, Transport and storage of CO2 in the ocean -- An inorganic ocean-circulation carbon cycle model, *Clim. Dyn., 2*, 63-69, 1987.

Marland, G.R. and R.M. Rotty, Carbon dioxide emissions from fossil fuels: A procedure for estimation and results for 1950-1982, *Tellus, Ser. B, 36*, 232-262, 1984.

Martel, Y. A., and E. A. Paul. Use of radiocarbon dating of organic matter in the study of soil genesis, *Soil Sci. Soc. Am. Proc., 38*, 501-506, 1974.

Neftal, A., et al. Ice core sample measurements give atmospheric CO2 content during the past 40,000 years, *Nature, 295*, 220-223, 1985.

Norby, R. J., C. A. Gunderson, S. D. Wullschleger, E. G. O'Neill, and M. K. McCracken, Productivity and compensatory responses of yellow-poplar trees in elevated CO2, *Nature, 357*, 322-324, 1992.

O'Brien, B. J., Soil organic carbon fluxes and turnover rates estimated from radiocarbon enrichments, *Soil Biol. Biochem., 16*, (2), 115-120, 1984.

O'Brien, B.J., The use of natural and anthropogenic C-14 to investigate the dynamics of soil organic carbon, *Radiocarbon, 28*, 2A, 358-362, 1986.

O' Brien, B.J., and J.D. Stout, Movement and turnover of soil organic matter as indicated by carbon isotope measurements, *Soil Biol. Biochem., 10*, 309-317, 1978.

Oeschger, H., U. Siegenthaler, U. Schotterer, and A. Gugelmann, A box diffusion model to study the carbon dioxide change in nature, *Tellus, 27*, 168-192, 1975.

Parton, W. J., D. S. Schimel, C. V. Cole, and D. S. Ojima, Analysis of factors controlling soil organic matter levels in Great Plains Grasslands, *Soil Sci. Am. Journal, 51*, 1173-1179, 1987.

Parton, W. J. , J. W. Stewart, and C. V. Cole, Dynamics of C, N, P and S in grassland soils: A model, *Biogeochemistry, 5*, 109-131, 1988.

Peng, T.-H., Uptake of anthropogenic CO2 by lateral transport models of the ocean based on the distribution of bomb produced C-14, *Radiocarbon, 28*, (2A), 363-375, 1986.

Peterson, B. J., and J. M. Melillo. The potential storage of carbon caused by eutropiphication of the biosphere. *Tellus, Ser. B, 37*, 117-127, 1985.

Sanford, R. L., W. J. Parton, and D. J. Lodge. Hurricane effects on soil organic matter dynamics and forest production in the Luquillo Experimental Forest, Puerto Rico: Results of simulation modeling, *Biotropica, 23* (4a), 364-372, 1991.

Scharpenseel, H.W., and P. Becker-Heidmann, H. U. Neue, and K. Tsutsuke, Bomb-carbon, C-14 dating and C-13 measurements as tracers of organic matter dynamics, *Sci. Total Environ., 81/82*, 99-110, 1989.

Scharpenseel, H.W., and P. Becker-Heidmann, Shifts in C-14 patterns of soil profiles due to bomb carbon, *Radiocarbon, 31*, 3, 627-636, 1989.

Schlesinger, W. H., *Biogeochemistry: An Analysis of Global Change*, Academic, San Diego, Calif., 1991.

Schoenau, J. J., Nutrient cycling processes in prairie and boreal forest soils, Ph. D. thesis,Univ. of Saskatchewan, 1988.

Siegenthaler, U., and H. Oeschger, Biospheric CO2 emissions during the past 200 years reconstructed by deconvolution of ice core data, *Tellus,Ser. B, 39*, 140-154, 1987.

Toggweiler, J. R., K. Dixon, and K. Bryan, Simulations of radiocarbon in a coarse resolution world ocean model, 1, Steady state pre-bomb distributions, *J. Geophys. Res, 94*, 8217-8242, 1989a.

Toggweiler, J. R., K. Dixon, and K. Bryan, Simulations of radiocarbon in a coarse resolution world ocean model, 2, Distributions of bomb-produced carbon-14, *J. Geophys. Res, 94*, 8243-8264, 1989b.

Trumbore, S. E., Carbon cycling and gas exchange in soils, Ph. D. thesis, Columbia Univ., 1988.

Trumbore, S. E., G. Bonani, and W. Wolfi. The rates of carbon cycling in several soils from AMS C-14 measurements of fractionated soil organic matter, in *Soils and the Greenhouse Effect*, edited by A. F. Bouwman, pp. 407-414, John Wiley, New York, 1990.

Tsutsuki, K., et al., Investigation on the stabilization of the humus in mollisols, *Z. Pflanzenernahr. Bodenkd., 151*, 87-90, 1988.

Warneck, P., *Chemistry of the Natural Atmosphere*, Academic, San Diego, Calif., 1988.

W. Broecker and K. Harrison, Department of Geochemistry, Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY 10964.
G. Bonani, ETH-Zürich, Intitut für Mittelenergiephysik, CH8093, Zürich, Switzerland.

(Received July 29, 1992;
revised November 30, 1992;
accepted December 11, 1992.)

Reprint Series
29 October 1993, Volume 262, pp. 725–726

SCIENCE

The Effect of Changing Land Use on Soil Radiocarbon

Kevin G. Harrison,* Wallace S. Broecker, and Georges Bonani

The Effect of Changing Land Use on Soil Radiocarbon

Kevin G. Harrison,* Wallace S. Broecker, Georges Bonani

Most carbon budgets require greening of the terrestrial biosphere as a sink for some of the excess carbon dioxide produced by fossil fuel burning and deforestation. Much of this storage is thought to occur in soils, but running counter to this conclusion is the observation that cultivation has reduced the agricultural reservoir of soil humus. Radiocarbon measurements in agricultural soils lend support to this browning of agricultural lands. Moreover, the loss is from the fast cycling portion of the humus.

Soil contains about three times the amount of carbon that was present in the preindustrial atmosphere. This study uses soil radiocarbon measurements to explore the dynamics of soil carbon loss associated with agriculture, a significant source of atmospheric CO_2.

In a survey of 1100 paired soil analyses (*1*), agriculturally modified topsoils averaged 25% less carbon than their native counterparts. As cultivated soil now contains about 180 gigatons of carbon (GtC) (*2*), this loss has added 60 GtC to the atmosphere and may have contributed as much as 0.5 GtC annually during the 1980s (*3*). There are a variety of reasons why disturbed soil might have less carbon than its native counterpart. These include reduction in the annual input of plant residues, increased decomposition as a result of elevated soil temperature, aeration, and extra moisture (*4*). In addition, plowing increases surface area, which accelerates soil carbon respiration (*5*). Although erosion is another way in which soil carbon could be lost from the profile, it should not change the carbon concentration. Only the thickness of the topsoil would be diminished. Further, carbon losses from the soil due to erosion are much less than losses due to oxidation (*4*).

As we have shown in a previous paper (*6*), based on radiocarbon data, the carbon in soil can be divided into fast and slow turnover time pools. We suggest that the carbon lost from agricultural soils must have come from the fast cycling pool. If so, then this loss should be matched by a decrease in the $^{14}C/C$ ratio of bulk soil carbon. The logic is as follows: The evolution of radiocarbon in the surface of natural soil can be modeled by the assumption that 25% of the carbon resides in a slow-turnover pool with a $^{14}C/C$ ratio averaging 0.63 of that for preindustrial carbon (*6*). Because of its slow turnover, no significant bomb ^{14}C has entered this reservoir. The remaining 75% of the carbon resides in a fast turnover pool with a mean replacement time of 25 years. A 3:1 mix of these two end-members yields a time history that passes through the median of the available radiocarbon measurements on bulk carbon from uncultivated topsoil collected at various times and places over the globe (Fig. 1). If the 25% loss were to have come entirely from the fast cycling carbon pool, then the fast:slow proportions would be changed from a 3:1 mixture to a 2:1 mixture. Although agricultural soil has a lower radiocarbon content than native soil, the deficiency is even greater than expected for a 25% loss (Fig. 1). Rather, the best fit curve corresponds to a 1:1 mixture of slow and fast cycling carbon pools. To accomplish this would require that two-thirds of the fast cycling carbon pool be lost (that is, 50% of the total carbon). In constructing these curves, for simplicity we have assumed that the carbon loss occurred largely before the nuclear era (1958 to the present). Were the calculation to assume, instead, that half was lost after 1958, the results would change only very slightly. The shape of the best fit curve through the cultivated soil suggests that the turnover time for the fast cycling carbon pool in cultivated soil carbon is 25 years, the same as for native soil.

The greater than expected $^{14}C/C$ reduction for mean cultivated soil may be, in part, the result of mechanical stirring by plowing. For most soils, the $^{14}C/C$ ratio decreases with depth, approaching values that are 30 to 50% lower than the prenuclear atmospheric ratio at the base of the profile. We attribute this drop to an ever-decreasing fractional contribution of the fast turnover carbon with depth. But, because plowing homogenizes only the upper 20 cm of soil, its impact would not be expected to be large.

Data on carbon content and $^{14}C/C$ ratio on a native soil from New Zealand (*7*) are

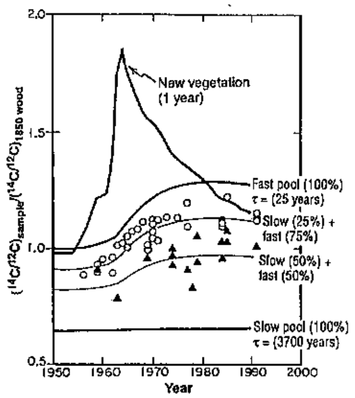


Fig. 1. Plot of radiocarbon versus time for the bulk carbon in topsoils (*8*). The natural soils (open circles) have higher radiocarbon values than the cultivated soils (solid triangles). The thick solid lines represent new vegetation, a fast (25-year turnover time) carbon pool's, and a slow (3700-year turnover time) carbon pool's responses to atmospheric bomb radiocarbon. The thin lines designate mixtures of fast and slow cycling carbon. A 75% fast and 25% slow mixture provides the best fit for the natural soils, but a 50% fast and 50% slow mixture provides the best fit for the cultivated soils.

K. G. Harrison and W. S. Broecker, Department of Geological Sciences and Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY 10964. G. Bonani, Eidgenössiche Technische Hochschule (ETH)–Zürich, Institut für Mittelenergiephysik, CH-8093 Zürich, Switzerland.

*To whom correspondence should be addressed.

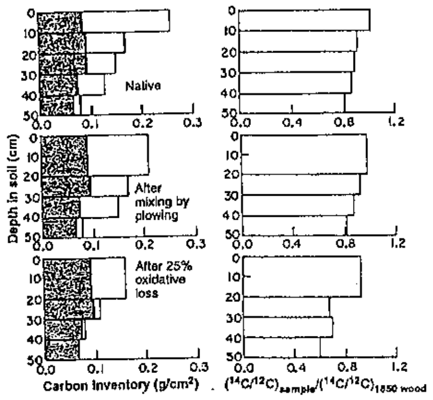


Fig. 2. Hypothetical evolution of native New Zealand soil carbon and radiocarbon subject to changing land use. The top figures illustrate the native radiocarbon ratios and carbon inventories, both of which decrease with depth (*6*). Also shown is the partitioning between fast turnover (unshaded region) and slow turnover (shaded region) carbon pools. The fast pool has a $^{14}C/C$ ratio of 1.26 and the slow pool a ratio of 0.63. The middle figures show how a farmer's plow would homogenize the upper 20 cm, thus decreasing the observed $^{14}C/C$ ratio and carbon inventory for the surface soil. The bottom figures show how the $^{14}C/C$ ratio and carbon inventory change with a 25% loss of carbon, all from the fast-turnover pool.

consistent with the hypothesis that a combination of plowing and oxidation of the fast cycling carbon pool are the cause of the downward shift in $^{14}C/C$ ratios observed for agricultural soil. To test this hypothesis, we considered what would happen if a native New Zealand soil was mixed to a depth of 20 cm and 25% of the carbon was oxidized (Fig. 2). Through mixing with underlying material, the $^{14}C/C$ ratio for the upper 10 cm of soil was reduced from a native value of 1.08 to 1.02 and the soil carbon inventory in this layer was reduced from 0.26 to 0.22 g/cm². We assumed that the increased oxidation took place in the fast cycling pool with an e-folding time of 25 years, eventually removing 25% of the soil's carbon. As a result, after a few decades, the $^{14}C/C$ ratio in the upper 10 cm of the soil dropped to 0.94 and the bulk carbon to 0.16 g/cm². The predicted $^{14}C/C$ ratio of 0.94 agrees with the observed average value for cultivated soil collected in 1975.

In summary, the observation that the $^{14}C/C$ ratios for agricultural soil are lower than those for native soils is consistent with a reduction in the amount of humus stored in these soils. Part, but not all, of the radiocarbon reduction can be attributed to preferential oxidation of humus in the fast cycling pool relative to that in the slow cycling pool. These observations suggest that as much as 60 GtC (10 years of fossil fuel CO_2 production at the current rates) could be sequestered if agricultural soil across the globe could be engineered back to its original carbon content.

REFERENCES AND NOTES

1. W. M. Post and L. K. Mann, in *Soils and the Greenhouse Effect*, A. F. Bowman, Ed. (Wiley, New York, 1990), pp. 401–407.
2. W. H. Schlesinger, *Biogeochemistry: An Analysis of Global Change* (Academic Press, New York, 1991), p. 135.
3. We estimated annual carbon fluxes using estimates of cultivated land area with time made by J. F. Richards [in *The Earth Transformed by Human Action: Global and Regional Changes in the Biosphere over the Past 300 Years*, B. L. Turner II *et al.*, Eds. (Cambridge Univ. Press, New York, 1990), pp. 163–178] and Schlesinger's (*2*) estimate that agricultural soil contains 180 GtC.
4. W. H. Schlesinger, in *The Changing Carbon Cycle—A Global Analysis* (Springer-Verlag, New York, 1986), pp. 194–200.
5. J. J. Schoenau, thesis, University of Saskatchewan (1988).
6. K. G. Harrison, W. S. Broecker, G. Bonani, *Global Biogeochem. Cycles* 7, 69 (1993).
7. B. J. O'Brien, *Radiocarbon* 28, 358 (1986).
8. The data for uncultivated surface soils were listed in (*6*). New data were obtained for uncultivated surface soils in Lodi, Italy (collected in 1984, ^{14}C = 109% modern), Saskatoon, Saskatchewan, Canada (collected in 1985, ^{14}C = 122% modern), Konza Prairie, KS (collected in 1991, ^{14}C = 115% modern), and Durham, NC (collected in 1991, ^{14}C = 112% modern). The data for cultivated surface soils was obtained from: D. W. Anderson and E. A. Paul, *Soil Sci. Soc. Am. J.* 48, 298 (1984); Y. A. Martel and E. A. Paul, *Can. J. Soil Sci.* 54, 419 (1974); *Soil Sci. Soc. Am. Proc.* 38, 501 (1974); H. W. Scharpenseel, P. Becker-Heidmann, H. U. Neue, K. Tsutsuke, *Sci. Total Environ.* 81, 99 (1989); S. E. Trumbore, G. Bonani, W. Wolfi, in *Soils and the Greenhouse Effect*, A. F. Bouwman, Ed. (Wiley, New York, 1990), pp. 407–414; (*7*). Values for cultivated surface soils and published for the first time in this paper are from: Lodi, Italy (collected in 1984, ^{14}C = 103% modern), Konza Prairie, KS (collected in 1991, ^{14}C = 101% modern), and Saskatoon, Saskatchewan, Canada (collected in 1985, ^{14}C = 103% modern).
9. This research was supported by a grant from the Department of Energy and a National Aeronautics and Space Administration Global Change Fellowship. We thank two anonymous reviewers, whose critiques led to a greatly improved manuscript, and B. Zambella, who lent a discerning eye, careful hand, and timely resources. LDEO contribution S128.

10 May 1993; accepted 8 September 1993

Chapter 4: The impact of changing land use on soil carbon storage: disturbance

Abstract:

Cultivation has been estimated to release about one-third of the amount of carbon dioxide emitted to the atmosphere via fossil fuel combustion. This chapter attempts to show why different sites have different fractional carbon losses. I identify farming techniques that limit soil carbon losses. I have measured radiocarbon, carbon, nitrogen and bulk density at paired native and cultivated sites at five locations: the forested sites included North Carolina and Saskatchewan and the grassland sites included Kansas and Lombardy, Italy. Each site had a unique climate and agricultural history. The forested sites lost a higher percentage of carbon than grassland sites.

Introduction:

Farmers have converted about 15% of the land into agriculture (Matthews, 1984), inadvertently conducting global land use "experiments". This research strives to assess the results of these informal experiments. The net terrestrial biospheric carbon release (vegetation and soil) is the global carbon budget flux term with the greatest uncertainty (Sundquist, 1993). Understanding the dynamics of the soil carbon loss associated with disturbance may lead to a reduction in this uncertainty and reduce the size of the so-called missing sink.

The disturbance of 15% of the land has released an enormous amount of carbon to the atmosphere. Houghton and Skole (1990) estimate that biospheric releases (vegetation and soil) total 90 to 120 GtC from 1850 to 1989. Siegenthaler and Oeschger (1987) estimate the net cumulative release for land as 90 to 150 Gt C from 1770 to 1980. Matthews (1984) has estimated that land disturbances have reduced pre-agricultural biomass by 105 Gt C. These estimates are about 20% of the carbon present in the preindustrial atmosphere. Clearly, man has released significant amounts of carbon to the atmosphere from the biosphere.

As population increases, the amount of cultivated land will likely increase. Therefore, understanding the dynamics of soil carbon loss has become a pressing question. How does cultivation reduce soil carbon and nitrogen inventories?

There are many reasons why cultivated soils have less humus than their native counterparts. Schlesinger (1986) suggests that soil carbon inventories diminish because of reduced input of plant residues and increased decomposition due to elevated soil temperature, aeration and extra moisture (for most climates). Schoenau (1988) adds that plowing accelerates soil respiration by increasing the surface area of soil carbon.

The soil carbon lost as the result of cultivation averages about 25% (Schlesinger, 1986, Post & Mann, 1990, and figure 4.1). But, there is considerable variability. This chapter explores how some factors, such as climate, vegetation and crop type, topography and cultivation style, have influenced the dynamics of soil carbon loss in forests in North Carolina and Saskatchewan and grasslands in Saskatchewan, Lombardy and Kansas.

Research Strategy:

Most of the sites were temperate, with the exception of a boreal site in Saskatchewan (see table 4.1). I have chosen the Duke Experimental Forest in North Carolina to show the loss of carbon from a native temperate forest upon cultivation. The native and cultivated sites are flat, and the farmers cleared the cultivated site for tobacco row cropping in 1949. Since then, farmers have continually cropped the land, but not irrigated. In contrast, the paired native and cultivated sites in the Saskatchewan boreal forest have a different climate and the farmers have left the land fallow every other year to store water for the next growing season (Jeff Schoenau, personal communication, 1991).

I have contrasted three grassland sites to test the hypotheses that soil carbon losses may be less under partially anaerobic conditions, that some surface soil carbon may be redeposited in deeper soil, and that N-fixing crops may reduce nitrogen losses from cultivated land. The Saskatchewan grassland site shows how anaerobic conditions due to frequent submersions would affect carbon inventories; the lower site was submerged about every other year. I have chosen the Lombardy grassland site because of its high subsurface clay content, hypothesizing that some carbon lost from shallow soils may be redeposited in deep soil, much like a chromatographic column. I have chosen the Kansas site to see if nitrogen fixing crops (soybeans) can reduce soil nitrogen losses.

Experimental Techniques:

To test the hypotheses outlined above, I have measured radiocarbon, bulk organic carbon and nitrogen. Before making these measurements, the soil had to be collected, the roots and litter picked out by hand, dried, de-littered/rooted by flotation, ground and homogenized, de-littered/rooted by flotation (again) and acid-washed to remove inorganic carbon (carbonates).

During sample collection, I removed litter and plant debris by hand (first with tweezers and then with a rough sieve (<5mm)), which eliminated most of the non-soil organic matter. Subsequent sieving and floating removed the remainder. After I collected the soils, they were dried until the weight remained constant at 60 degrees C in a Grieve oven. This usually took two to three days. I chose this temperature to drive off moisture. Higher temperatures may oxidize soil organic carbon. Samples that were used for making bulk density measurements were dried at 110 degrees C.

I sieved the sample though a <2mm sieve and washed a sub-sample with distilled water (after the initial drying process) to float off remaining vegetation debris and charcoal (Trumbore, 1988). Samples were ground with a glass mortar and pestle. I removed carbonates with dilute acid (0.1 N HCl at 40 degrees C for one hour (Tiessen et al., 1982)), which in turn was removed by rinsing with distilled water six times. The procedure for removing carbonates may have removed some of the soil organic material. However, these losses are likely to be small because of the amount and acidity of the rainwater passing through soil. I dried the soil again in the oven at 60 degrees C.

I prepared radiocarbon targets for accelerator mass spectrometry following the procedures of Trumbore (1988) and Trumbore (1993). I sealed the soil sample in a quartz tube with 0.25 g of CuO and a few strands of Ag (<5mg). The CuO releases oxygen when heated for the combustion of organics, which is catalyzed by the silver. I placed the quartz tubes in a Fisher oven and heated them to 950 degrees C for at least two hours. After oxidizing the soil organics to carbon dioxide, water vapor resulting from the combustion of soil organics was removed cryogenically using a slurry of dry ice and alcohol. Liquid nitrogen froze out the carbon dioxide and the vacuum pump removed the non-condensible gases. I reduced the carbon dioxide to graphite in a hydrogen atmosphere in the presence of an MnO catalyst at 600 degrees C using tube heaters. The targets, which contain from 1 to 3 mg of carbon, were sent to Zurich, Switzerland for AMS analysis.

Verardo et al.(1990) have described a flash combustion/gas chromatographic technique for measuring carbon and nitrogen. The Carlo Erba NA-1500 Elemental Analyzer machine heats about 10 mg of sample to 1050 degrees C in the presence of catalysts. Catalysts convert the resulting nitrous oxides to N_2, which is chromatographically separated from CO_2. Thermal conductivity detectors measure the N_2 and CO_2.

The procedure involves preparing aluminum foil sample cups, which are formed from thin aluminum foil. These cups are heated to 550 degrees C in a muffle furnace for at least 8 hours to clean organics off the cups, and then stored in an airtight container. 5 to 10 mg of sample are then placed in the cup using a micro-spatula, forceps and a Microbalance (Cahn Model C-30). Standards of Acetanilide were prepared and empty cups were used for blanks. The cups were folded into a ball, with care taken to avoid sample loss or contamination and placed in the AS200 autosampler tray.

The sample is introduced into a sample reactor, where it undergoes flash combustion. The sample reactor is kept at 1050 degrees C and consists of a porous layer of chromium trioxide (Cr_2O_3) over silvered cobaltous cobaltic oxide (Co_3O_4 + Ag). Ultra pure oxygen is added and the combustion products consist of a mixture of carbon dioxide, nitrogen oxides and water. These products are carried through the combustion chamber to a reduction reactor with helium. This reactor contained metallic copper at 650 degrees C and removes oxygen while reducing nitrous oxides to N_2. The N_2, CO_2 and water pass through a magnesium perchlorate trap, which removes water vapor. A 2-m long chromatographic column (6 mm OD, 4 mm ID, at 54 degrees C) of Porapak QS separates the gases for detection by thermal conductivity. A Hewlett--Packard 3390A Integrator integrated the peaks.

This device recovered >99% of carbon from finely ground graphite. Sample sizes ranged from 5 to 10 mg. The precision for carbon was ± 0.3% and for nitrogen was ± 1.6%. Estimated absolute and relative detection limits are 0.62 ug-carbon and 0.01% respectively. Blank levels were 0.31 ± 0.85 for carbon and 0 for nitrogen.

<u>Soil sampling experiment</u>:

Lamont forest surface soil from a forest was collected south of the Geochemistry building parking lot in Palisades, NY, to see how different sample processing techniques would influence measurements and to measure how much litter was present in surface soil. One technique was to float the organics off the sample before drying the sample. This has the advantage of removing organics before the sample is broken up and ground together. After this method, the sample was processed following the procedure described above. For five samples, this technique measured 2.09±0.16% carbon, which was about the same as the standard technique, 2.02± 0.25% carbon. The second part of this experiment was to measure the amount of carbon present in soil, the amount present in the litter that was removed by hand and the carbon present in the litter that was removed by flotation. For this experiment 200 grams of Lamont surface soil were used. From this soil, 4 grams of litter were removed by hand, 0.8 grams were removed by the sieve (<2mm) and less than 0.30 grams of litter were removed by flotation. These values are all given for their dry weight. Assuming that litter and roots are about 50% carbon by dry weight, 3.9 grams of carbon were present in soil, 2 grams of carbon was present in the litter that was removed by hand, 0.4 grams of carbon in the litter that was removed by the sieve and <0.13 mg in the litter that was floated out (table 4.2).

Considerable care was taken to insure that the samples contained no litter or carbonate before they were analyzed for carbon and radiocarbon. Before graphite targets were prepared, the sample was analyzed for total carbon and nitrogen to make sure the C/N ratio was reasonable for soil organic material. A ratio higher than 30 would indicate the presence of litter or $CaCO_3$, which would result in an erroneous radiocarbon determination.

Discussion: North Carolina Forest

The Duke Experimental Forest is associated with Duke University in the city of Durham, North Carolina. The latitude and longitude are 36 degrees N and 79 degrees W. The native site was located in compartment 67-CU of the Duke Experimental Forest. The two meter deep soil pit for this site was 1 meter by 1 meter and the 5 replicate soil pits were 50 cm deep by 50 x 50 cm. The cultivated site was a private farm owned by Mr. Burke, which is located on the southeast corner of the intersection of Kerley Rd. and Mt. Sinai Rd., six miles from the native site. Here, only one pit was dug that was 50 cm deep, by 75 by 75 cm. Unlike other paired sites in this study, the disturbed and native sites were not next to each other, but were of the same soil series and both were originally forests.

The land use history of the native site will be described in chapter 5. The land consists of mixed-age deciduous hardwoods with no evidence of disturbance. The tobacco plantation had been a forest until 1949, when farmers began planting tobacco; they have continuously row-cropped the land ever since. Workers harvest tobacco leaves by hand, leaf by leaf, so very little plant residue is added to the soil. The farmer would not allow me to sample the one-foot mounds of soil that he had raised to support the plants, therefore, I sampled only the soil between the rows. This could account for some carbon since the mounds consisted of predominantly surface soil. The Duke sites had an annual average rainfall of 1075 mm and an average annual temperature of 15 degrees centigrade. Soil scientists classify the Duke soil as an Ultic alfisol.

The North Carolina site had a 70% carbon loss, which was considerably higher than the Post and Mann (1990) 25% average depletion. If the mounds had been spread evenly, they would have only added 2-3 cm of soil to the top of the profile. One reason this forest site lost carbon was because the native C/N ratio of 17 was reduced to about 8 for the cultivated site, which reduced the amount of carbon produced per available nitrogen. The farmers plant the tobacco stems far apart to facilitate harvesting, which is done leaf by leaf, which reduces the amount of plant residue input. The 30% reduction in nitrogen also helps explain the large carbon inventory reduction. Nitrogen is continually removed during the harvest and not replenished by fertilization or by using rotations of nitrogen fixing crops.

Saskatchewan Forest:

The Canadian forest site was located in Saskatchewan slightly north of the city of Saskatoon. The latitude and longitude of the site are about 54 degrees N and 106 degrees W. The parent material was unsorted glacial till, the sites were adjacent north facing slopes with an 8% grade, the native and disturbed sites were adjacent. Both sites were sampled by digging soil pits in all slope positions. The sites were located on the property of Mr S. Johnson and Mr. R. Menzies. The grassland site is located in section 24, Township 20, Range 4, West of the Third Meridian and owned by Mr. Robert Menzies (General Delivery, Central Butte, Saskatchewan, Canada, S0H 0T0). Mr. Harry Van Dyke (General Delivery, Rabbit Lake Saskatchewan, Canada, S0M-2L0) owns the forested site. Samples were collected under the guidance of Dr. D.W. Anderson and Mr. Glenn Padbury (U. Saskatchewan).

The native site was ungrazed and undisturbed by man. The trees that were present were mostly aspen with a few green alder with various grasses and legumes making up the understory. The cultivated site had been cleared for cultivation. The litter was scraped off and piled on the hills and burned. The upper slope position contained the remnants of one of these burned piles. The cultivated site had been undergoing a barley/fallow rotation for 70 years at the time of collection. The cultivated site had 40% less carbon and 30% less nitrogen than its native counterpart.

The boreal Saskatchewan site sharply contrasts the temperate forest site in North Carolina (see tables 4.3 and 4.4). Its mean annual temperature is about 8 degrees C cooler and it receives about half as much rainfall. The boreal site contains significantly more soil carbon than the temperate site. This is probably because it has a lower rate of decomposition of soil organic material than the temperate site.

Samples were taken from three altitudes at each Canadian site: top, middle, and bottom. Slope position for this Saskatchewan native site did not seem a major factor in soil carbon distribution. The middle slope position had the most carbon, but all the values were similar. Still, the slope position for the cultivated Canadian forest site made a significant difference in the carbon distributions (see tables 4.4 and 4.5). The cultivated bottom site had 62% more carbon than the cultivated top. Further, the native site had about 70% more carbon than the cultivated site at the top of the slope. Clearly, slopes accelerate the downward transport of soil carbon in the cultivated sites, but not the native site. Before farmers cultivated the land, they scraped off the litter layer, which also accelerated erosion and reduced soil carbon input. The technique used in farming the soil involves letting the land sit idle every other year to build up soil moisture for the next growing season. While the land lies fallow, farmers frequently plow under any vegetation to cut losses due to evapotranspiration (Schoenau, personal communication, 1991). This accelerates soil carbon decomposition because the higher moisture and temperature speed microbial decay relative to its native counterpart. The lack of significant carbon input in these fallow years has also reduced carbon inventory at this site. The soil scientists have classified this soil as a Gray luvisol. The average annual temperature is 6 degrees C and the average rainfall is 425 mm.

The 40% carbon inventory reduction for the Saskatchewan forest site is greater than the 25% predicted by Past and Mann (1990). The 30% nitrogen loss is also 4-5 times greater. The large nitrogen loss stems from the removal of the forest litter layer prior to cultivation, the fallow farming techniques and because no nitrogen was added through crop rotations or fertilization.

Saskatchewan grassland:

The Canadian grassland site was located in Saskatchewan, Canada, south of the city of Saskatoon. The latitude and longitude of the site are 54 degrees N and 106 degrees W. The slope for both Canadian sites was 8 degrees. The sites were adjacent north facing slopes with 100 m long north facing slopes with an 8% grade. The lower slope of the grassland area was submerged 5 out of 10 years depending on the amount of snowfall. This submergence created prolonged anaerobic conditions as evidenced by the gleying or mottles in the soil. The upper and mid-slope positions were sampled by genetic horizon using a hydraulic coring device mounted on a truck. Five cores were randomly sampled within a 5 meter radius at each position in both the native and cultivated soils. The lower position was sampled by digging soil pits. The cultivated site has been under cereal/fallow management for 70 years and no fertilizer or manure has been added. The cultivated site was planted in the dry years and its productivity was higher than the non-submerged areas. At the native site, the dominant vegetation species in the upper and mid-slope position was blue gama grass (*Bouteloua gracilus*). The lower slope vegetation consisted of hydrophilic grasses.

Unlike the the native Canadian forest site, the grassland native site did show a trend of increasing carbon inventory the lower one went down the slope. The native grassland site had 28% more carbon at the bottom of the slope than at the top of the slope (tables 4.6 and 4.7). The cultivated grassland site had 16% less carbon than its native counterpart. One expects carbon losses for cultivated grassland sites to be less than cultivated forest sites, because cultivated crop residues are similar to grassland litter. The highest concentrations of carbon were present at the bottom of the slope and the lowest concentrations were present at the top. Carbon and/or nutrients and water migrated downward and cultivation accelerated this process. Here, the bottom cultivated site contained three times the amount of carbon as the top cultivated site (table 4.7). In contrast, the native bottom site had only 28% more carbon than the native top site. Soil scientists classified the upper and mid-slope positions as having Chernozem soil and the lower site as a Gleysol.

The 15% carbon loss from the cultivated site (top, middle and bottom slope positions) was significantly less than the average 25% value found by Schlesinger (1986) and Post & Mann (1990). I hypothesize that this preservation is because the bottom site was frequently under water (every other year on average). This submergence made the site anaerobic, which slowed the rate of decomposition.

Nitrogen shows the same trend as carbon. The native site had 15% more nitrogen than the cultivated site. This is about twice the difference predicted by Post and Mann (1990).

This site shows less carbon loss than predicted by Post and Mann (1990) because the C/N ratios between the native (C/N=10) and cultivated (C/N=10) were the same and because of the anaerobic conditions at the lowest slope position.

Lombardy grassland:

The Italy grassland sites were located near Lodi, Lombardy, Italy. The soil was obtained from the Instituto Sperimentale per lo studio in Firenze. The native site was site MI-1 and the cultivated site was MI-5.

Only 15% of the carbon and 10% of the nitrogen were lost from this grassland site. Since the site received enough rainfall to allow crops to be grown every year, the carbon losses were less than the Saskatchewan grassland site, where the land lay fallow every other year. The C/N ratios for the native (C/N=11) and the cultivated (C/N=11) were the same. The clay content, 70%, about twice as high as the other sites, may also have limited soil organic matter losses.

Soil carbon appears to have been transported from the surface soil to deeper soil in Italy (table 4.8). The crop grown at this site was wheat. Carbon appears to have been trapped in a deeper layer of soil having a very high clay content. Perhaps, not all the soil lost from shallow soils is oxidized, but some may be lost as dissolved organic carbon or trapped in deeper layers of soil, like a chromatographic column. The high clay content (twice as high as the other sites; see table 4.1) of this soil may have limited the carbon loss to 15%. The average annual temperature is 13 degrees C and the average annual rain fall is 860 mm. Soil scientists classified this Italian soil as a Hapludalf mollici.

Kansas grassland:

The Kansas site was located on the Konza Prairie, a National Science Foundation Long Term Ecological Research (LTER) site near Manhattan, Kansas. The cultivated site was used to grow foundation soy beans and was located at latitude 39 degrees - 6' - 31" N and longitude 96 degrees - 36'-36" W. The native site was located at latitude 39 degrees - 05' - 30" N and at longitude 96 degrees - 35' - 14" W. The samples were collected using a Giddings soil probe mounted on a truck in August, 1991.

The Kansas grassland site shows how nitrogen-fixing crops can reduce soil nitrogen losses (see table 4.9). The native site had less carbon than the cultivated site for shallow soils, but this difference diminished with depth (see table 4.9). The nitrogen inventories for the two sites were almost identical. The farmers had irrigated the foundation soybeans, which also cut carbon losses. Post and Mann (1990) have found that cultivation can elevate soil carbon levels over native values if soil carbon content is very low because of irrigation and fertilization.

Adding N to cultivated land using nitrogen fixing crops, such as soybeans, may be an attractive alternative to chemical fertilizers. The production, transport and application of fertilizers requires energy (the release of CO_2 to the atmosphere) and can lead to NO_3 groundwater contamination. Reganold et al. (1993) discuss the economic viability of organic farming. They conclude that organic farming improves soil quality over industrial farming, while providing similar profits to the farmer.

The average temperature is 13 degrees C and the average annual rainfall is 750 mm. Soil scientists classify this grassland soil as a fine, Montmorillonitic mesic typic calciaquoll.

The nitrogen fixing soybeans kept the nitrogen inventories between the native and cultivated site virtually identical. However, 30% of the carbon was lost from the cultivated

site. The foundation soybean plants were spaced far apart to limit competition between the plants. The greater than 25% carbon loss is also due to the energy required for nitrogen fixation.

Future Research:

The loss of organic carbon from soils because of cultivation has been documented (Schlesinger, 1986, and Post & Mann, 1990). Still, these studies, as this current one does, have relied on measurements of bulk carbon. A more accurate assessment of soil carbon losses could be achieved by estimating the amount of active carbon lost using the techniques described in chapter 2. Specifically, radiocarbon measurements could be used to estimate the inventory of fast cycling carbon in the native and cultivated sites (table 4.10). Then the percentage in fast cycling carbon could be calculated, which would be greater than the reduction in bulk soil carbon if the passive carbon inventories remained the same.

Conclusion:

The North Carolina forest site showed the largest loss of carbon because the cultivated land was not fertilized or watered and almost no plant residues other than roots had entered the soils (table 4.11). The fallow farming technique had accelerated the rate of decomposition and lowered the input of plant residues at the Saskatchewan forest site. The Saskatchewan grassland site showed very little carbon loss despite having the same land use treatment at the forested site because a portion of the site has been submerged occasionally, which hinders the rate of decomposition. The Kansas grassland site had very little nitrogen loss. The Lombardy site's surface carbon appears to have been partially redeposited deeper in the soil column.

Forested sites had greater fractional carbon losses than grassland sites, so limiting new agriculture to non-forested sites would reduce future biospheric carbon emissions from soils. High clay content and submerged land also limits carbon losses, so crops grown in water such as rice may release less carbon to the atmosphere than crops grown on land. Crop rotations using soybeans may be one way to reduce the need for fertilization.

Table 4.1: Site characteristics: temperature, rainfall, clay content, and measurements made.

site	ecosystem	average temp (°C)	average ppt (mm)	clay %	C/N	C-14	bulk
North Carolina	forest	15	1075	--	X	X	X
Sask.	forest	6	425	31	X	X	X
Sask.	grass	7	325	33	X	X	X
Lombardy	grass	13	860	70	X	X	X
Kansas	grass	13	750	35	X	X	X

Table 4.2: Litter removal experiment.

method 1	litter (g)	method 2	litter (g)
hand sort	4.0	hand sort	4.5
sieve (<2mm)	0.8	float	1.1
float	0.3	sieve(<2mm)	<0.1
total	5.1	total	5.6-<5.7

Table 4.3: North Carolina forest native and cultivated carbon, nitrogen and C/N data.

depth cm	native site (n=5) %C	%N	C/N	cultivated site (n=1) %C	%N	C/N
0-2.5	4.91	0.24	20	0.41	0.04	10
2.5-5	2.61	0.14	19	0.33	0.04	8
5-10	1.94	0.11	18	0.48	0.04	12
10-15	1.11	0.06	18	0.25	0.03	8
15-20	0.88	0.05	18	0.21	0.03	7
20-30	1.11	0.05	22	0.12	0.02	6
30-40	0.33	0.03	11	0.11	0.02	6
40-50	0.42	0.04	10	0.18	0.03	6

Table 4.4: Saskatchewan forest native and cultivated carbon, nitrogen and C/N data.

slope position	depth(cm)	C(g/cm²)	N (g/cm²)	C/N
Native:				
top	0-5	0.346	0.0198	17
	5-17	0.164	0.0117	14
	17-68	0.545	0.0482	11
	68-95	0.074	0.0128	6
	total	1.129	0.0925	13
mid	0-5	0.311	0.019	17
	5-13	0.102	0.008	13
	13-90	0.813	0.072	11
	90-105	0.048	0.007	7
	total	1.274	0.106	13
bot	0-7	0.586	0.037	16
	7-21	0.143	0.011	13
	21-70	0.368	0.036	10
	70-90	0.097	0.012	8
	total	1.194	0.097	12
Cultivated:				
top	0-7	0.196	0.017	12
	7-48	0.281	0.028	10
	48-70	0.069	0.009	8
	total	0.546	0.054	11
mid	0-16	0.372	0.031	12
	16-65	0.238	0.026	9
	65-95	0.061	0.012	5
	total	0.671	0.069	10
bot	0-17	0.352	0.031	11
	17-80	0.426	0.044	10
	80-104	0.010	0.015	7
	total	0.788	0.090	10

Table 4.5: Saskatchewan forest summary.

slope position	C(g/cm2)	N(g/cm2)	C/N
Native:			
top	1.13	0.093	13
middle	1.27	0.106	13
bottom	1.19	0.097	12
Cultivated:			
top	0.55	0.054	11
middle	0.67	0.069	10
bottom	0.88	0.090	10

Table 4.6: Saskatchewan grassland native and cultivated carbon, nitrogen and C/N data.

slope position	depth(cm)	C(g/cm2)	N(g/cm2)	C/N
Native:				
top	0-15	0.438	0.043	10
	15-30	0.162	0.018	9
	30-45	0.064	0.006	10
	45-70	0.094	0.011	9
	70-90	0.058	0.007	9
	total	0.816	0.085	9
mid	0-14	0.421	0.040	11
	14-25	0.158	0.016	10
	25-40	0.200	0.023	9
	40-70	0.267	0.031	9
	70-90	0.058	0.007	8
	total	1.104	0.117	9
bot	0-5	0.169	0.015	12
	5-15	0.578	0.055	11
	15-27	0.245	0.025	10
	27-70	0.421	0.047	9
	total	1.413	0.142	10
Cultivated:				
top	0-15	0.271	0.030	9
	15-27	0.128	0.015	9
	27-50	0.110	0.017	6
	total	0.509	0.062	8
mid	0-15	0.280	0.029	10
	15-39	0.267	0.028	9
	39-50	0.048	0.007	7
	50-70	0.051	0.007	7
	total	0.646	0.071	9
bot	0-15	0.412	0.041	10
	15-40	0.837	0.083	10
	40-70	0.454	0.049	9
	total	1.703	0.173	10

Table 4.7: Saskatchewan grassland summary.

Slope position	C(g/cm2)	N(g/cm2)	C/N
Native			
top	0.816	0.085	9
middle	1.104	0.117	9
bottom	1.413	0.142	10
Cultivated			
top	0.509	0.062	8
middle	0.646	0.071	9
bottom	1.703	0.173	10

Table 4.8: Lombardy grassland native and cultivated carbon, nitrogen and C/N data.

Native:

depth (cm)	%C	%N	C/N
0-10	1.75	0.200	9
10-40	1.90	0.200	10
40-55	0.20	0.020	10
55-82	0.10	0.000	--
82-105	0.10	0.000	--

Cultivated:

depth (cm)	%C	%N	C/N
0-23	0.96	0.127	8
23-33	0.96	0.105	9
34-100	0.65	0.036	18
100-160	0.37	0.011	34

Table 4.9: Kansas grassland native and cultivated carbon, nitrogen and C/N data.

depth	Native:			Cultivated		
(cm)	%C	%N	C/N	%C	%N	C/N
0-2	6.800	0.500	14	1.900	0.200	10
2-4	4.600	0.400	12	1.800	0.200	9
4-6	3.700	0.300	12	1.900	0.200	10
6-8	3.200	0.100	32	1.700	0.200	8
8-10	2.500	0.200	12	1.800	0.200	9
10-15	2.400	0.200	12	1.700	0.200	8
15-20	2.000	0.200	10	1.900	0.200	10
20-30	1.900	0.200	10	1.900	0.200	10
30-40	1.600	0.100	16	1.900	0.200	10
40-50	1.400	0.100	14	1.200	0.200	6
50-60	1.200	0.100	12	1.300	0.200	6
60-70	1.000	0.100	10	1.000	0.200	5
70-80	0.800	0.100	8	0.700	0.100	7
80-90	0.800	0.100	8	1.100	0.100	11

Table 4.10: Comparison of radiocarbon measurements at native and cultivated sites.

Site	Native	Cultivated	sampling date
NC Forest	1.15*	(in Zurich)	1991
Saskatchewan Forest			1985
top	1.23	1.04	
middle	(in Zurich)	1.04	
bottom	1.10	1.02	
Lombardy Grass	1.09	1.03	1987
Kansas grass	1.15	1.01	1991
Saskatchewan Grass			
top	(in Zurich)	1.04	1985
middle	(in Zurich)	(in Zurich)	
bottom	1.09	(in Zurich)	

*The units for radiocarbon are $(^{14}C/C)_{sample}/(^{14}C/C)_{1850\ wood}$

As discussed in chapter 3, cultivated sites have significantly lower radiocarbon values than their native counterparts. The depths for these radiocarbon values are listed in Appendix B.

Table 4.11: Summary of carbon and nitrogen losses for paired native and cultivated sites.

Site	Native C(g/cm2)	N(g/cm2)	Cultivated C(g/cm2)	N(g/cm2)	% loss(native-cult.) C	N
NC Forest (0-50 cm)	0.601	0.036	0.181	0.024	70	32
Saskatchewan Forest	1.200	0.098	0.700	0.070	40	30
Saskatchewan Grass	1.110	0.115	0.950	0.100	15	13
Lombardy Grass	1.385	0.122	1.163	0.108	15	10
Kansas Grass	2.290	0.210	1.640	0.220	30	0

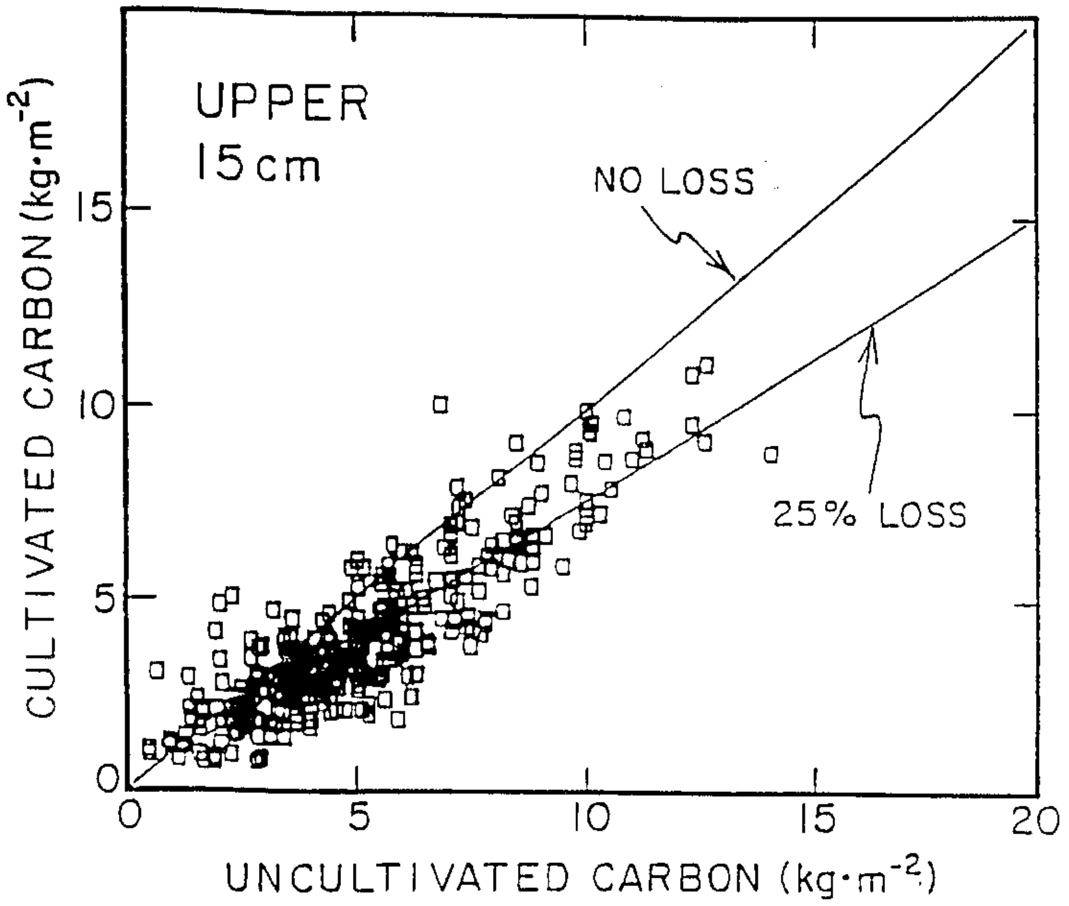


Figure 4.1: Post and Mann (1990) found that cultivation reduces native carbon inventories by 25% and native nitrogen inventories by 6%. It is not clear if the cultivated sites used in their study were fertilized.

Chapter 5: The Impact of Changing Land Use on Soil Carbon Storage: Recovery

Abstract:

After farmers abandon land, the soil carbon and nitrogen inventories usually begin to increase or recover as natural vegetation begins to take over. This chapter explores both the rate and extent of recovery, and investigates the possibility for enhanced recovery. I contrast a North Carolina forested site with a Kansas grassland site, exploring possible explanations for why the North Carolina site has recovered more carbon than the Kansas site. A series of archived South Carolina soils from a recovering Loblolly pine forest provide the venue for studying carbon turnover times in soil that is accumulating. This recovering ecosystem's carbon turns over twice as quickly as the global average for soil carbon.

Introduction:

Currently, scientists cannot explain the fate of 1.8 Gt of carbon per year for the 1980's (Sundquist, 1993). The amount of carbon thought to be released by the biosphere is 1.6 GtC per year for this period, which is about the same size as the so-called missing sink. Land may recover more carbon than expected because of N-deposition and natural N-fixation.

Since the estimate of biospheric release of carbon is based largely on changing land use records, knowing the amount of soil carbon lost through cultivation and the extent of recovery is crucial. Houghton et al. (1983) assume that temperate forests can only recover up to 90% of their carbon after they have recovered and achieved a new steady state. The losses upon agricultural disturbance appear robust. Post & Mann (1990) have compared 1,100 paired native and disturbed soils and have found losses to average about 25%.

Schlesinger (1986) supports this value. But, the 90% recovery used by Houghton et al. (1983) is not well-supported. Schlesinger (1986) states that very few studies have measured soil carbon content after secondary succession. Billings (1938) has reported that accumulation of soil organics during secondary succession of 250% in the surface soil and 150% in the A2 horizon over pre-recovery values for pines in Durham County North Carolina. Schiffman and Johnson (1989) have found that natural reforestation of old fields increases carbon content from 55,000 kg/ha to 185,000 kg/ha. About 25% of the increase occurred in soils and the remainder was in vegetation. Clearly, the potential exists for soil carbon recovery to exceed 90%. In 1968, the southern US had 16.6 x 10^6 hectares of land that were recovering (Hart, 1968). The North and South Carolina sites are representative of this type of recovery.

Anthropogenic N-deposition and natural N-fixation are possible mechanisms for enhanced soil carbon recovery. Below, I explain how each of these mechanisms might work to boost recovered soil carbon up to and over the pre-disturbance carbon content.

Recovering forests may retain industrial nitrogen more efficiently. Schindler & Bayley (in press) discuss this possibility. Therefore, although the same amount of N is deposited on native and recovering ecosystems, the recovering forest retains more N and has the potential to sequester more carbon with this additional nitrogen. Not only can the age of vegetation affect recovery, the type of vegetation can also impact the rate and extent of recovery. Recovering forests typically consist of pine, while their native counterparts are deciduous in North and South Carolina.

N-fixation is another possible way to promote enhanced recovery. N-fixation can boost nitrogen levels above native levels in only a few years, and this extra nitrogen can be combined with carbon to increase levels of soil organic matter. Asymbiotic N-fixation rates range from 1 to 5 kg/ha/yr, whereas symbiotic N-fixation can exceed 100 kg/ha/yr. N-fixing scrub frequently covers abandoned land and constitutes an important stage in early succession by stabilizing the soil and adding usable nitrogen to the soil.

Nitrogen-fixation is the conversion of N_2 into a form available for plants and animals. Stryer (1981) estimates that 2 x 10^{11} kg N/year are fixed naturally. Only procaryotes, such as bacteria and blue-green algae, fix nitrogen and these can be either free living or symbiotic. The amount of nitrogen fixed by asymbiotic bacteria range from 1 to 5 kg/ha/yr (Schlesinger, 1991). Symbiotic nitrogen fixers, such as *Rhizobium*, colonize the roots of legumes. Specific types of nitrogen fixing bacteria infect specific types of plants and the resulting nodule is the plants response to this infection. A form of mutualism results, where organic carbon is exchanged for fixed nitrogen.

The biological process of N-fixation is energy intensive because the extremely strong N-to-N triple bond must be broken (225 kcal/mole) and because energy must be expended to keep oxygen away from nitrogenase. Nitrogenase, the enzyme responsible for fixing N_2, contains Mo, Fe and inorganic S. Splitting one molecule of nitrogen requires 12 molecules of adenosine triphosphate (ATP) for the reaction and additional ATP molecules to exclude oxygen from the enzyme, which would be destroyed if it came into contact with air. Industrially, nitrogen is fixed using the Haber process: $N_2 + 3H_2 \Longrightarrow 2NH_3$ at a pressure of 300 atmospheres and 500 degrees C temperature.

This energy cost of fixing N represents about 1/5th of all the energy used by the plant (Stryer, 1981), and puts nitrogen-fixing plants at a disadvantage compared to non-fixing plants in soils where nitrogen is abundant. However, in soil with low nitrogen, nitrogen-fixing plants have an advantage over their non-fixing counterparts. Hence, the greatest N-fixation rates are seen in species that colonize disturbed land, such as *Ceonothus velutinus* which can fix up to 100 kg N/ha/yr. Eventually, the nitrogen-fixation on disturbed land builds up nitrogen inventories, which indirectly gives non-nitrogen fixing plants an advantage and directly inhibits nitrogen fixing bacteria. Hence, N-fixing plants are rare outside of disturbed communities.

<u>Research Strategy:</u>

I have selected two sites to compare and contrast to test the hypothesis of advanced recovery. I have chosen the Duke Experimental Forest in Durham, North Carolina to maximize the chances of enhanced recovery. This site was adjacent to the site described in the previous chapter (see chapter 4 for a detailed site description). The site's recovering vegetation is Loblolly pine, which has shown increased net primary productivity in response to elevated levels of atmospheric carbon dioxide (Strain & Cure, 1985). The North Carolina site receives a moderate amount of N-deposition (100 mg/m2/yr). Before foresters planted the abandoned land with Loblolly pine, workers removed scrub. Therefore, the opportunity existed for N-fixing scrub to raise the amount of N present in the soil.

In contrast, I chose the Kansas site to minimize the possibility of enhanced recovery. The Kansas site was located on the Konza Prairie, which is a National Science Foundation Long Term Ecological Research (LTER) site. This site is located near Manhattan, Kansas (see chapter 4 for a more detailed site description). The N-deposition is very low in this region (the amount of rain falling in this region is much lower that the North Carolina site) and grasses are less efficient than forest at intercepting atmospheric N. Also, there was no opportunity for N-fixing scrub to build up N-reserves in the soil. I examine the sites in specific detail below.

North Carolina forest:

The native site in the Duke Experimental Forest, Durham, North Carolina consists of a deciduous hardwood stand of mixed ages, primarily oak. Some trees may have been harvested, but no evidence or record of major disturbances has been found. The recovering site is adjacent to the native site (compartment 67, section 7).

Before 1931, farmers cultivated and abandoned the land at the recovering site. It is not known how long the land was cultivated before abandonment. In 1931, foresters removed all of the successional scrub and planted Loblolly pines. The successional vegetation that was removed included a dense stand of broom sedge, some blackberry briers, quite a bit of poorly developed sassafras, persimmon, scattered hickory and blackgum; abundant well developed red cedar and yellow poplar; clumps of briers, scattered Loblolly pine, and Virginia pine. In 1932, foresters took steps to reduce erosion. Workers cleared the plantation in 1934 and thinned the site in 1949, 1953 and 1958. Tip moths heavily infested the plantation from 1933 to 1935.The plantation was clear-cut in 1988, and foresters replanted pines in 1990. Table 5.1 gives a complete chronology of the land use history and table 5.2 gives the characteristics of the sites studied in this chapter.

I sampled the sites in May of 1991 and in August of 1992. In 1991, I dug two soil pits to a 2 meter depth with a shovel (1 meter x 1 meter). In 1992, I dug 5 additional pits to a depth of 50 cm (50 cm x 50 cm) at each site.

Table 5.3 shows the carbon results. I sampled the soil column every 10 cm down to the 2 meter depth. In the 0-10 cm interval, the native site had slightly more carbon than the recovering site, but from 10-30cm, the recovering site had more carbon than the native site. Below 50 cm, the differences between the sites were slight and tended to average out. The recovering site had a total of 88,600 kg C/ha and the native site had 76,200 kg C/ha. Hence, the recovering site had about 15% more carbon than the native site. The C and N results of samples collected at10 additional excavations in 1992 support these results (see table 5.4).

The nitrogen data provide some insight into enhanced carbon recovery and exhibit the same trends as the carbon: The recovering surface 10 cm has more nitrogen in the native site, but the next 30 cm have significantly more nitrogen in the recovering site than in the native site. Below 150 cm, the gas chromatograph could not detect N.

The radiocarbon data for the sites are nearly identical. The C-14 values were 112% modern for the native site and 115% modern for the recovering site, suggesting that the carbon turnover times and inventories are similar and that carbon had not been accumulating in the recovering site during the atmospheric C-14 bomb spike. Chapter 3 discusses how cultivation affects radiocarbon levels. After the land was abandoned, the land had at least 60 years to rebuild inventories of active carbon. If significant accumulation had taken place after 1960, this would have been reflected by higher radiocarbon values for the recovering site. For example, see the radiocarbon values for the Calhoun Experimental Forest, South Carolina, which started recovering just prior to atmospheric bomb testing (figure 5.1).

The recovering site may have more carbon than the native site due to N-deposition, residual fertilizer, N-fixation, or a combination of the three. To explore these possibilities, I have estimated the amount of carbon and nitrogen present when farmers abandoned the land (see table 5.5).

Post & Mann (1990) have shown that on average cultivation reduces the soil carbon inventory by 25% and soil nitrogen inventory by 6%. Therefore, multiplying the native carbon inventory (76,200 kg C/ha) by 75% leads to an estimated pre-abandonment inventory of 58,700 kg/ha. Multiplying the native nitrogen inventory by 94% leads to an estimated pre-abandonment figure of 4,300 kg/ha. The recovering ecosystem gained 635 kg N/ha from abandonment until I sampled the site in 1991 and 1992.

The additional nitrogen could have been residual fertilizer, added by industrial N-deposition or added by N-fixation (see table 5.6). Nitrogen-fixation gives a possible explanation for additional nitrogen and its retention by the ecosystem. Nitrogen-fixation can occur asymbiotically or symbiotically. Asymbiotic nitrogen-fixations occurs when free living bacteria convert N_2 into NH_3. Symbiotic bacteria live in the nodules of plants, such as legumes (e. g. soy beans). Their populations appear greatest after disturbances, such as forest fires or strip mining, but their occurrence in undisturbed land is limited. As the

recovery of disturbed land proceeds, their populations diminish. Schlesinger (1991) estimates that nitrogen-fixation rates range from 1-5 kg N/ha/yr for asymbiotic fixation and up to 100 kg N/ha/yr for symbiotic N-fixation. Asymbiotic nitrogen-fixation could have added about 150 kg N over a 60-year period using a 2.5 kg N/ha/yr fixation rate. The amount of scrub cleared before the workers planted pines suggest scrub was present for about 10 years after abandonment. If a representative symbiotic fixation rate of 50 kg N/ha/yr is used, 500 kg N/ha can be explained through symbiotic N-fixation.

Another potential source of N is industry. A reasonable rate of N deposition in this region from 1930 to 1960 might be as high as 1 kg N/ha/yr. Although this nitrogen would have been deposited on both the native and recovering sites, it may have been retained more efficiently in the aggrading site (table 5.6). Therefore, of the 60 kg N/ha/yr deposited on the site, about 20% more N or 12 kg N/ha could have been retained by the pine system.

In summary, N-fixation could have added up to 650 kg N/ha. If the nitrogen were added by nitrogen fixing scrub, one would expect the bulk of the nitrogen to be present in the upper soil, where the roots of the scrub can reach. Hence, the observation that most of the additional nitrogen is in the upper 40 cm is consistent with this hypothesis, but does not necessarily exclude other possibilities. The nitrogen-fixation hypothesis assumes that the crops grown before abandonement reduced soil carbon and nitrogen inventories by 23% and 6% respectively. It's possible that cultivation reduced inventories by more or less. If a nitrogen fixing crop such as soybeans were grown, this could explain the added nitrogen. However, some think the land was most likely abandoned because of low agricultural yield, possibly because of diminished soil nutrients. The addition of industrial N and residual fertilizer may have contributed from 10-50 kg N/ha. This small input would counter losses due to leaching and denitrification. Therefore, nitrogen- fixation has the potential to explain the N recovery. Once the levels of soil nitrogen have been built up, the pine forest could have used the additional nitrogen to efficiently sequester carbon (see table 5.7).

Conifers and deciduous trees vary in the amount of litter they produce. Cole & Rapp (1981) suggest that conifers produce about 4400 kg of biomass /ha/yr with a C/N ratio of 50. In contrast, deciduous trees produce 5400 kg/ha/yr of litter and have a C/N ratio of about 24. Therefore, although conifers produce less litter, the litter's higher C/N ratio may make it more resistant to microbial attack. Pastor & Post (1984) show that pine litter contains 28% lignin, while deciduous litter has only 18.7% lignin. Melillo, Aber & Muratore (1982) have shown that higher lignin content makes litter more recalcitrant, which could speed up the carbon recovery by slowing decay. Pastor & Post (1986) have found that conifers produce 194 kg of biomass/kg N, contrasting deciduous trees, which produce 143 kg of biomass/kg N. Therefore, conifers sequester more C per N and produce more recalcitrant litter.

Nitrogen-fixation is a possible mechanism to explain why the recovering North Carolina site had 8% more nitrogen than the native site; samples are being analyzed for N-15 as a test of this hypothesis. Total P is being measured to check for residual fertilizer. This additional nitrogen stimulated soil carbon production, so the recovering land had 15% more soil carbon than the native site. The conifers aided this process with their lower N losses, higher C/N ratios and decay-resistant litter.

Kansas grassland:

The Kansas grassland native site location is described in chapter 4. The nearby recovering site is also located on the Konza Prairie National Science Foundation Long Term Ecological Research (LTER) site. Its latitude is 36 degrees -06' - 00" N and its longitude is 96 degrees - 35' - 22"W. It is located 1900 feet east and 850 feet west of the NW corner of section 18.

The grassland site in Kansas is among the least likely places to show enhanced recovery: no nitrogen fixing scrub has grown after abandonment and the region has had little industrial N-deposition.

The Kansas grassland sites were rare specimens of native grassland, which is scarce because most of it has been cultivated or used as pasture. Farmers have never plowed the native site or used it for pasture, according to the available land use records.

The abandoned Kansas site has 40% less carbon than the native site (table 5.8). The native site appears to have a much higher inventory of active soil carbon than the recovering site. The radiocarbon value for the native site is 115% modern, but the radiocarbon value for the recovering site is only 101%. As discussed in chapter 3, the radiocarbon differences are due to mixing deep soil depleted in soil radiocarbon with enriched surface soil; surface soils also lose active soil carbon through increased oxidation of soil organics and decreased crop residue input.

In summary, the Kansas site has shown very little recovery in soil carbon content, even though farmers abandoned it over 40 years ago. I have selected this site to show retarded recovery because N-deposition and N-fixation are not likely to have elevated the levels of usable nitrogen. After this land was abandoned for cultivation, it was seeded with brome, which prevented the succession of nitrogen fixing scrub.

South Carolina forest:

The South Carolina site is located in the Calhoun Experimental Forest, in Sumter National Forest, Union County, South Carolina, 100 km northwest of Columbia. Soil scientists classify this soil as an Ultisol. The site averages 1170 mm of rainfall per year and the average temperature is 16 degrees C. The slope is less than 3 percent. The parent material is granite gneiss bedrock, which is located 6 meters below the soil surface.

The site had been cultivated for at least 150 years prior to abandonment and is representative of old-field Loblolly pine forests in the Piedmont of South Carolina. In addition to written records of vegetation regrowth, aerial photographs of the site have also documented recovery. The last cotton crop was harvested in 1954. In 1957, the abandoned field was planted as a Loblolly pine plantation to investigate the growth and nutrient dynamics of successional forests. There are 8 permanent plots in this study (4 are 3200 m^2 and 4 are 6400 m^2), each of which has been sampled by compositing soil from at least 20 individual samples in four soil layers. These samples have been measured separately for nitrogen and carbon (Richter et al., In Press), but combined for radiocarbon. Radiocarbon was measured in the upper 0-7.5 cm. Scientists have sampled biomass and soil at this site in 1962, 1968, 1977 and 1988.

During the period of recovery from 1962 to 1988, the carbon concentration in the upper soil (0 to 7.5 cm) went from 0.52 to 0.70 g/cm2. I have modified the soil carbon model described in chapter 2 to take carbon accumulation into account.

I have analyzed 165-cm deep soil to estimate the turnover time of the slow cycling component. The radiocarbon value is 77% modern, which corresponds to a 2300-year replacement time. The radiocarbon values for 1962, 1968, 1977 and 1988 were 99%, 123%, 128% and 121% modern respectively (see figure 5.1). The accumulating carbon model provides the best fit to the data using a 35% passive and 65% active mixture of initial surface soil carbon, with a 12-year turnover time for the active soil carbon. Since the model and the measurements started after agricultural abandonment, plowing was not included in the model. The active soil carbon is turning over at a rate twice as fast as the 25 year time for the global average for native ecosystems discussed in chapter 2.

In short, the soil for a recovering site that has been accumulating soil carbon provides an interesting challenge to model. Because carbon has accumulated during the bomb peak, the steady-state carbon model requires adjustment to accommodate

accumulating ecosystems. The results suggest that carbon turns over almost twice as fast in recovering forests than in their native counterparts.

Why is the soil carbon turning over so quickly in this aggrading forest? The plant residue supply to soils is greater than a mature forest, and decomposition must lag the input of soil organic material because soil carbon is accumulating. Possible factors include temperature, moisture and litter quality. Perhaps, the organic residues added to soil in an aggrading forest have a different composition than those of a mature forest, resulting in a shorter turnover time. Also, these residues may support a larger bacterial population.

<u>Discussion</u>:

The Duke Experimental Forest in North Carolina, the Konza Prairie, Kansas grassland site and the Calhoun Experimental Forest in South Carolina provide insights into the dynamics of soil carbon recovery. The land use histories for the three sites have been described in table 5.1. At Duke, the recovering site has more carbon and nitrogen stored in soils than the native site. N-fixation provides the most likely candidate for boosting the nitrogen inventory, which in turn allows the pines to efficiently sequester more soil carbon. The Kansas site shows how poorly grasslands recover from disturbances, most likely because of the low productivity of the subsequent vegetation. The Calhoun forest shows that recovering forests that have not achieved steady-state turn over soil carbon at twice the rate of steady-state forests.

If soil carbon recovery can be enhanced by natural N-fixation, then estimates of global biospheric release may be too high. If so, then the size of the so-called missing sink may shrink.

These results also raise the possibility that the terrestrial ecosystem could be engineered to enhance soil carbon recovery to speed the removal of atmospheric carbon dioxide. After foresters clear cut land or farmers abandon marginal agricultural lands, the seeds of N-fixing shrubs could be introduced to build up usable soil nitrogen inventories. This nitrogen would stimulate the growth of subsequent vegetation and soil carbon inventories. This contrasts with current forestry practice, which discourages the growth of scrub.

Wofsy et al. (1993) have studied the recovery of the Harvard Experimental Forest (a temperate forest located in Petersham, MA), which is on land that was originally farmed until early in this century, abandoned and then blown down by a hurricane in 1938. They estimated that carbon was accumulating at a rate of 3.7 ± 0.7 metric tons of carbon per hectare per year using an eddy correlation technique. This value is supported by allometric measurements of net forest growth in nearby plots that range from 3.1 to 3.6 metric tons carbon/ha/year. The observed rate of recovery is faster than values used by others in global carbon sequestration calculations. For example, Houghton et al. (1983, 1987 & 1992) use a range from 0 to 2.5 metric tons C/ha/year. The results from the North Carolina forest suggest that the rates of recovery used in global biospheric carbon exchange estimates may be too low. Similarly, Wofsy (1993) suggests that the rate of carbon build-up in recovering forests may be faster than values used to estimate biospheric carbon eschange.

Table 5.1: Land use histories for North Carolina, Kansas and South Carolina.

<u>North Carolina</u>	<u>Recovering Forest</u>
pre-1931	land cultivated*/abandoned
1931	scrub removed/Loblolly pines planted
1932	erosion control
1933-35	heavy tip moth infestation
1934	clearing
1936	recovery from tip moths
1949, 53, 58	thinning
1988	clear cut
1990	pine release
1991,92	sampled
<u>Kansas**</u>	<u>Recovering Grassland</u>
pre-1960	cultivated and abandoned
<u>South Carolina</u>	<u>Recovering Forest</u>
1700-1850	cotton, corn &wheat
1850-1954	continuous cropping/application of lime, fertilizer, & soil conservation
1954	last crop of cotton planted two year fallow followed by planting of Loblolly pine
1962, 68, 77, 90	samples collected and later analyzed for radiocarbon

*There are no records indicating the duration and type of crop grown at the North Carolina site. However, the most likely crops for this region are cotton, corn and wheat.

**Almost nothing is definitively known about the Kansas recovering site.

Table 5.2: Site characteristics: temperature, rainfall, clay content, and measurements made.

site	ecosystem	averave temp (°C)	average ppt (mm)	clay %	C/N	C-14	bulk
North Carolina	forest	15	1075	--	X	X	X
Kansas	grass	13	750	35	X	X	X
South Carolina	forest	16	1170	15	X	X	X

Table 5.3: North Carolina forest native and recovering carbon, nitrogen and C/N data, 1991.

depth	Native			Recovering		
(cm)	%C	%N	C/N	%C	%N	C/N
0-10	2.664	0.140	19	1.379	0.061	23
10-20	0.865	0.042	21	0.881	0.046	19
20-30	0.332	0.021	16	0.419	0.024	17
30-40	0.474	0.020	14	0.321	0.021	15
40-50	0.333	0.024	14	0.196	0.014	14
50-60	0.339	0.017	20	0.178	0.014	12
60-70	0.173	0.015	12	0.154	0.012	13
70-80	0.167	0.010	17	0.224	0.017	13
80-90	0.148	0.014	11	0.116	0.006	19
90-100	0.189	0.017	11	0.142	0.013	11
100-110	0.229	0.020	12	0.117	0.011	11
110-120	0.124	0.010	9	0.112	0.01	11
120-130	0.080	0.014	6	0.108	0.009	11
130-140	0.050	<.010	--	0.094	0.009	10
140-150	0.035	0.010	4	0.038	<.010	--
150-160	0.043	<.010	--	0.054	<.010	--
160-170	0.056	<.010	--	0.050	<.010	--
170-180	0.530	<.010	--	0.037	<.010	--
180-190	0.053	<.010	--	0.056	<.010	--
190-200	0.053	<.010	--	0.024	<.010	--

Table 5.4: North Carolina forest native and recovering carbon, nitrogen and C/N data, 1992.

depth cm	native site (n=5) %C	%N	C/N	recovering site (n=5) %C	%N	C/N
0-2.5	4.91	0.24	20	8.52	0.38	23
2.5-5	2.61	0.14	19	2.50	0.12	21
5-10	1.94	0.11	18	1.66	0.08	21
10-15	1.11	0.06	18	1.02	0.06	17
15-20	0.88	0.05	18	0.99	0.06	17
20-30	1.11	0.05	22	0.62	0.06	11
30-40	0.33	0.03	11	0.43	0.04	11
40-50	0.42	0.04	10	0.40	0.03	13

Table 5.5: North Carolina forest native and recovering carbon and nitrogen inventories, 1991.

Site	Carbon inventory (kg/ha)	Nitrogen inventory (kg/ha)
present native	76 200	4 580
calculated pre-abandonment	58 700	4 300
present recovered	88 600	4 940

Table 5.6: Nitrogen sources to North Carolina Forest.

Symbiotic N fixation:

Rate up to 100 kg N/ha/yr

Use intermediate value of 50 kg N/ha/yr for 10 years

(50 kg N/ha/yr)(10 years) = 500 kg N/ha

Assymbiotic N fixation:

Rate = 1-5 kg N/ha/yr

Use intermediate value of 2.5 kg N/ha/yr for 70 years

(2.5 kg N/ha/yr)(70 years) = 175 kg N/ha

N-deposition:

Rate = 1 kg N/ha/yr

70 kg N deposited on both sites

Approximately equals losses due to denitrification and leaching

Recovering site 20% more efficient at retaining nitrogen, so about 14 kg N/ha of additional N could be stored at the recovering site.

Total N additons to recovering site:

~700 kg N/ha (approximately equals the observed increase of 635 kg/ha)

Table 5.7: Contrasting coniferous and deciduous litter production and quality.

Characteristics of litter	Recovering vegetation: Conifers	Native vegetation: Deciduous trees
Production (kg biomass/ha/yr)	4 400	5 400
C/N Ratio	50	24
Lignin content (%)	28	19

(Pastor & Post, 1984 & Cole & Rapp, 1981)

Table 5.8: Kansas grassland native and recovering C, N and C/N data.

depth	Native:			Recovering:		
(cm)	%C	%N	C/N	%C	%N	C/N
0-2	6.800	0.500	14	2.517	0.300	8
2-4	4.600	0.400	12	2.190	0.300	7
4-6	3.700	0.300	12	1.678	0.200	8
6-8	3.200	0.100	32	1.742	0.200	9
8-10	2.500	0.200	12	1.727	0.200	9
10-15	2.400	0.200	12	1.438	0.300	5
15-20	2.000	0.200	10	1.312	0.200	7
20-30	1.900	0.200	10	0.938	0.200	5
30-40	1.400	0.100	14	0.686	0.100	7
40-50	1.200	0.100	12	0.585	0.100	6
50-60	1.000	0.100	10	0.479	0.100	5
60-70	0.800	0.100	8	0.372	0.100	4
70-80	0.800	0.100	8	0.372	0.100	4

The carbon inventory for the native site is 2.29 g/cm2 and 1.35 g/cm2 for the recovering site. The nitrogen inventory for the native site is 0.21 g/cm2 and 0.39 g/cm2 for the recovering site.

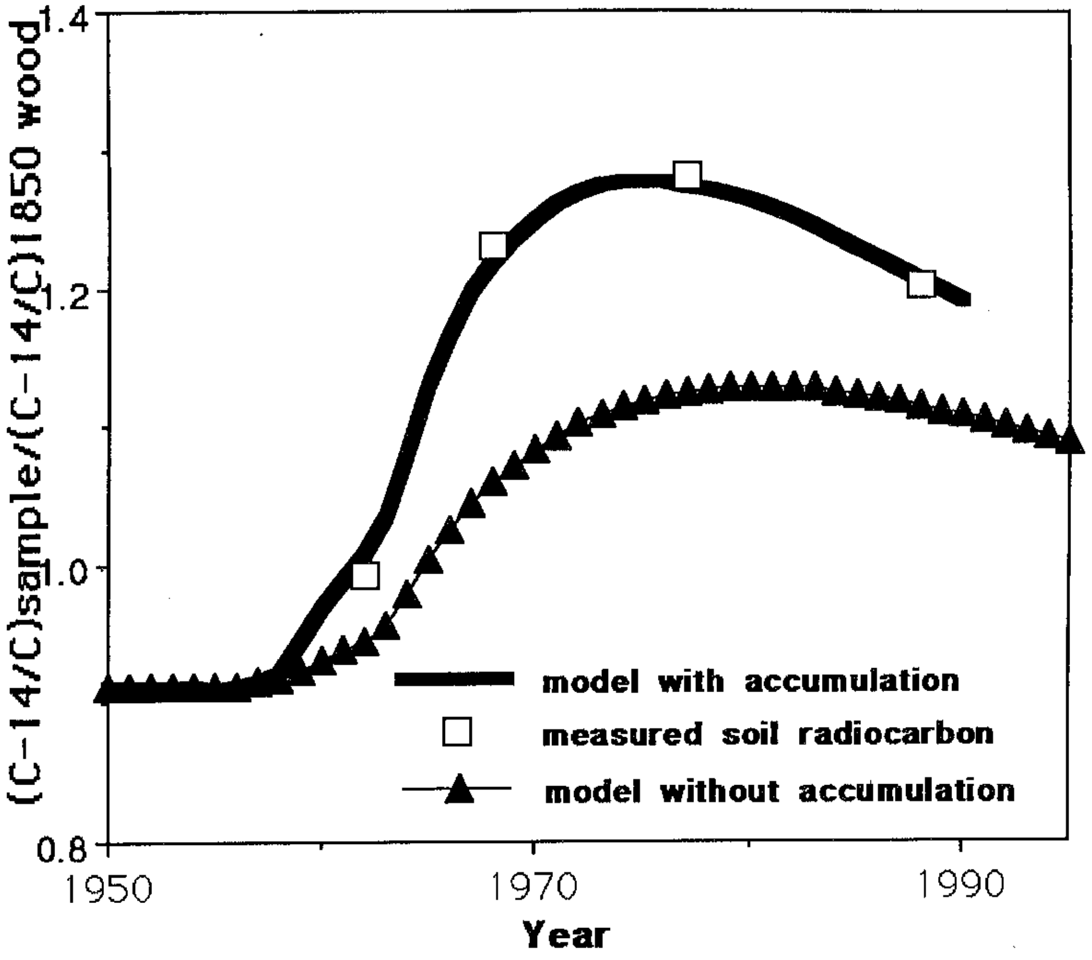


Figure 5.1. Radiocarbon measurements and model results for South Carolina

The model results that best fit the surface soil radiocarbon measurements were those from an accumulation model that took into account the increase in carbon inventory. The best model fit consisted of a mixture of 65% active carbon (having a turnover time of 12 years) and 35% passive carbon (having a turnover time of 2300 years). The passive carbon turnover time was estimated from radiocarbon measurements of soil carbon in the upper 50 cm of the B horizon. The active reservoir turnover time is about twice as fast as the global average for native soils.

Chapter 6: The impact of N-deposition on soil carbon storage

Abstract:

Anthropogenic nitrogen stimulates terrestrial and oceanic productivity. Estimates of nitrogen-induced greening range from 0.5 GtC/year to as high as 2.0 GtC/year. This chapter attempts to reconcile the different estimates. The amount of carbon sequestered because of anthropogenic nitrogen deposition depends on the location of deposition, the amount of nitrogen retained by terrestrial ecosystems, and the C/N ratios of the resulting organic compounds. This requires measurement of the geographical distribution of total fixed N fallout and separation of this fallout into anthropogenic and natural components. The fate of deposited N is examined to determine the amount of carbon sequestered due to anthropogenic nitrogen deposition.

N-production, deposition and distribution:

Nitrogen gets converted from inaccessible forms to biologically utilizable forms through a variety of natural and anthropogenic processes. The anthropogenic processes that release ammonia to the atmosphere include decomposing domestic animal and human waste, application of fertilizer, biomass burning, coal combustion and automobile emissions. Natural processes that release ammonia to the atmosphere include emissions from undisturbed soil, natural forest fires and ammonia released from the world's oceans (table 6.1). The total amount of ammonia released to the atmosphere is 75 Tg N/year (Tg= 10^{12} grams). Table 6.1 illustrates how much of this nitrogen is anthropogenic and shows where this industrial nitrogen is deposited. Of this, 42 Tg N/year is from anthropogenic sources. The sources listed in table 6.2 exceed the sinks by about 30 percent. Schlesinger and Hartley (1992) suggest this imbalance may be due to poorly constrained emissions from undisturbed soils. Since ammonia has an atmospheric lifetime of only a few days, most of the nitrogen added to the atmosphere gets deposited on land and in the ocean. About 30 Tg N/year are deposited on land and 12 Tg N/year are deposited on the ocean.

The sources for atmospheric nitrate include fossil fuel combustion, biomass burning, emissions from soil, lightning, ammonia oxidation, ocean emissions, and high flying planes. Sinks include wet and dry deposition on land and in the ocean (see table 6.2). The total release of nitrate to the atmosphere is 44 Tg N/year and the total amount of nitrate deposition is 43 Tg N/year, which nearly matches the total sources. Table 6.2 shows how the anthropogenic inventory was estimated and illustrates where this industrial nitrogen is deposited. The land receives about 17 Tg N/year and the ocean receives about 12 Tg N/year of anthropogenic nitrogen.

The total amount of anthropogenic N being deposited on land is 47 Tg N/year, while the amount being deposited in the ocean is 24 Tg N/year (see table 6.3). The retention and fate of deposited nitrogen is the next consideration.

Retention of deposited nitrogen:

What percentage of the 47 Tg N/year that falls on land gets retained by the terrestrial ecosystem? Aber et al. (1993) showed that 95 to 100% of the nitrogen added to pine and hardwood stands remains in the ecosystem. They estimated that atmospheric deposition of nitrogen added 0.8 g N/m^2 throughout the three year duration of the experiment; in addition, they added 15 to 40 times that amount as ammonium nitrate 6 times during each growing season. Leaching losses were estimated as lysimeter concentration times the volume of water leaching below the rooting zone. However, retention of deposited nitrogen may be less for different ecosystems. For example, Duce et al. (1991) estimate that rivers add 21 Tg N/year to the world's oceans. If three quarters of this nitrogen was originally deposited on land as anthropogenic nitrogen, then terrestrial ecosystems retention of deposited nitrogen would approach 80%. Melillo and Gosz (1983) found ecosystems that retained only 60% of the deposited nitrogen using deposition and stream measurements. For this study, I assume that 80% (37.6 Tg N/year) of the nitrogen deposited on land is retained by terrestrial ecosystems.

Fate of retained nitrogen:

Before reaching roots, water laden with nitrogen must pass through the soil, which presents a large amount of surface area rich with microbes. While these microbes are generally carbon limited, they will not hesitate to take up inorganic nitrogen and immobilize it as part of their tissue or as humus. By the time the water reaches the roots of plants, much of the inorganic nitrogen has been removed. Supporting this idea, Berg (1988) found that soil microbes retain nutrients from organics they metabolize and accumulate nutrients from soil solutions and other sources. He used N-15 tracer experiments with Scots pine needles in one laboratory and two field experiments. In the lab experiment, 71% of the mass was lost closely following first order kinetics. The increase in soil nitrogen concentration was linearly correlated with loss from the litter (r=0.993, n=15). The results of the forest experiments in a mature pine forest (trees about 120 to 130 years old) and a forest that had just been clear-cut supported the lab experiments. However, the N in the clear-cut area had a faster turnover time than the N in the mature forest.

The type of organic compounds formed by the retained nitrogen depends on the rate at which nitrogen is added to the terrestrial biosphere. One can also look at the nitrogen dynamics of whole ecosystems in three regimes:

1) extremely low levels of nitrogen addition resembling natural levels,
2) chronic low levels of nitrogen input, and

3) rapid pulse like additions to further understand the addition of nitrogen to terrestrial ecosystems.

Johnson (1992) looked at native ecosystems that received very little deposited nitrogen (regime 1). In these systems, plants obtain most of their nitrogen from the decomposition of soil organic material rather than from deposition of inorganic forms.

At higher levels of acid deposition, the additional nitrogen gets incorporated into soil organic matter with a small portion participating in nitrification reactions (regime 2). Hence, when low levels of anthropogenic nitrogen are added to native ecosystems, the microbes outcompete the plants for most of the additional nitrogen. Specifically, Johnson (1992) found that 95% of the 150 kg N/ha added to the system ended up as soil organic material. McNulty et al. (1991) found that most of the 1000 kg N/ha that was added to a forest over a 30 to 40 year period via wet and dry deposition ended up as soil organic matter. Only 1 to 10% ended up in vegetation. Hence, most of the nitrogen that was deposited was retained, and the retained nitrogen ended up as soil organic material.

In typical forest fertilization experiments, fertilizers are added in giant, pulse-like additions (regime 3) that do not mimic the chronic low level additions typical of anthropogenic nitrogen deposition to native ecosystems. Aber et al. (1993) added N in six equal applications of 5 and 15 g/m2 six times throughout the growing season to a pine stand and a hardwood stand at the Harvard Experimental Forest in Petersham, Massachusetts. They made soil, lysimeter, foliage, fine root and tree biomass increment measurements. They concluded that the retention of N was nearly 100% for all but the high application pine plot, in which leaching started to occur in the third year of application. Further, 75% to 92% of the nitrogen ended up in soil organic material. Perhaps, the retention was so high because the Harvard Experimental Forest is recovering from both agricultural abandonment around the turn of the century and a hurricane in the 1930's that blew down many of the trees. Johnson (1992) found that up to 40% of the nitrogen added by pulse-like additions to a forest could be taken up by trees.

In short, although forests have the capacity to assimilate enormous amounts of nitrogen, at some point the soil and vegetation will saturate and start to lose nitrogen. This has been shown to occur primarily in very heavily polluted regions. Soils seem to accumulate most of this anthropogenic nitrogen. Hence, knowing the C/N ratios of soil has become a critical question.

Does immobilizing deposited anthropogenic N sequester carbon?

Since most of the deposited nitrogen retained by the terrestrial biosphere is caught in the soils without any direct link to photosynthetic carbon fixation, it is possible that no additional carbon is sequestered. Supporting this hypothesis, McNulty et al (1991) found that forest floor litter in regions receiving large amounts of nitrogen deposition had lower C/N ratios than regions receiving lower amounts of nitrogen deposition (see table 6.4). The lower deposition region received 2.9 kg N/ha/yr and had a corresponding C/N ratio of 43 for forest floor litter. In contrast, the higher deposition site received 5.7 kg N/ha/yr and had a corresponding C/N ratio of 22 for florest floor litter. These sites were both high elevation spruce-fir forests. Although soil C/N ratios were not measured, one expects an analogous decrease in soil C/N ratios in areas of high nitrogen deposition. Aber (1992) suggests that the nitrogen deposition induced C/N ratio shift is greater in soil than in vegetation and that areas that are nitrogen limited have high C/N soil ratios contrasting nitrogen saturated areas, which have low C/N soil ratios.

Correcting soil organic matter C/N ratios for passive soil carbon:

However, if nitrogen immobilized by soil does sequester additional carbon, knowing the C/N soil ratio of soil organic matter becomes an important consideration. There are two possible ways of interpreting C/N ratios in soils. One way is to assume that both passive and active soil organic matter has the same C/N ratio. This hypothesis provides an upper limit for the amount of carbon that can be sequestered due to N deposition and provides a simple and rational explanation of the observed data, at least in the upper soil. Another way is to assume that most of the N is present in the active soil organic material. This provides a lower limit to the amount of carbon that can be sequestered by anthropogenic N.

Considerable evidence supports the assertion that C/N ratios are similar for active and passive soil organic material. For the majority of soils, the C/N ratio decreases as one goes deeper in the soil column, but stays within 5 units of the average, which can range from 10 to 20, until the N begins to disappear. Table 6.5 shows C and N variations for a grassland soil and table 6.6 shows C and N changes for a forest soil. However, this hypothesis cannot explain the observed ratio changes with increasing depth if soil organic matter decomposition is analogous to litter decomposition.

The hypothesis that passive carbon compounds contain only trace amounts of nitrogen requires a complex explanation. This argument starts with the premise that soil microbes are carbon limited and that microbial biomass (population) correlates with total carbon content. This was an implicit assumption in the carbon model described in chapter 2 and is supported by the work of Zak et al. (1993). Post and Mann (1990) found that cultivation decreased carbon concentrations four times as much as N concentrations because of decreased input of crop residues and accelerated microbial oxidation. They concluded that decomposition of organic material was limited by the microbes' ability to break the carbon-carbon bonds rather than nitrogen availability. Researchers have experimented with the changes of C/N ratios in plant residues as a function of increasing decomposition and time. Schlesinger (1991) summarizes some of the results of these experiments: The C/N ratio decreases with increased microbial oxidation (table 6.7). Further, Sollins (1984) found that fractionated plant residues that were less dense released N faster than more dense fractions. While this observation may be an artifact of the fractionation scheme, it is consistent with the observation that the densest component of fractionated soil typically has the greatest radiocarbon age (Trumbore, 1993). Post et al. (1985) find that as decay of organics progresses, the nitrogen gets immobilized in microbes and decay products with lower C/N ratios. Their conclusion is based on data from 3,000 soil profiles of non-cultivated and non-wetland soil. The profiles taken in regions having the fastest rates of decomposition had the lowest C/N ratios.

Estimates of soil nitrogen turnover times suggest that significant amounts of nitrogen cannot be permanently bound to passive carbon. Estimates of nitrogen turnover times range from a few months to 50 years. Schlesinger (1991) estimates that the average turnover time for terrestrial nitrogen is 50 years. Aber (1992) suggests that N turnover times are closer to a few years, based on soil incubation studies, but N-15 tracer studies suggest a cycling time of a few months. Since all of the specific estimates are less than 100 years, clearly nitrogen cycles faster than the 3700-year turnover time for passive soil carbon.

Profiles of carbon and nitrogen, which include radiocarbon, further support this hypothesis. In the Wohldorf forest, Germany, N concentrations fall from .23% at the surface to 0.005% in the 88-100 cm interval, and radiocarbon values drop from 110% modern at the shallow depths to about 80% modern in the deeper depths (Becker-Heidmann, 1989 and table 6.8). The average C/N ratio is around 12, but ranges from 8 to 18.

Martel & Paul (1974) show similar results in a grassland site in Canada. Radiocarbon values at Waldheim fell from about 99% modern at the surface to 65% modern at the base of the profile, while nitrogen dropped from 0.22%at the surface to 0.07% at the base of the profile.

If the bulk of the nitrogen is in active soil organic matter, which decreases with increasing depth, how can the C/N ratios remain relatively constant with depth? Consider the following thought experiment (table 6.9): Suppose we start with active and passive carbon inventories of soil organic matter as a function of depth. In this case, we will use the New Zealand grassland profile discussed in chapters 2 and 3. The passive inventory changes slightly with depth, but the active carbon inventory starts at 0.18 g C/cm^3 in the 0 to 10 cm interval and drops by a factor of 10 to 0.02 g C/cm^3 in the 40 to 50 cm interval. Suppose we impose the constraint that the C/N ratio for the bulk soil must be 12±3 to simulate the natural C/N variation with depth. If the trace amount of nitrogen present in passive organic material is neglected, the active component in the surface soil would have a C/N ratio of about 10.5. As discussed by Schlesinger (1991), and mentioned in table 6.7, microbial oxidation of plant residues decreases the C/N ratio of the organic matter. Hence, if the active organic matter in the 0 to 10 cm layer is the freshest, it will have the highest C/N ratio. Since, the active organic matter in the 40-50 cm interval has received more microbial processing, one expects the 40 to 50 cm segment to have the lowest C/N ratio. It follows that the C/N ratio for the active component drops to 3 in the deepest segment to preserve the C/N ratio of 11 in the bulk soil. While this thought experiment cannot be proven with the available data, it does provide a lower limit for the C/N ratio of soil organic material (i. e. if the passive soil organic matter contains no nitrogen, then C/N ratios need to be reduced by 25% to correct for this).

Ecosystem distribution of deposited nitrogen:

The anthropogenic nitrogen is not deposited equally on the ecosystems of the world. Peterson & Melillo (1985) have estimated that temperate forests receive two-thirds of the landfall nitrogen, boreal and peat ecosystems receive 17% and the tropics and scrubland/grassland each receive about 8% (see table 6.10).

Peterson & Mellilo (1985) have assumed that additional N will be absorbed and stored in the same proportions as in nature (see table 6.10). Soil organic matter stores about 85% of the N and short-lived vegetation and litter stores the remaining 15%. I hypothesize that very little nitrogen ends up in the long-lived structural components of trees. Although woody parts of trees contain nitrogen, it is not an integral part of the structural material, which is mainly cellulose. A small amount of nitrogen may be present in the outermost ring of the tree and a small portion may be stored in the tree after the leaves have fallen off.

N-stimulating oceanic productivity:

Unlike the terrestrial biosphere, plankton dominates the oceanic biosphere with extremely consistent C/N ratios, which average around 7. Plants and trees consist largely of organic compounds having only trace amounts of nitrogen, such as cellulose, in their support structures. Plankton float and are magnitudes smaller than trees, so they require much less structural material. Some species of plankton have skeletons made up of calcium carbonate, but others have silicate and cellulose structural parts shells. The proportions of C/N/$CaCO_3$ are 28/4/7. Therefore, for every four molecules of organic carbon formed, one molecule of $CaCO_3$ is formed (Broecker and Peng, 1982).

Adding N to the ocean's mixed layer will result in the export of organic and inorganic carbon from the mixed layer, thus lowering its tCO_2. But, the formation and loss of calcium carbonate changes alkalinity and raises the oceanic pCO_2. Therefore, the $CaCO_3$ formation reduces the effectiveness of the soft tissue pump by 25% (Broecker & Peng, 1982). I assume that the hard shells formed are calcite and the effects of nitrate on alkalinity can be neglected.

About 0.024 Gt N get deposited directly on the ocean annually (table 6.3). I estimate that rivers add 0.009 Gt of industrial N through runoff (20% of the total 0.047 Gt of anthropogenic N deposited on land that is not retained by ecosystems). Using the C/N/$CaCO_3$ ratio of 28/4/7, the organic carbon produced will be 0.2 Gt. Because of the formation of $CaCO_3$, the effective export could be as low as 0.15 Gt.

Summary of carbon sequestered by industrial nitrogen:

The amount of industrial N put into the oceans is about 0.03 Gt, which has the potential to remove 0.15 to 0.20 GtC from the mixed layer. About 0.038 Gt of industrial N deposited and retained by the land sequesters 0.7-0.9 Gt C. The combined total ranges from 0.5 to 1.1 Gt C per year.

Discussion:

Estimating the amount of carbon sequestered because of industrial N remains a challenging problem. In response to this challenge, I add two new considerations. Many researchers have overlooked the role of calcite formation when calculating the amount of carbon exported from the ocean's mixed layer. The correction reduces the amount of carbon that can be sequestered by the ocean by 25%. The second consideration concerns the possible reduction of C/N soil organic matter ratios by 25% if active soil organic matter contains most of the nitrogen in bulk soil organic matter, thus establishing a lower bound on the amount of carbon sequestered in soils because of anthropogenic nitrogen deposition.

There is much confusion in the literature concerning the fate of N after it has been retained by the ecosystem. This confusion stems from different experimental techniques. If one dumps nitrogen onto soil, up to one half of it will be absorbed into vegetation. But, if one simulates industrial N deposition by adding the N gradually, soil retains most of the N.

All three of these areas demand future research. Further, the addition of N may be reinforcing CO_2 fertilization that stems from elevated levels of atmospheric carbon dioxide concentration (Harrison et al., 1993b). A common criticism of the CO2 fertilization hypothesis is that the lack of N will limit growth. The deposition of anthropogenic N counters this argument.

Tans et al. (1990) suggest that temperate forests are a likely location for sequestering carbon. N-deposition, which is most pronounced in the temperate zone, is a likely means to sequester a part of the missing sink because most of the anthropogenic is deposited in the temperate zone.

Table 6.1: Atmospheric ammonia budget.

Sources	"Best" estimate (Tg N/year)	Potential range (TgN/year)
animals[1]	32	24-40
ocean release[1]	13	8-18
native soils[1]	10	6-45
fertilizers[1]	9	5-10
human waste[1]	4	
coal combustion[1]	2	
cars[1]	0.2	
TOTAL SOURCES	**75**	**50-128**
Sinks		
wet deposition, land[2]	30	
dry deposition, land[2]	10	
wet deposition, sea[3]	16	
reaction with OH radical[2]	1	
TOTAL SINKS:	**57**	
Anthropogenic nitrogen		
total deposition[4]	42	34-52
land deposition[5]	30	24-36.5
ocean deposition[5]	12	10-15.5

[1] Schlesinger & Hartley, 1992.

[2] Warneck, 1988.

[3] Duce et al., 1991.

[4] The upper limit for the total anthropogenic deposition is the sum of animal, fertilizer, human waste, coal combustion and cars; the lower limit is the total sinks less the release from oceans and native soils and the best guess is the average of these two values.

[5] The amount of anthropogenic deposition on land and on the ocean assumes the proportions of land and ocean deposition for all the nitrate also applies to the anthropogenic fraction.

Table 6.2: Atmospheric nitrate budget.

Sources	”Best” estimate (Tg N/year)	Potential range (Tg N/year)
fossil fuel burning[1]	19.9	14-28
biomass burning[2]	5	5-7
soil release[1]	8.0	4-16
lightning[1]	8.0	2-20
NH_3 oxidation	1[4]	0-10[1]
ocean release[1]	1	--
high flying planes[3]	0.3	0.2-0.3
Stratosphere[1]	0.5	--
TOTAL SOURCES	**44**	**25-99**
Sinks		
wet deposition, land[1]	19	8-30
dry deposition, land[5]	10	
wet deposition, ocean[1]	8	4-12
dry deposition, ocean[5]	6	
TOTAL SINKS	**43**	**23-64**
Anthropogenic nitrogen[6]		
total deposition	29	
ocean deposition	12	
land deposition	17	

[1] Logan, 1983.
[2] Crutzen, 1990.
[3] Drummond, 1982.
[4] Warneck, 1988.
[5] By difference, total dry deposition is 16 Tg N/year[1] , ocean dry deposition is 6 Tg N/year (Duce, 1991).
[6] The total anthropogenic nitrogen is the sum from animals, high flying planes, NH3 oxidation , and 80% of the biomass burning, and 50% of the soil release. The amount of ammonia deposited to the ocean and land assumes the proportions of the total land and ocean deposition apply to the anthropogenic fraction.

Table 6.3: Anthropogenic nitrogen inputs to land and sea.

Species	Input (Tg N/year)		
	Land	Sea	Total
ammonia	30	12	42
nitrate	17	12	29
total	47	24	71

Table 6.4: Transect of C/N ratios in forest floor litter for varying amounts of nitrogen deposition (McNulty, 1991).

Site	N deposition (kg/ha/yr)	C/N forest litter (by mass)
1	2.9	43.1
2	3.4	35.1
3	3.9	48.7
4	4.0	28.4
5	4.1	27.7
6	4.5	30.2
7	5.1	21.1
8	5.7	22.3
9	5.6	18.9
10	5.2	25.2
11	5.1	24.3

Table 6.5: Kansas grassland native carbon, nitrogen and C/N data.

depth	percent C	percent N	C/N
0-12	5.94	0.454	13
12-33	2.99	0.216	14
33-43	2.00	0.155	13
43-53	1.09	0.098	11
53-68	0.69	0.077	9
68-86	0.63	0.059	11
86-121	0.45	<.010	--
121-140	0.71	<.010	--
140-155	0.63	<.010	--
155-156	0.00	<.010	--

This profile was taken in collaboration with the U. S. Department of Agriculture Soil Conservation Service National Soil Survey (Lincoln, Nebraska 68508-3866). The profile was Pedon 91P1024. The soil was collected on the Konza Prairie, which is a National Science Foundation Long Term Ecological site located in Riley County, Kansas.

The concentrations of carbon and nitrogen diminish in depth in approximately the same proportions until nitrogen can no longer be detected. Below this depth, carbon is still present. The C/N ratio is by mass.

Table 6.6: North Carolina forest native carbon, nitrogen and C/N data.

depth (cm)	Native %C	%N	C/N
0-10	2.664	0.140	19
10-20	0.865	0.042	21
20-30	0.332	0.021	16
30-40	0.474	0.020	14
40-50	0.333	0.024	14
50-60	0.339	0.017	20
60-70	0.173	0.015	12
70-80	0.167	0.010	17
80-90	0.148	0.014	11
90-100	0.189	0.017	11
100-110	0.229	0.020	12
110-120	0.124	0.010	9
120-130	0.080	0.014	6
130-140	0.050	<.010	--
140-150	0.035	0.008	4
150-160	0.043	<.010	--
160-170	0.056	<.010	--
170-180	0.530	<.010	--
180-190	0.053	<.010	--
190-200	0.053	<.010	--

Table 6.7: Ratios of nutrient elements to carbon litter of Scots Pine at sequential stages of decomposition (Schesinger, 1991).

	C/N
initial	134
after incubation of:	
1 year	85
2 years	66
3 years	53
4 years	46
5 years	41

The C/N ratio decreases by a factor of three after 5 years of incubation. One expects soil organic matter to show a similar trend.

Table 6.8: Depth profiles of carbon, nitrogen, C/N and radiocarbon for Wohldorf Forest, Germany.

depth (cm)	carbon%	nitrogen%	C/N	radiocarbon*
0-3	3.46	0.230	15	1.05
3-5	0.72	0.040	18	1.14
5-11	1.36	0.100	14	1.05
11-23	0.74	0.060	12	1.00
23-40	0.54	0.030	18	1.02
40-50	0.15	0.014	11	0.97
50-63	0.12	0.012	10	0.90
63-73	0.17	0.017	10	0.87
73-88	0.09	0.010	9	0.87
88-100	0.05	0.005	10	0.80
100-110	0.03	0.005	8	0.85

(Becker-Heidmann, 1989)

*Radiocarbon units are (C-14/C)sample/(C-14/C)1850 wood.

Table 6.9: Passive carbon, active carbon, nitrogen, bulk organic matter C/N and active soil organic matter C/N.

depth (cm)	passive C (g/cm3)	active C (g/cm3)	N(g/cm3)	$(C/N)_{bulk}$	$(C/N)_{act}$
0-10	0.08	0.18	0.020	13	9
10-20	0.09	0.08	0.012	14	7
20-30	0.09	0.06	0.011	14	5
30-40	0.07	0.04	0.009	12	4
40-50	0.06	0.02	0.007	11	3

The concentrations of passive and active carbon have been calculated using a method described in chapter 2. Hypothetical values for nitrogen are provided to calculate the C/N ratio that would be observed in bulk soil. The ratios of the active soil organic matter are calculated assuming that the majority of the nitrogen forms active soil organic matter. The active ratio decreases by a factor of three resembling the trend observed in litter decomposition (table 6.7).

Table 6.10: Calculating the amount of terrestrial carbon resulting from anthropogenic N-deposition.

Ecosystem	C pool[a]	% total N-deposition[b]	%N-Partitioning[c]	C/N ratio[d]	Carbon sequestered (GtC/yr)[e] [veg]	Carbon sequestered (GtC/yr)[f] [soil]	
						upper	lower
temperate	soil	67%	87%	17		0.35	0.26
	veg		13%	65	0.27		
boreal/peat	soil	17%	92%	29		0.16	0.12
	veg		8%	51	0.03		
tropic	soil	8.3%	85%	15		0.04	0.03
	veg		15%	60	0.03		
scrub/grass	soil	8.3%	92%	12		0.03	0.02
	veg		8%	50	0.01		
total					0.34	0.58	0.43

Table 6.10 illustrates the calculations described in the text for estimating how much carbon is sequestered because of industrial N-deposition. Four ecosystems, temperate, boreal/peat, tropic and scrub/grass, are considered.

[a] The terrestrial biosphere is broken into two pools: soil and short-lived vegetation.

[b] The fraction of total anthropogenic nitrogen deposited on each ecosystem.

[c] How the retained nitrogen is distributed between soil and short-lived vegetation.

[d] The C/N ratio by mass (Schlesinger, 1991; Schindler & Bayley, In Press; Peterson & Melillo, 1985).

[e] The mass of carbon sequestered per year in vegetation.

[f] The mass of carbon sequestered per year using bulk C/N soil organic matter ratios forms the upper limit for the amount of carbon sequestered in soil due to anthropogenic nitrogen deposition if immobilized N sequesters additional carbon. The mass of carbon sequestered per year using corrected C/N soil organic matter ratios represents the lower limit. The correction accounts for passive soil organic matter having very little nitrogen present.

Chapter 7: Conclusion

Summary:

This research advances our understanding of soil's role in the global carbon cycle in several ways: it has determined the inventory (@ 500 GtC), and residence time (@ 25 years) of the active component of soil carbon using radiocarbon measurements, and examined how this carbon pool responds to CO_2 fertilization, changing land use and anthropogenic nitrogen deposition. CO_2 fertilization could have sequestered from 1.1 to 1.5 GtC/year in the terrestrial biosphere, for an average year in the 1980's. Anthropogenic N-deposition could have sequestered from 0.5 to 1.1 GtC/year in the 1980's. Therefore, CO_2 fertilization and anthropogenic nitrogen deposition could potentially balance deforestation, which is releasing carbon from the terrestrial biosphere.

This research also investigated how disturbing native soil released carbon to the atmosphere and identified procedures that could limit the future releases. Radiocarbon measurements of cultivated soil were substantially less than native soil. Oxidation of active carbon and mixing neatly explained this depletion.

Disturbed land that has been abandoned and allowed to recover shows variation in the extent of recovery. The North Carolina site showed how recovering coniferous forest soil carbon inventories could surpass the soil carbon inventory of its native deciduous counterpart. Nitrogen-fixing scrub could play an important role in this enhanced recovery and be potential means of engineering abandoned land to sequester greater amounts of soil carbon. On the other hand, recovery of grassland ecosystems appears slower and less complete than forested ecosystems.

Future Research:

This research suggest myriad new research directions. For example, there is an acute dearth of soil radiocarbon data for the tropics and boreal and sub-boreal climes. More data needs to be gathered and published from these areas, and more depth profiles in general are needed to estimate active soil carbon inventories.

Once the soil carbon inventories for native ecosystems are better understood, research can begin to address how inventories will change in response to elevated CO_2 levels, anthropogenic nitrogen and changing climate. To this end, inventories of active carbon will be assessed at the start of Free Air Carbon Enrichment (FACE) experiments and similar soil warming and soil moisture experiments currently being planned.

REFERENCES

Aber, J. D. "Nitrogen cycling and nitrogen saturation in temperate forest ecosystems." Trends in Ecology and Evolution, 7,7, 220-224, 1992.

Aber, J. D. & J.M. Melillo. "Litter Decomposition: measuring relative contributions of organic matter and nitrogen to forest soils." Canadian Journal of Botany, 58, 416-421, 1980.

Aber, J. D., A. Magill, R. Boone, J. M. Melillo, P. Steudler & R. Bowden. "Plant and soil responses to chronic nitrogen additions at the Harvard Forest, Massachusetts." Ecological Applications, 3,1, 156-166, 1993.

Anderson, D.W. & E.A. Paul. "Organo-mineral complexes and their study by radiocarbon dating." Soil Sci. Soc. Am. J., 48, 298-301, 1984.

Bacastow, R. & C. D. Keeling. "Atmospheric carbon dioxide concentration and the airborne fraction." In Carbon Cycle Modelling, Scope 16, ed. by B. Bolin, pp. 103-112. New York: John Wiley, 1981.

Becker-Heidmann, P. "Die Teifenfunktionen der naturlichen Kohlenstoff-Isotopengehalte von vollstandig dunnschichtweise beprobten Parabraunerde und ihre Relation zur Dynamic der organischen Substanz in diesen Boden." Ph. D. Thesis, Hamburg University, 1989.

Becker-Heidmann, P., Liu Liang-wu, & H.W. Scharpenseel. "Radiocarbon dating of organic matter fractions of a Chinese mollisol." Z. Pflanzenernahr. Bodenk., 151, 37-39, 1988.

Becker-Heidmann, P. & H.W. Scharpenseel. "Carbon isotope dynamics in some tropical soils." Radiocarbon, 31, 3, 672-679, 1989.

Berg, B. "Dynamics of N-15 in decomposing Scots Pine needle litter. Long term decomposition in a Scots Pine Forest VI." Canadian Journal of Botany, 66, 1539-1546, 1988.

Billings, W.D. "The structure and development of old field shortleaf pine stands and certain associated properties of the soil." Ecological Monographs, 8, 437-499, 1938.

Blank, R. R. "Cultivated and adjacent virgin soils in Northcentral South Dakota: I. Chemical and physical comparisons." Soil Sci. Soc. Am. J., 53, 1484-1490, 1989.

Bolin, B. "Changes in land biota and their importance for the carbon cycle." Science, 196, 613-615, 1977.

Bolin, B. "How much CO2 will remain in the atmosphere?" In The Greenhouse Effect, Climate Change, and Ecosystems, Scope 29, ed. by B. Bolin, B.R. Doos & J. Jager, pp. 93-155. New York: John Wiley, 1986.

Bopp, R., M. Gross, H. Tong, H.J. Simpson, S.J. Monson, B.L. Deck, & F. Moser. "A major incident of dioxin contamination: sedimentary New Jersey estuaries." ES &T, 25, 951-956, 1991.

Botkin, D.B., & L.G. Simpson. "Biomass of North American boreal forest." Biogeochemistry, 9, 161-174, 1990.

Bouwman, A.F. (ed.) Soils and the Greenhouse Effect. Proceedings of the International Conference on Soils and the Greenhouse Effect. Wageningen, The Netherlands: Wiley & Chichester, 1990.

Broecker, W.S. & T.H. Peng. Tracers in the Sea. New York: Eldigio Press, 1982.

Broecker, W.S., T. Takahashi, H.J. Simpson, & T.H. Peng. "Fate of fossil fuel carbon dioxide and the global carbon budget." Science, 206, 409-418, 1979.

Buringh, P. "Organic carbon in soils of the world." In The role of the Terrestrial Vegetation in the Global Carbon Cycle, Scope 23, ed. by G.M. Woodell, pp. 91-109. New York: John Wiley, 1984.

Burke, I.C., W.A. Reiners & D.S. Schimel. "Organic matter turnover in a sagebrush landscape." Biogeochemistry, 7:11-31, 1989.

Burke, I.C., D.S. Schimel, C.M. Yonker, W.J. Parton, L.A. Joyce & W.K. Lavenroth. "Regional modeling of grassland biogeochemistry using GIS." Landscape Ecology, 4 ,1, 45-54, 1990.

Burke, I.C., C.M. Yonker, W.J. Parton, C.V. Cole, K. Flach & D.S. Schimel. "Texture, climate and cultivation effects on soil organic matter content in U.S. grassland soils." Soil Science Society of America Journal, 53,3, 800-805, 1989.

Campbell, C.A., E.A. Paul, D.A. Rennie & K.J. McCallum. "Applicability of the carbon-dating method of analysis to soild humus studies." Soil Science, 104, 3, 217-223, 1967.

Chan, Y-H. & J.S. Olson. "Limits on the organic storage of carbon from burning fossil fuels." Journal of Environmental Management, 11, 147-163, 1980.

Dai, A. & I.Y. Fung. "Can climate variability contribute to the 'missing' CO2 sink?" Global Biogeochemical Cycles, 7, 3, 599-609, 1993.

Dörr, H. & K.O. Münnich. "Annual variations of the ^{14}C content of soil CO_2." Radiocarbon, 28, 2A, 338-345, 1986.

Duce, R.A., P.S. Liss, J.T. Merrill, et al. "Atmospheric input of trace species to the world oceans." Global Biogeochemical Cycles, 5, 3, 193-259, 1991.

Emanuel, W.R., G.G. Killough, W.M. Post & H.H. Shugart. "Modeling terrestrial ecosystems in the global carbon cycle with shifts in carbon storage capacity by land use change." Ecology, 65, 3, 970-983, 1984.

Esser, G. "Sensitivity of global carbon pools and fluxes to human and potential climate impacts." Tellus, 39B, 245-260, 1987.

Gilbert-Blein, N., G. Marien & J. Evin. "Unreliability of C-14 dates from organic matter of soils." Radiocarbon, 22, 3, 919-929, 1980.

Goh, K.M, T.A. Rafter, J.D. Stout & T.W. Walker. "Accumulation of soil organic matter and its carbon isotope content in a chronosequence of soils developed on aeolian sand in New Zealand." J. Soil Science, 27, 89-100, 1976.

Goh, K.M., J.D. Stout & T.A. Rafter. "Radiocarbon enrichment of soil organic fractions in New Zealand soils." Soil Science, 123, 6, 385-390, 1977.

Harkness, D.D., A.F. Harrison, & P.J. Bacon. "Temporal distribution of bomb C-14 in a forest soil." Radiocarbon, 28, 2A, 328-337, 1986.

Harrison, K. G., W. S. Broecker & G. Bonani. "A strategy for estimating the impact of CO2 fertilization on soil carbon storage." Global Biogeochem. Cycles, 7, 1, 69-80, 1993a.

Harrison, K. G., W. S. Broecker & G. Bonani. "The effect of changing land use on soil radiocarbon." Science, 262, 725-726, 1993b.

Hart, J.F. "Loss and abandonment of cleared farmland in the eastern United States." Annals, Association of American Geog., 58, 417-440, 1968.

Henderson, S. & R.K. Dixon (Eds.). Management of the terrestrial biosphere to sequester atmospheric CO2. Ohldendorf, Germany: InterResearch, 1993.

Hendrey, G. R. (ed.). "FACE: Free-air CO2 enrichment for plant research in the field." Critical Reviews in Plant Sciences, 11, 2/3, 1992.

Houghton, J.T., B.A. Callander & S.K. Varney (eds.). Climate Change 1992. The Supplementary Report to the IPCC Scientific Assessment. Cambridge: Cambridge University Press, 1992.

Houghton, J.T., B.A. Callander & S.K. Varney (eds.). Climate Change. The IPCC Scientific Assessment. Cambridge: Cambridge University Press, 1990.

Houghton, R.A. & D.L. Skole. "The long-term flux of carbon between terrestrial ecosystems and the atmosphere as a result of changes in land use." Oak Ridge, TN: Carbon Dioxide Information Analysis Center, July, 1990.

Houghton, R.A., J.E. Hobbie, J.M. Melillo, B. Moore, B.J. Peterson, G.R. Shaver & G.M. Woodwell. "Changes in carbon content of terrestrial biota and soils between 1860 and 1980: a net release of CO2 to the atmosphere." Ecological Monographs, 53,3, 235-262, 1983.

Hsieh, Y-P. "Pool size and mean age of stable soil organic carbon in cropland." Soil Sci. Soc. Am. J., 56, 460-464, 1992.

Jenkinson, D.S. "The turnover of organic carbon and nitrogen in soil." Phil. Trans. R. Soc. Lon., B, 329, 361-368, 1990.

Johnson, D.W. "Nitrogen retention in forest soils." J. of Environ. Quality, 21, 1, 1-12, 1992.

Kauppi, P.E., K. Mielikainen & K. Kuusela. "Biomass and carbon budget of European forests, 1971-1990." Science, 256, 70-74, 1992.

Keeling, C.D. "The carbon dioxide cycle: reservoir models to depict the exchange of atmospheric carbon dioxide with the oceans and land plants." In Chemistry of the Lower Atmosphere, ed. by S. Rasool, pp. 251-329. New York: Plenum, 1973.

Keeling, C.D., R.B. Bacastow, A.F. Carter, S.C. Piper, T.P. Whorf, M. Heimann, W.G. Mook & H. Roeloffzen. "A three-dimensional model of atmospheric CO_2 transport, 1. Analysis of observational data." In Aspects of Climate Variability in the Pacific and Western Americas (Geophysical Monograph 55), ed.by David H. Peterson, pp. 165-236. Washington, DC: American Geophysical Union, 1989.

Keeling, C.D., S.C. Piper & M. Heimann. "A three-dimensional model of atmospheric CO_2 transport based on observed winds: 4. Mean annual gradients and interannual variations. In Aspects of Climate Variability in the Pacific and Western Americas (Geophysical Monograph 55), ed.by David H. Peterson, pp.305-363. Washington, DC: American Geophysical Union, 1989.

Keeling, R. F. & S. R. Shertz. "Seasonal and interannual variations in atmospheric oxygen and implications for the global carbon cycle." Nature, 338, 723-727, 1992.

Kohlmaier, G.H., E.O. Sire, A. Janecek, C.D. Keeling, S.C. Piper & R. Revelle. "Modelling the seasonal contribution of a CO2 fertilization effect on the terresttrial vegetation to the amplitude increase in atmospheric CO2 at Mauna Loa Observatory." Tellus, 41B, 487-510, 1989.

Korner, C. & J.A. Arnone. "Responses to elevated carbon dioxide in artificial ecosystems." Science, 257, 1672-1675, 1992.

Kulp, J.L. The Photosystem as a Sink for Carbon Dioxide. EN-6786, Special Report. Palo Alto, CA: Electric Power Research Institute, 1990.

Ladyman, S.J. & D.D. Harkness. "Carbon isotope measurement as an index of soil development." Radiocarbon, 22,3, 885-891, 1980.

Maier-Reimer, E. & K. Hasselmann. "Transport and storage of CO2 in the ocean -- an inorganic ocean-circulation carbon cycle model." Climate Dyn., 2, 63-69, 1987.

Mann, L.K. "Changes in soil carbon storage after cultivation." Soil Science, 142, 5, 279-288, 1986.

Marland, G.R. & R.M. Rotty. "Carbon dioxide emissions from fossil fuels: a procedure for estimation and results for 1950-1982. Tellus, 36B, 232-262, 1984.

Martel, Y.A. & A.F. MacKenzie. "Longer-term effects of cultivation and land use on soil quality in Quebec." Can. J. Soil Sci., 60, 411-420, 1980.

Martel, Y. A. & E.A. Paul. "Effects of cultivation on the organic matter of grassland soils as determined by fractionation and radiocarbon dating." Can. J. Soil Sci., 54, 419-426, 1974.

Martel, Y.A. & E.A. Paul. "Use of radiocarbon dating of organic matter in the study of soil genesis." Soil Sci. Soc. Amer. Proc., 38, 501-506, 1974.

Matthews, E. "Global inventory of pre-agricultural and present biomass." Progress in Biometerology, 3, 237-246, 1984.

McGuire, A.D., J.M. Melillo, L.A. Joyce, D.W. Kicklighter, A.L. Grace, B. Moore, & C.J. Vorsmarty. "Interactions between carbon and nitrogen dynamics in estimating net primary productivity for potential vegetation in North America." Global Biogeochemical Cycles, 6, 101-124, 1992.

McNulty, S.G., J.D. Aver & R.D. Boone. "Spatial changes in forest floor and foliar chemistry of spruce-fir forests across New England." Biogeochemistry, 14: 13-29, 1991.

Meints, V.W. & G.A. Peterson. "The influence of cultivation on the distribution of nitrogen in soils of the ustoll suborder." Soil Science, 124, 6, 334-342, 1977.

Melillo, J. M. & J.R. Gosz. "Interaction of biogeochemical cycles in forest ecosystems." In The major biogeochemical cycles and their interactions, Scope 21, ed. by B. Bolin & R.B. Cook, pp. 177-222. New York: John Wiley & Sons, 1983.

Mooney, H.A., B.G. Drake, R.J. Luxmoore, W.C. Oeachel & L.F. Pitelka. "Predicting ecosystem responses to elevated CO2 concentrations." Bioscience, 41, 2, 96-104, 1991.

Neftal, A. et al. "Ice core sample measurements give atmospheric CO2 content during the past 40,000 years." Nature, 295, 220-223, 1985.

Norby, R.J., C.A. Gunderson, S.D. Wullschleger, E.G. O'Neill & M.K. McCracken. "Productivity and compensatory responses of yellow-poplar trees in elevated CO2." Nature, 357, 322-324, 1992.

Oades, J.M. "The retention of organic matter in soils." Biogeochemistry, 5, 35-70, 1988.

O'Brien, B.J. "Soil organic carbon fluxes and turnover rates estimated from radiocarbon enrichments." Soil Biol. Biochem., 16, 2, 115-120, 1984.

O'Brien, B.J. "The use of natural and anthropogenic C-14 to investigate the dynamics of soil organic carbon." Radiocarbon, 28, 2A, 358-362, 1986.

O'Brien, B.J. & J.D. Stout. "Movement and turnover of soil organic matter as indicated by carbon isotope measurements." Soil Biol. Biochem., 10, 309-317, 1978.

Oeschger, H., U. Siegenthaler, U. Schotterer & A. Gugelmann. "A box diffusion model to study the carbon dioxide change in nature." Tellus, 27,168-192, 1975.

Parton, W.J., C.V. Cole, J.W.B. Stewart, D.S. Ojima & D.S. Schimel. "Stimulating regional patterns of soil, C,N and P dynamics in the U.S. central grasslands region." In Ecology of Arable Land, ed. by M. Clarholm and L. Bergström, pp. 99-108. Norwell, MA: Kluwer Academic Publishers, 1989.

Parton, W.J., D.S. Schimel, C.V. Cole, & D.S. Ojima. "Analysis of factors controlling soil organic matter levels in Great Plains Grasslands." Soil Science America Journal, 51, 1173-1179, 1987.

Pastor, J. & W.M. Post. "Influence of climate, soil moisture and succession on forest carbon and nitrogen cycles." Biogeochemistry, 2, 3-27, 1986.

Peng, T.H. "Uptake of anthropogenic CO2 by lateral transport models of the ocean based on the distribution of bomb produced C-14." Radiocarbon, 28, 2A, 363-375, 1986.

Peterson, B.J. & J.M. Melillo. "The potential storage of carbon caused by eutrophication of the biosphere." Tellus, 37B, 117-127, 1985.

Post, W.M. & L.K. Mann. "Changes in soil organic carbon and nitrogen as a result of cultivation." In Soils and the Greenhouse Effect, ed. by A.F. Bouwman, pp. 401-407. New York: John Wiley and Sons, 1990.

Post, W.M., P.J. Zinke, A.G. Strangenberger, W.R. Emanuel, H. Jenny, & J.S. Olson. "Summaries of soil carbon storage in world life zones." In Global Dynamics of Biospheric Carbon, ed. by S. Brown, pp. 131-139. 1982.

Prentice, K.C. & I. Y. Fung. "The sensitivity of terrestrial carbon storage to climate change." Nature, 346, 48-51, 1990.

Quay, P. D., B. Tilbrook & C. S. Wong. "Oceanic uptake of fossil fuel CO2: C-13 evidence." Science, 256, 74-79, 1992.

Reganold, J.P, A.S. Palmer, J.C. Lockhart & A.N. Macgregor. "Soil quality and financial performance of biodynamic and conventional farms in New Zealand." Science, 260, 344-349, 1993.

Revelle, R. & W. Munk. "The carbon dioxide cycle and the biosphere." In Energy and Climate, Studies in Geophysics, pp. 140-158. Washington, DC: National Research Council, National Academy of Sciences, 1977.

Rice, C.W. & K.L. Rogers. "Denitrification in the vadose zone: The microbial factor in nitrate persistance." Report #G1563, Kansas Water Resources Research Institute, 1991.

Ritchey, J.C. & J.R. McHenry. "Application of radioactive fallout Cs-137 for measuring soil erosion and sediment accumulation rates and patterns: a review." J. Environ. Qual., 19, 215-233, 1990.

Sarmiento, J.L. & E.T. Sundquist. "Revised budget for the oceanic uptake of anthropogenic carbon dioxide." Nature, 356, 589-593, 1992.

Scharpenseel, H.W. & P. Becker-Heidmann. "Shifts in C-14 patterns of soil profiles due to bomb carbon." Radiocarbon, 31, 3, 627-636, 1989.

Scharpenseel, H.W., P. Becker-Heidmann, H.U. Neue, & K. Tsutsuke. "Bomb-carbon, C-14 dating and C-13 measurements as tracers of organic matter dynamics." The Science of the total environment, 81, 81, 99-110, 1989.

Schiff, S. L., R. Aravena, S. E. Trumbore, & P. J. Dillon. "Dissolved organic carbon cycling in forested water sheds: A carbon isotope approach." Water Resources Research, 26, 2949-2957, 1990.

Schiffman, P.M. & W.C. Johnson. "Phytomass and detrital carbon storage during forest regrowth in the southeastern US Piedmont." Canadian Journal of Forestry Research, 19, 69-78, 1989.

Schimel, D.S. "Carbon and nitrogen turnover in adjacent grassland and cropland ecoystems." Biogeochemistry, 2, 345-357, 1986.

Schimel, D.S., D.C. Coleman, & K.A. Horton. "Soil organic matter dynamics in paired rangeland and cropland toposequences in North Dakota." Geoderma, 36, 201-214, 1985.

Schimel, D.S., M.A. Stillwell, & R.G. Woodmansee. "Biogeochemistry of C, N and P in a soil catena of the shortgrass steppe." Ecology, 66, 1, 276-282, 1985.

Schindler, D.W. & S.E. Bayley. "The biosphere as an increasing sink for atmospheric carbon: estimates from increased nitrogen deposition." In press.

Schlesinger, W. H. Biogeochemistry: An Analysis of Global Change. New York: Academic Press, 1991.

Schlesinger, W.H. "Changes in soil carbon storage and associated properties with disturbance and recovery." In The Changing Carbon Cycle - A global Analysis, ed. by J.R. Trabalka and D.E. Reichle, pp. 194-220. New York: Springer-Verlag, 1986.

Schlesinger, W. H. "Evidence from chronosequence studies for a low carbon storage potential of soils." Nature, 348, 232-234, 1990.

Schlesinger, W.H. "Soil organic matter: a source for atmospheric CO_2." In The Role of Terrestrial Vegetation in the Global Carbon Cycle, Scope 23, ed. by G.W. Woodell, pp. 111-127. New York: John Wiley and Sons, 1984.

Schoenau, J. J. "Nutrient cycling processes in prairie and boreal forest soils." Ph.D. Thesis, University of Saskatchewan, 1988.

Sedjo, R. A. "Temperate forest ecosystems in the global carbon cycle." Ambio, 21, 274-277, 1992.

Shearer, G. & D.H. Kohl. "Estimates of N2 fixation in ecosystems: the need for and basis of the N-15 natural abundance method." In Stable Isotopes in Ecological Research, ed. by P.W. Rundel, J.R. Ehleringer & K.A. Nagy, pp. 342-374. New York: Springer-Verlag, 1989.

Shearer, G. & D. H. Kohl. "Natural N-15 abundance as a method of estimating the contribution of biologically fixed N to N2 fixing systems." Plant & Soil, 110, 317-327, 1988.

Siegenthaler, U. & H. Oeschger. "Biospheric CO2 emissions during the past 200 years reconstructed by deconvolution of ice core data." Tellus, 39B, 140-154, 1987.

Singh, J.S. & S.R. Gupta. "Plant decomposition and soil respiration in terrestrial ecosystems." The Botanical Review, 43, 449-528, 1977.

Sollins, P., G. Spycher, & G.A. Glassman. "Net nitrogen mineralization from light and heavy fraction forest soil organic matter." Soil Biology & Biochemistry, 16, 31-77, 1984.

Stewart, J.W.B. & C.V. Cole. "Influence of elemental interactions and pedogenic processes in organic matter dynamics." In Ecology of arable land -- Perspectives and Challenges, ed. by L. Clarholm and L. Bergstrim. *Development in Plant and Soil Sciences*, vol. 39. Norwell, MA: Kluwer Academic Publishers, 1989.

Strain, B.R. & J.D. Cure. Direct Effects of Increasing Carbon Dioxide on Vegetation. DOE/ER-0238, 1985.

Stryer, L. Biochemistry. New York: W. H. Freeman & Company, 1981.

Sundquist, E. T. "Geological perspectives on carbon dioxide and the carbon cycle." In The Carbon Cycle and Atmospheric CO_2: Natural Variations Archean to Present. *Geophysical Monograph* 32, 1985.

Sundquist, E. T. "The global carbon dioxide budget." Science, 259, 934-941, 1993.

Tans, P. P., J. A. Berry, & R.F. Keeling. "Oceanic C-13/C observations: a new window on ocean CO2 uptake." Global Biogeochem. Cycles, 7, 2, 353-368, 1993.

Tans, P.P., I.Y. Fung, & T. Takahashi. "Observational constraints on the global atmospheric CO_2 budget." Science, 247, 1431-1438, 1990.

Tegen, I., H. Dorr, & K.O. Munnich. "Laboratory experiments to investigate the influence of microbial activity on the migration of cesium in a forest soil." Water, Air and Soil Pollution, 57-58, 441-447, 1991.

Tiessen, H., J.W.B. Stewart, & J.R. Bettany. "Cultivation effects on the amounts and concentration of carbon, nitrogen, and phosphorus in grassland soils." Agronomy Journal, 74, 831-835, 1982.

Toggweiler, J.R., K. Dixon, & K. Bryan. "Simulations of radiocarbon in a coarse resolution world ocean model 1. Steady state pre-bomb distributions." J. Geophys. Res, 94, 8217-8242, 1989.

Trumbore, S. E. "Carbon cycling and gas exchange in soils." Ph.D. Thesis, Columbia University, 1988.

Trumbore, S.E., G. Bonani, & W. Wolfi. "The rates of carbon cycling in several soils from AMS C-14 measurements of fractionated soil organic matter." In Soils and the Greenhouse Effect., ed. by A.F. Bouwman, pp. 407-414. New York: John Wiley and Sons, 1990.

Trumbore, S.E., J.S. Vogel, & J.R. Southon. "AMS C-14 measurments of fractionated soil organic mater." Radiocarbon, 31, 3, 644-654, 1989.

Tsutsuki, K., C. Suzuki, S. Kuwatsuka, P. Becker-Heidmann, & H.W. Scharpenseel. "Investigation of the stabilization of the humus in mollisols." S. Pflanzenernahr. Bodenk., 151, 87-90, 1988.

Virginia, R.A. & C.C. Delwiche. "Natural N-15 abundance of presumed N2 fixing plants from selected ecosystems." Oecologia., 54, 317-325, 1982.

Virginia, R.A., W.M. Jarrell, P.W. Rundel, G. Shearer, & D.H. Kohl. "The use of variation in the natural abundance of N-15 to assess symbiotic nitrogen fixation by woody plants." In Stable Isotopes in Ecological Research, ed. by P.W. Rundel, J.R. Ehleringer & K.A. Nagy, pp. 375-394. New York: Springer-Verlag, 1989.

Warneck, P. Chemistry of the Natural Atmosphere. New York: Academic Press, 1988.

Woodwell, G.M., R.H. Whittaker, W.A. Reiners, G.E. Likens, C.C. Delwiche, &D.B. Botkin. "The biota and the world carbon budget." Science, 199, 141-146, 1978.

Yonker, C.M., D.S. Schimel, E. Paroussis, & R.D. Hiel. "Patterns of organic carbon accumulation in a semiarid shortgrass steppe, Colorado." Soil Science Society of America Journal, 52, 2, 478-483, 1988.

Zak, D.R., K.S. Pregitzer, P.S. Curtis, J.A. Teeri, R. Fogel, & D.L. Randlett. "Elevated atmospheric CO2 feedback between carbon and nitrogen cycles." Plant & Soil, 151, 105-117, 1993.

Zielke, R.C. & D.R. Christenson. "Organic carbon and nitrogen changes in soil under selected cropping systems." Soil Sci. Soc. Am. J., 50, 363-367, 1986.

Zinke, P.J., A.G. Strangenburger, W.M. Post, W.R. Emanuel, & J.S. Olson, "Worldwide Organic Soil Carbon and Nitrogen Data." Report ORNL/TM-8857, Oak Ridge National Laboratory, Oak Ridge, TN, 1984.

Appendix A. Estimates of CO_2 fertilization for various carbon pools for an average year in the 1980's.

Active soil carbon(ASC)	τ	β	**Inventory(GtC)**		
			350	**500**	**650**
			annual carbon storage (GtC/year)		
(Harrison et al.,1993)	15	60	0.7	1.0	1.4
		35	0.4	0.6	0.8
		15	0.2	0.3	0.3
	25	60	0.7	0.9	1.2
		35	0.4	0.5	0.7
		15	0.2	0.2	0.3
	40	60	0.5	0.7	0.9
		35	0.3	0.4	0.5
		15	0.3	0.2	0.2

			Inventory(GtC)		
			450	**500**	**550**
			annual carbon storage (GtC/year)		
Long-lived vegetation[1] (LLV)	25	60	0.9	0.9	1.0
		35	0.5	0.5	0.6
		15	0.2	0.2	0.3
	63	60	0.5	0.5	0.7
		35	0.3	0.3	0.4
		15	0.1	0.1	0.2

			Inventory(GtC)		
			60	**90**	**120**
			annual carbon storage (GtC/year)		
Short-lived vegetation[2] (SLV)	1.0	60	0.2	0.3	0.3
		35	0.1	0.2	0.2
		15	<0.05	0.1	0.1
	1.5	60	0.2	0.3	0.3
		35	0.1	0.2	0.2
		15	<0.05	0.1	0.1
	2.0	60	0.2	0.3	0.3
		35	0.1	0.2	0.2
		15	<0.05	0.1	0.1

			Inventory(GtC)	
			60	**100**
			annual carbon storage (GtC/year)	
Litter[3] (L)	0.5	60	0.2	0.7
		35	0.1	0.4
		15	<.0.05	0.2
	1.2	60	0.2	0.3
		35	0.1	0.2
		15	<0.05	0.1
	2.2	60	0.2	0.3
		35	0.1	0.2
		15	<0.05	0.1

			Inventory(GtC)
			132
			annual carbon storage (GtC/year)
Woody litter[4] (WL)	25	60	0.2
		35	0.1
		15	0.1

	ASOC	**LLV**	**SLV**	**L**	**WL**	**SUM**
Low best guess (Gt C/yr)	0.5	0.3	0.2	0.1	0	= 1.1
High best guess (Gt C/yr)	0.5	0.5	0.2	0.2	0.1	= 1.5

The terrestrial biosphere can be broken into four components: active soil carbon, long-lived vegetation, short-lived vegetation and litter. Each of these pools has uncertainties associated with its turnover time, carbon dioxide fertilization factor, and inventory. For active soil carbon the turnover times (τ) ranged from 15 to 40 years with 25 years being the most likely value (Harrison et al., 1993). The carbon dioxide fertilization factor (β) ranged from 60% to 15% with 35% being the most likely value for all pools. The soil carbon inventories ranged from 350 to 650 GtC, with 500 GtC being the most likely value. Long-lived vegetation had turnover time estimated from 25 years (Emanuel et al., 1984) to 63 years (Warneck, 1988). The low best guess explains 60% of the "missing sink", while the high best guess can explain 80 of the "missing sink."

[1] Emanuel et al., 1984 estimate the long-lived vegetation has a turnover time of 25 years. Warneck, 1988 think its 63 years. The estimates differ because they assume different NPP for this component.

[2] Warneck(1988) estimates short lived vegetation to have a 1.5 year residence time and a 90 GtC inventory.

[3]Warneck (1988) estimates litter turnover to be every 1.2 years and have a inventory of 60 GtC. Potter (In press) estimates the inventory to be 100 GtC.

[4]Potter (In press) estimates that there are 132 Gt C in woody litter.

Appendix B: Radiocarbon values.

Native

location	vegetation	sampling date	depth (cm)	C-14(%mod)
North Carolina	hardwood	1991	0-10	112
North Carolina	hardwood	1991	10-20	(In Zurich)
North Carolina	hardwood	1991	20-30	98
North Carolina	hardwood	1991	30-40	(In Zurich)
North Carolina	hardwood	1991	40-50	(In Zurich)
North Carolina	hardwood	1991	70-80	(In Zurich)
Saskatchewan	boreal forest	1985	0-5	123
Saskatchewan	boreal forest	1985	0-7	110
Saskatchewan	grass	1985	0-5	109
Kansas	grass	1991	0-2	115
Lombardy	grass	1984	0-23	109

Recovering radiocarbon values

location	vegetation	sampling date	depth (cm)	C-14(%mod)
North Carolina	pine	1991	0-10	115
North Carolina	pine	1991	20-30	98
Kansas	grass	1991	0-2	113
South Carolina	pine	1962	0-7.5	99
South Carolina	pine	1968	0-7.5	123
South Carolina	pine	1977	0-7.5	128
South Carolina	pine	1988	0-7.5	121
South Carolina	pine	1990	165	77

Cultivated radiocarbon values

location	vegetation	sampling date	depth (cm)	C-14(%mod)
Saskatchewan	cereal/fallow	1985	0-7	104
Saskatchewan	cereal/fallow	1985	0-16	104
Saskatchewan	cereal/fallow	1985	0-17	102
Lombardy	grass	1984	0-10	103
Kansas	soybeans	1991	0-2	103
Saskatchewan	cereal/fallow	1985	0-15	104

Surface radiocarbon values for native soil.

Sampling date	%Mod	Location	vegetation/ soil type	Reference
1982	113	Ohlendorf, Ger.	hapludalf	(Becker-Heidman, 1989)
1982	107	Ohlendorf, Ger	hapludalf	(Becker-Heidman, 1989)
1983	113	Wohldor, Ger.	hapludalf	(Becker-Heidman, 1989)
1983	120	Timmendorf, Ger.	hepludalf	(Becker-Heidman, 1989)
1976	109	Scotland	birch	(Harkness, 1992)
1976	102	Scotland	birch	(Harkness, 1992)
1976	106	Scotland	birch	(Harkness, 1992)
1976	109	Scotland	birch	(Harkness, 1992)
1977	116	Scotland	birch	(Harkness, 1992)
1959	96	CA	temp. forest	(Trumbore, 1993)
1990	111	CA	temp. forest	(Trumbore, 1993)
1959	90	Amazon, Braz	trop. forest	(Trumbore, 1993)
1986	120	Amazon, Braz.	trop. forest	(Trumbore, 1993)
1985	123	Sask., Can.	boreal forest	This Work
1985	110	Sask., Can	boreal forest	This Work
1985	109	Sask., Can	grass	This Work

Surface soil radiocarbon values for cultivated soil.

Sampling date	%Mod	Location	Reference
1983	88	Kleinaltendorf, Ger.	(Becker-Heidmann, 1989)
1985	104	Saskatchewan, Can.	This Study
1985	104	Saskatchewan, Can.	This Study
1985	102	Sask. Can.	This Study
1985	104	Sask., Can.	This Study
1984	103	Lodi, Italy	This Study
1991	103	Manhatten Kansas	This Study.

Appendix C: Carbon, Nitrogen and C/N data for tundra (Kayak Island, Canada).

depth (cm)	% C	%N	C/N
0-10	4.72	0.42	11
10-20	21.72	1.59	14
20-30	32.77	2.08	16
30-40	30.42	1.86	16
40-50	40.53	2.26	18
50-60	39.27	2.40	16
60-70	41.43	2.50	17
340-342	21.55	1.01	21

Table 1: Wetland C-14 and C data vs. depth .

Site	depth (cm)	C-14 (PMC)	% C
1	2-10	108	40
	10-16	100	42
	16-27	96	30
2	2-8	112	28
	8-16	98	42
	16-22	94	43
	22-29	90	40
	29-33	69	9
3	2-8	108	39
	8-14	96	31
	14-18	89	17
	18-27	80	10
	27-35	82	9
4	3-14	96	39
	14-28	64	6
	28-44	68	6
	45-58	70	10
	58-87	69	15
5	0-15	99	7
	6-7	112	5
	10-13	69	3
	27-30	57	
	37-41	35	
	42-45	37	
6	2-10	81	12
	10-20	72	9
	20-31	60	6
7	2-11	73	10
	11-20	74	13
	20-32	89	13
	32-42	83	11
8	2-10	77	22
	19-31	35	9
	31-46	30	16
	47-61	33	20

9	2-10	102	35
	10-20	78	33
	20-35	75	23
	35-45	77	28
	45-55	70	26
10	2-10	97	39
	10-23	70	10
	23-33	86	16
	33-43	78	12
	43-70	35	25
	70-79	39	19
11	2-10	90	39
	10-20	88	35
	20-31	83	28
	31-45	80	32
	45-72	58	15
12	2-10	68	22
	10-21	62	24
	21-32	53	23
	32-48	53	15
	48-64	51	9
13	0-12	92	22
	12-24	57	9
	24-34	38	16
	35-45	35	21
14	1-6	92	
	6-18	66	
	18-38	51	
	40-60	40	
	50-60	38	
15	0-15	91	
	15-30	80	
	30-40	72	

Data from Donald M. Schell and Bruce Barnett, "Peat Carbon Accumulation Rates in Artic Alaska," Draft for Final Report DOE #19X-SE394V, 1991.

Appendix D: Wet and dry weights of collected soil.

Native Duke 1992.

depth (cm)	Wet weight (g)	Dry weight (g)
0-2.5	172.0	154.8
2.5-5	210.8	188.7
5-10	182.2	162.8
10-15	190.1	168.8
15-20	210.4	183.8
20-30	252.0	219.0
30-40	189.4	162.5
40-50	159.2	136.1
0-2.5	197.6	175.9
2.5-5	170.5	153.4
5-10	139.3	123.5
10-15	190.5	168.6
15-20	180.6	159.7
20-30	162.3	142.4
30-40	202.7	171.4
40-50	209.5	173.3
0-2.5	253.8	221.6
2.5-5	179.6	160.1
5-10	177.1	157.0
10-15	181.5	160.5
15-20	138.6	122.4
20-30	175.4	153.8
30-40	161.0	137.7
40-50	163.3	137.3
0-2.5	129.5	107.9
2.5-5	161.6	137.8
5-10	218.8	182.6
10-15	129.7	
15-20	153.6	123.3
20-30	233.8	180.9
30-40	193.1	146.8
40-50	117.9	90.9
0-2.5	187.8	156.0
2.5-5	110.3	92.9
5-10	143.4	124.1
10-15	147.4	124.5
15-20	168.7	136.0
20-30	162.0	125.7
30-40	147.8	114.2
40-50	100.2	79.0

Disturbed Duke 1992.

depth (cm)	Wet weight (g)	Dry weight (g)
0-2.5	357.6	351.7
2.5-5	239.4	230.9
5-10	268.5	256.7
10-15	343.9	325.0
15-20	383.3	357.7
20-30	361.3	336.8
30-40	285.3	255.2
40-50	193.1	179.4

Recovering Duke 1992.

depth (cm)	Wet weight (g)	Dry weight (g)
0-2.5	164.2	125.9
2.5-5	167.8	145.5
5-10	209.8	180.9
10-15	190.2	164.2
15-20	253.5	210.1
20-30	179.5	142.5
30-40	189.5	146.9
40-50	127.8	98.5
0-2.5	127.0	109.9
2.5-5	129.0	114.0
5-10	130.8	113.4
10-15	140.1	121.7
15-20	135.8	116.6
20-30	161.9	133.2
30-40	134.9	105.5
40-50	109.9	84.4
0-2.5	176.6	157.0
2.5-5	143.0	125.0
5-10	134.9	119.0
10-15	187.1	165.9
15-20	114.5	99.9
20-30	142.8	118.7
30-40	113.4	90.5
40-50	138.4	108.4
0-2.5	135.7	115.5
2.5-5	124.8	110.8
5-10	146.6	129.2
10-15	102.1	87.7
15-20	97.2	81.9
20-30	113.3	91.5
30-40	147.2	116.0
40-50	136.3	106.0
0-2.5	137.0	124.5
2.5-5	176.6	159.6
5-10	126.3	112.6
10-15	103.7	89.6
15-20	106.5	88.8
20-30	143.6	115.4
30-40	163.4	129.2
40-50	110.3	87.1

Recovering Duke 1991.

depth (cm)	Wet weight (g)	Dry weight (g)
1-10	156.6	126.0
10-20	358.6	297.2
20-30	379.7	315.2
30-40	293.7	
40-50	399.3	319.7
50-60	333.0	264.9
60-70		
70-80	277.1	222.5
80-90	354.1	233.7
90-100	238.2	190.3
100-110	386.6	282.7
110-120	374.7	
120-130	367.5	263.8
130-140	398.1	286.1
140-150	253.3	178.4
150-160	269.2	188.6
160-170	265.0	189.3
170-180	188.2	132.9
180-190	272.1	
190-200	240.4	
200-202.5	389.8	276.8
202.5-205	349.7	252.0
205-207.5	407.6	292.7
207.5-210	275.4	
210-212.5	262.6	
212.5-215	263.9	191.8
215-217.5	327.4	233.5
217.5-220	342.2	249.1
220-222.5	322.8	235.6
225.5-225	310.6	226.7
225-227.5	364.6	270.0
227.65-230.3	301.5	220.6
230.3-233	314.5	242.7
233-235.6	291.3	212.4
238.25-240.9	293.3	215.7
240.9-246.2	420.1	303.3
246.2-248.9	280.9	
248.9-251.5	412.7	297.9
251.5-254.2	320.6	233.5
254.2-256.8	321.4	233.4
256.8-259.5	318.8	231.7
259.5-262.1	275.0	
262.1-264.75	374.1	269.9
264.75-267.4	356.6	256.5
267.4-270.05	293.1	213.8

Native Kansas 1991.

depth (cm)	Wet weight (g)	Dry weight (g)
0-2	27.9	26.4
2-4	35.8	33.0
4-6	38.4	35.5
6-8	40.3	36.8
8-10	46.7	43.1
10-15	58.9	54.0
15-20	84.2	77.1
20-30	127.1	115.0
30-35	72.3	66.1
35-50	109.9	98.2
50-60	135.4	123.4
60-70	149.6	133.5
70-80	120.7	108.9
80-90	94.5	85.7
90-100	47.8	44.6
100-120	87.8	80.6
120-135	57.0	52.9
135-170	50.4	47.3
170-200	40.7	38.6
200-342	76.0	66.0

Disturbed Kansas 1991.

depth (cm)	Wet weight (g)	Dry weight (g)
0-2	67.7	45.5
2-4	99.3	72.0
4-6	77.8	55.0
6-8	73.7	51.5
8-10	107.8	80.8
10-15	187.9	147.8
15-20	211.1	164.2
20-30	353.1	282.4
30-40	354.8	283.6
40-50	415.0	345.6
50-60	408.4	342.6
60-70	404.3	335.9
70-80	448.9	382.4
80-90	431.9	375.1
90-100	431.6	375.4
100-120	788.1	688.2
120-140	845.1	736.7
140-160	719.7	626.0
160-180	867.7	724.1
180-200	799.0	681.5
200-240	1199.2	1009.6
240-300	188.0	163.3
300-360	107.2	91.3

Recovering Kansas 1991.

depth (cm)	Wet weight (g)	Dry weight (g)
0-2	75.7	74.2
2-4	60.0	57.6
4-6	68.6	66.9
6-8	53.9	50.3
8-10	62.0	60.5
10-15	97.3	91.1
15-20	110.6	104.9
20-30	169.9	161.4
30-40	252.5	229.6
40-50	346.0	314.0
50-60	385.1	349.5
60-70	294.4	268.4
70-80	148.7	140.5
80-90	280.1	258.7
90-100	312.2	281.7
100-120	413.4	370.9
120-145	469.6	419.5

Appendix E: Cs-137 values.

location	vegetation	sampling date	depth (cm)	Cs-137(dpm/g)
Italy	native grass	1984	0-23	31
Italy	crops	1984	0-10	11.5
Kansas	grass	1991	0-2	10.73
Kansas	rec. grass	1991	0-2	11.9
Kansas	soybeans	1991	0-2	5.46
Duke	hardwood	1991	0-10	22.32
Duke	rec. pine	1991	0-10	20.16
Canada	grass	1985	0-15	5.8
Canada	grass	1985	0-14	4.83
Canada	grass	1985	0-15	3.16
Canada	crop	1985	0-15	4.83
Canada	crop	1985	0-15	5.66
Canada	crop	1985	0-15	13.50
Canada	forest	1985	0-5	5.16
Canada	forest	1985	0-5	5.33
Canada	forest	1985	0-7	8.66
Canada	cereal	1985	0-7	2.5
Canada	cereal	1985	0-16	4.33
Canada	cereal	1985	0-17	6.00