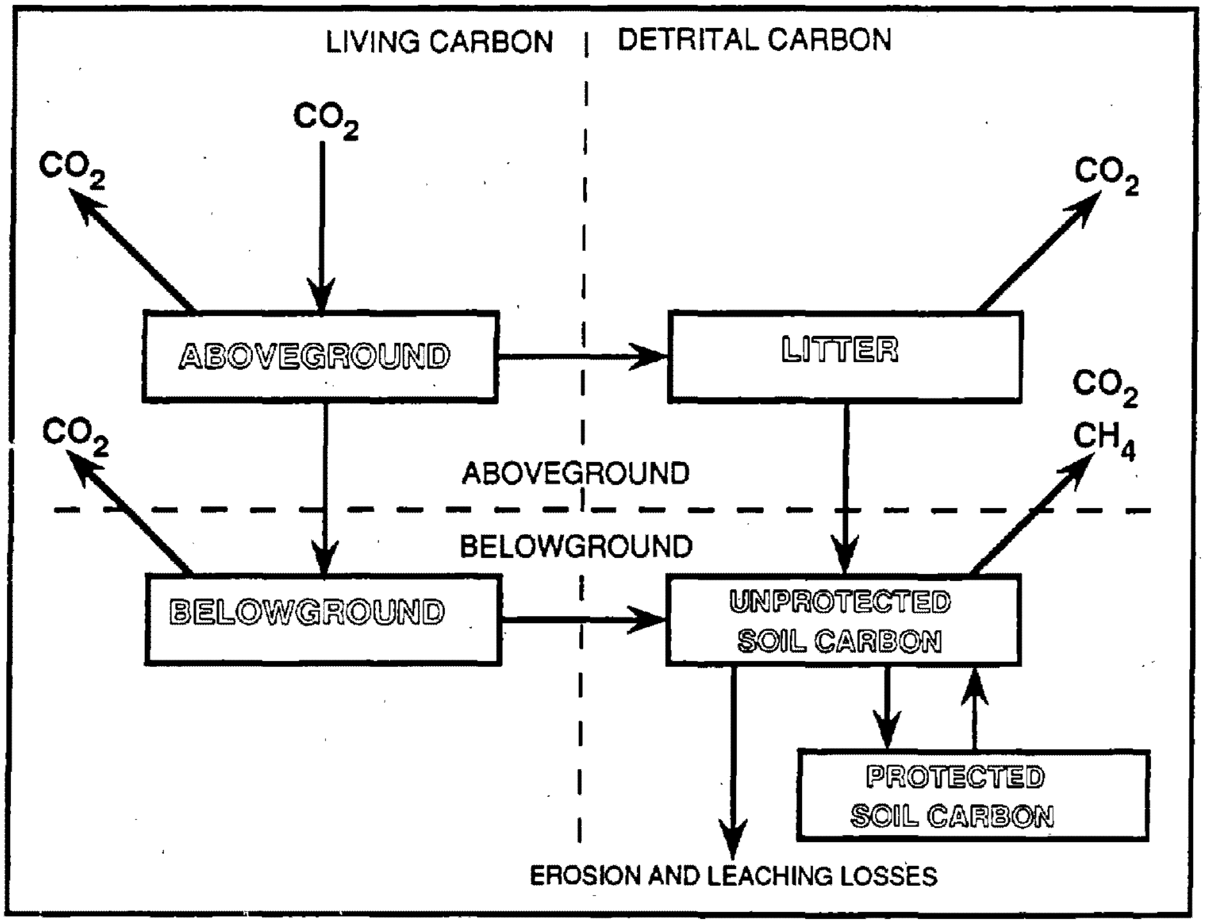
United States
Environmental Protection
Agency

Envionmental Research
Laboratory
Corvallis, OR 97333

EPA/600/3-91/031
April 1991

Research and Development

EPA Sequestering Carbon in Soils: A Workshop to Explore the Potential for Mitigating Global Climate Change



SIMFLIFIED CONCEPTUAL MODEL OF CARBON POOLS AND FLUXES IN TERRESTRIAL SYSTEMS

EPA/600/3-91/031
April 1991

SEQUESTERING CARBON IN SOILS: A WORKSHOP TO EXPLORE THE POTENTIAL FOR MITIGATING GLOBAL CLIMATE CHANGE

26-28 February, 1990
Corvallis, Oregon, USA

Sponsored by the

US ENVIRONMENTAL PROTECTION AGENCY
Office of Research and Development
Environmental Research Laboratory
Corvallis, Oregon

and the

US ENVIRONMENTAL PROTECTION AGENCY
Office of Policy, Planning, and Evaluation
Office of Policy Analysis
Washington, D.C.

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April 15, 1991

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COVER GRAPHIC

The cover graphic depicting a simplified conceptual model of carbon pools and fluxes in terrestrial systems is the product of discussions between M.G. Johnson and K.G. Mattson.

ACKNOWLEDGMENTS

We acknowledge the participation and contributions of everyone who took part in the workshop on soils and climate change. We are grateful to Ken Andrasko and Kate Heaton of the EPA's Office of Policy Planning and Evaluation (OPPE) in Washington, D.C., for their curiosity about soils and for OPPE's financial sponsorship of the workshop. We are particularly indebted to Michael Beare, Sandra Brown, Stan Buol, Dale Cole, Kermit Cromack, John Duxbury, Richard (Skee) Houghton, Dale Johnson, Rattan Lal, Ariel Lugo, Bill Parton, Mac Post, Paul Rasmussen, Bill Schlesinger, and Phil Sollins for their thought-provoking presentations, contributions, or reviews. We also thank Chris Andersen, Deborah Coffey, Kate Dwire, Ann Hairston, Duane Lammers, Leon Liegel, Jeff Lee, Kim Mattson, Paul Shaffer, Bill Ferrell, Hermann Gucinski, Jack Winjum, and Bob Dixon for their reviews and contributions to this document. Finally, we are thankful for the encouragement and patience of Bruce McVeety and Dave Tingey who have helped us stay on track and complete this report.

M.G.J and J.S.K, Corvallis, OR

TABLE OF CONTENTS

EXECUTIVE SUMMARY

SEQUESTERING CARBON IN SOILS: A WORKSHOP TO EXPLORE THE POTENTIAL FOR MITIGATING GLOBAL CLIMATE CHANGE

INTRODUCTION

Soils are an important component of the global carbon cycle and a major reservoir of carbon. Oxidation of soil carbon through agriculture, deforestation, and changing land use practices contributes to the buildup of atmospheric carbon dioxide and methane. Increases in atmospheric concentrations of greenhouse gases, such as carbon dioxide and methane, are causing additional solar energy be retained in the earth's atmosphere leading to global warming that may alter global climatic patterns (Mitchell, 1989). Strategies to mitigate global warming include reducing greenhouse gas emissions (U.S. Congress, 1991) and sequestration of atmospheric carbon in terrestrial vegetation (Houghton, 1990; Grainger, 1990). Because soils can function as either a source of atmospheric carbon or a sink, and because they are the growth medium of terrestrial plants, they may have an important role in mitigating global warming. Because the linkage between soils and climatic change is not fully known a workshop was convened to address the question "Can soils be used to store sufficient carbon to aid in mitigating global climate change?".

ANTHROPOGENIC CONTRIBUTION TO RADIATIVE FORCING - 1980 TO 1990

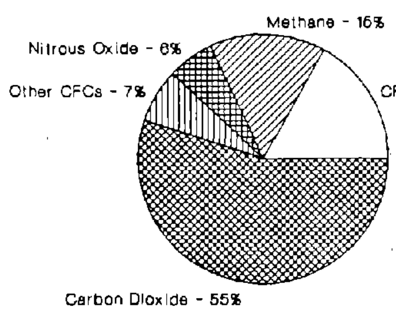


Figure 1

SCIENTIFIC SETTING

Recent scientific and public concerns have focused on the potential for global warming and global climatic change. The principal reason for these concerns is the documented increase in greenhouse gases in the atmosphere. These gases absorb solar energy and translate it into thermal energy, resulting in some degree of atmospheric warming. Greenhouse gases include water, carbon dioxide, methane, nitrous oxide, and chlorofluorocarbons. Carbon dioxide, methane, and nitrous oxide are naturally occurring greenhouse gases, yet their increased concentrations are linked with human activities [Figure 1]. Of particular interest is carbon dioxide because its increase is correlated with fossil fuel combustion and biomass burning associated with large-scale deforestation.

GLOBAL RESERVOIRS OF CARBON
(Petagrams of Carbon)

Vegetation	550
Soils	1,500
Atmosphere	750
Oceans	38,000
Recoverable Fossil Fuels	4,000

Carbon circulates between three very large reservoirs (oceans, atmosphere, and terrestrial systems) and can be found in a plenitude of compounds in each reservoir. These reservoirs, or pools, exchange large amounts of carbon annually. A fourth reservoir, the geological reservoir, contains fossil and mineral carbon including carbonates, and consists primarily of inactive or non-circulating carbon. Perturbations, disturbances, or additions of carbon (e.g. fossil fuel combustion) to any of the reservoirs will have a concomitant effect on the others because of the dynamic linkage of the reservoirs. Global warming is also expected to have an effect on the balancing of the global carbon cycle. One projected effect is the shifting of global vegetation and the amount of carbon stored therein.

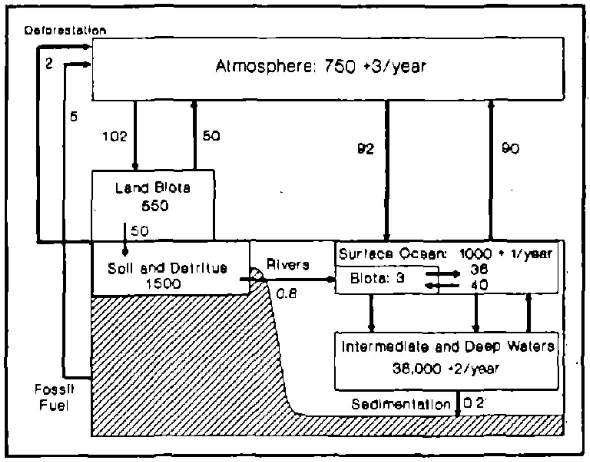


Figure 2. Current estimates of global carbon pools and fluxes in petagrams of carbon including annual increases due to human activities. (source: Houghton et al., 1990)

Globally, there are approximately 41,000 Pg (Pg = petagrams = 10^{15} grams) of active, or circulating, carbon [Figure 2]. Of this, the oceanic reservoir contains 38,000 Pg; the atmosphere 750 Pg; and terrestrial ecosystems about 2100 Pg of carbon. Of the terrestrial carbon, living plants account for about 550 Pg of carbon and soils approximately 1500 Pg. Soils are therefore the largest, non-fossil, terrestrial reservoir of carbon. Annually, the current net loss of carbon from plants and soils is estimated to be 1 Pg. The cumulative loss over the last 100 or 200 years has been considerable, but there is a great deal of uncertainty in the actual amount of carbon lost due to the lack of reliable data and the heterogeneity of the earth's soils and vegetation.

WORKSHOP ON SOIL CARBON

The US Environmental Protection Agency (EPA) sponsored this workshop to evaluate the potential of soils to sequester and store carbon. The workshop was attended by 40 scientists, including internationally recognized soil and carbon cycling experts. The workshop was held in Corvallis, Oregon and consisted of two days of informal presentations and discussions, preceded by a one-day field trip to observe agricultural and forestry practices that affect above- and belowground carbon storage.

The workshop had three specific goals:

(1) to provide the EPA with an informed scientific opinion as to whether or not carbon can be sequestered in soils on a global scale to the extent that it can be used to reduce the rate of atmospheric carbon dioxide increases;

(2) to identify the major unknowns regarding this opinion;

(3) to recommend research that the EPA should pursue to eliminate knowledge gaps and uncertainties in this area.

To achieve these goals, the workshop was organized around three key areas: (1) the global carbon cycle, (2) soil carbon pools, and (3) managing soil carbon. Scientists were invited to speak in each of these areas, emphasizing what is known, identifying uncertainties and limitations, and making research recommendations. Agricultural and forestry practices were accentuated because of the potential for using them or adapting them for managing soil carbon.

WORKSHOP FINDINGS

In setting the stage for deliberations on the mitigating potential of soils, the speakers conveyed important background information. This information is summarized here.

- **GLOBAL CARBON CYCLE:** At steady state, the flow of carbon between the global carbon pools is in equilibrium. The amount of carbon fixed annually by terrestrial plants through photosynthesis ranges from 100 - 120 Pg. Plant respiration releases approximately 40 - 60 Pg of carbon annually, and decomposition of organic residues, including soil carbon, releases approximately 50 - 60 Pg. At steady state the amount of carbon oxidized by these two processes would balance that fixed by photosynthesis. Through agricultural practices and land use changes, including deforestation, the oxidation of plant and soil carbon may be exceeding the amount being fixed by photosynthesis, and therefore contributing to the net 3 Pg annual increase in atmospheric carbon dioxide.

  One of the concerns and unknowns associated with global warming and the carbon cycle is the effect of warming on the distribution of carbon in the various reservoirs. Will increased temperatures cause a massive shift in carbon now sequestered in soils to the atmosphere thereby increasing global warming? It was reported that if soil temperatures increase 3°C, approximately 10% of the carbon in temperate and agricultural soils (approximately 50 Pg) could be released into the atmosphere. A 10% loss of all the carbon currently held in soils would result in 150 Pg of carbon being injected into the atmosphere. Either scenario would exacerbate the amplitude and extent of global warming. If half of a percent were lost per year, it would only take 20 years.

- **SOIL CARBON POOLS:** The accumulation and distribution of soil carbon depend on a variety of biotic and abiotic factors including: (1) soil chemical and physical characteristics; (2) precipitation; (3) above- and belowground biology; (4) temperature; (5) solar radiation; (6) atmospheric chemistry and processes; (7) landscape characteristics; (8) site history; and (9) time. Land use practices affect these factors and thus affect soil carbon.

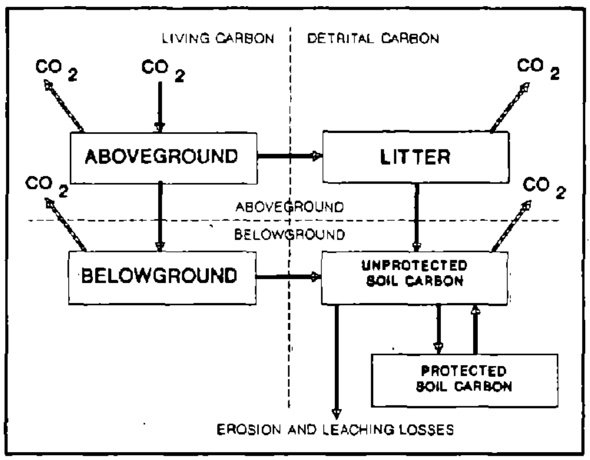


Figure 3. Simplified conceptual model of carbon pools and fluxes in terrestrial systems.

Carbon fixation via photosynthesis is the ultimate source of soil carbon and provides the energy that drives soil biological processes [Figure 3]. The non-mineral carbon in soils (organic carbon) can be associated with either living organisms or their residues. Living soil organisms include plant roots, macroorganisms or fauna, and microorganisms. Combined these comprise less than four percent of total soil carbon. The remaining 96 - 98% of soil carbon is detrital and consists of about 20% macroorganic matter and 80% humified (partially decomposed or altered) material.

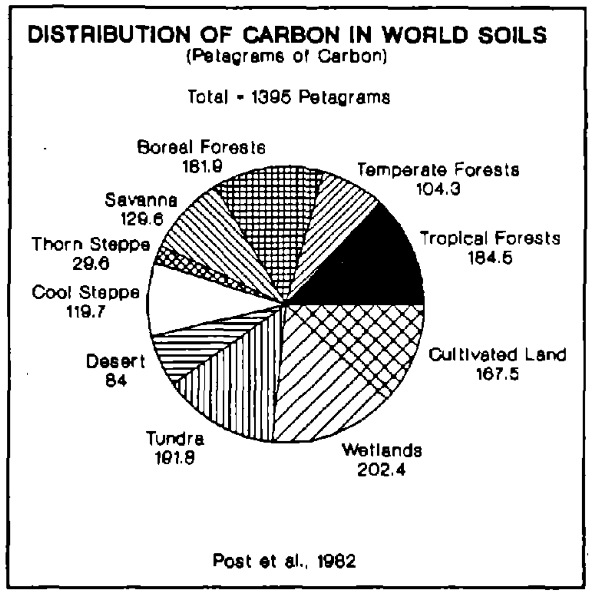


Figure 4.

The carbon content of soils can be quite high, as in the case of wet peat or muck soils (Histosols) with carbon contents as high as 72.3 kg carbon m^{-2} [Figure 4]. It can also be quite low as in dry desert soils (Aridisols) with values as low as 1.4 kg carbon m^{-2}. Soil carbon oxidation rates are subject to soil temperature, oxygen supply, and the nature of the organic material. The difference is due primarily to soil moisture and temperature. Soil carbon contents tend to increase curvilinearly with increasing rainfall at a constant mean annual air temperature (Jenny, 1980). However, at a constant moisture content soil carbon content tends to decrease curvilinearly with constant temperature. Soils with mean summer and winter temperatures (measured at a depth of 50 cm) that differ less than 5°C tend to have more soil carbon than soils with more than 5°C difference but the same mean annual temperatures. Soils saturated with water for long periods of time have low oxygen contents and therefore low decomposition rates and carbon tends to accumulate. Other factors such as clay content and mineralogy also affect soil carbon contents.

An important characteristic of soil carbon is its retention time or turnover time. Retention times are a measure of stability of organic matter under existing conditions. Soil carbon retention times range from as short as a few years or as long as thousands of years, with the longer times being associated with cold and wet climates. Carbon retention times are also a function of depth within the soil. Organic material on, or near, the soil surface is susceptible to decomposition. Materials contained within the soil profile tend to be more protected and less susceptible to decomposition. For example, the carbon in forested soils is derived from leaf litter deposited on the soil surface and from fine root turnover near the soil surface. The primary source of carbon in grassland soils is root mortality which is incorporated within the soil to depths of a meter or more. For this reason, within a given climate regime, a grassland soil will generally have more carbon (longer retention times) than a forested soil even though the forested system will have greater net primary production and aboveground biomass because of depth of organic matter incorporation.

SOIL CONDITIONS AND MANAGEMENT PRACTICES THAT PROMOTE CARBON ACCUMULATION IN SOILS

Soil Change	Practice	Applications
Cooler soil	Mulch, shade	All soils
Wetter soil	Irrigation	Dry regions
Increase Fertility	Fertilizer	Most soils
Raise subsoil pH	Deep liming	Acid subsoils
Reduced aeration	Limited tillage	All soils

(source S.W. Buol and UNEP)

- **MANAGING SOIL CARBON:** In general, soils have not been managed to retain or conserve carbon. Although economics, as measured by crop yields and board feet of lumber, has been the common metric driving agricultural and forest system management, soils are an important component in the production equation. In addition to being an important carbon reservoir, organic carbon in soils is important for maintaining the productivity of soils. Organic carbon in soil contributes to soil productivity by: promoting soil aggregation, absorbing and holding water, serving as a natural reservoir of plant nutrients, minimizing wind and water erosion, and providing exchange sites for plant nutrients.

Soil fertility is essential for primary production and is therefore key to sequestering carbon in soils. Soils that have lost carbon or that are naturally low in fertility have the potential to store carbon by improving their fertility status. To sequester carbon in soils, fertility limitations need to be identified and eliminated. Judicious fertilizer use is recommended, however, because even though more carbon may be sequestered in soils there may be negative effects too and there are carbon costs associated with fertilizer production and application. Use of nitrogen fertilization may promote the emission of nitrous oxide from soil. Per molecule, the radiative forcing effect of N_2O is about 200 times greater than CO_2 (U.S. Congress, 1991).

The amount of organic carbon in soils is a function of the quantity and quality of carbon inputs and subsequent losses through decomposition and erosion. Soil carbon is also a function of soil chemical and physical properties. Increasing the inputs of carbon to soils can increase the amount of carbon sequestered and immobilized in soils. Minimizing soil mixing and warming will slow decomposition. Managing agricultural soils to conserve and store carbon requires the use of conservation tillage practices to minimize soil disturbances, and the incorporation of crop residues into the soil to increase carbon inputs to the soil. Soil temperature is positively related to decomposition. The use of mulches or cover crops reduce soil temperatures, thereby reducing soil carbon losses.

Although forest management is markedly different than agricultural management, the principles of minimizing soil disturbance and taking steps to lower soil temperatures are still applicable for conserving carbon in forested soils. The removal of forest cover results in increased oxidation of soil carbon through increased soil temperatures, particularly in large exposed clear-cuts. Soil disturbances associated with forest harvesting also contribute to the net loss of soil carbon. Implementing management practices that minimize soil disturbance during forest harvesting and providing soil mulches following harvesting will conserve soil carbon in forested soils.

As soils near their carbon carrying capacity, or equilibrium carbon content, the carbon accumulation rate becomes very low

(Schlesinger, 1991). Similarly, soils forming in newly exposed geologic material accumulate carbon slowly because they lack the functional organization to support high levels of primary production, but with time the rate will increase. The soils having the greatest carbon accumulation rates are those that are not at their carbon carrying capacity which includes young soils and soils that have been somewhat carbon depleted due to management.

Currently there is about 1.5 billion hectares of cropland (World Resources Institute, 1990). Conservation tillage could be implemented on many of these soils, thereby reducing soil carbon losses and converting these soils from sources of atmospheric carbon to sinks. Additionally, with proper management carbon could be restored to many other carbon-depleted soils. In the tropics there is an estimated 865 million hectares of deforested and abandoned land that could be is potentially available for afforestation (Houghton, 1990). If reforested, these systems would withdraw approximately 1.5 Pg carbon a year from the atmosphere sequestering it in soils and vegetation over the next century. Similar opportunities exist in other regions of the world as well.

STRATEGIES FOR MANAGING SOIL CARBON AT THE GLOBAL-SCALE

Workshop participants recognized that some soils could be used to store additional carbon, but based upon currently available data, could not definitively conclude whether or not the storage of new carbon in soils would be sufficient to offset atmospheric increases in carbon or to mitigate global warming. They emphasized the importance of managing soils to prevent soils from continuing to be a source of greenhouse gases, thereby reducing the amplitude and extent of global warming.

Workshop participants identified three general soil carbon management strategies to optimize carbon sequestration and storage: (1) manage soils to maintain the size and integrity of the global pool of soil carbon, (2) manage soils to restore carbon that has been lost, and (3) manage soil to increase the amount of carbon sequestered in the global soil carbon reservoir. Each of these described below, followed by descriptions of specific management practices that the workshop participants determined would be important for achieving the soil management goals.

SOIL CARBON MANAGEMENT STRATEGIES

- Manage to <u>MAINTAIN</u> the global soil carbon pool
- Manage to <u>RESTORE</u> carbon to carbon-depleted soils
- Manage to <u>ENLARGE</u> the global soil carbon pool

MAINTAINING THE GLOBAL POOL OF SOIL CARBON: Because soils are the largest terrestrial pool of active, or cycling, carbon and because a large portion of this carbon is potentially available to the atmosphere through human activities and conventional soil management practices, workshop participants recommended that management practices be implemented to preserve the size and integrity of the pool. Managing soils to maintain their current carbon levels recognizes that soil carbon is labile and is lost to the atmosphere relatively easily when the soil is mixed and stirred as in conventional agricultural systems. On the other hand it takes a substantially longer even with sustained carbon inputs to accumulate significant amounts carbon in soils. Workshop participants concluded that it is best to protect and preserve soil carbon before it is lost, than it is to allow it to be lost and then try to restore it. They also recognized that a significant loss of soil carbon to the atmosphere could exacerbate global warming.

HIGH PRIORITY MANAGEMENT PRACTICES FOR MAINTAINING GLOBAL SOIL CARBON POOLS

- Maintain Soil Fertility
- Concentrate Tropical Agriculture
- Preserve Natural Wetlands
- Increase Efficiency of Forest Product Use

Management Practices to Maintain Soil Carbon Levels

The management practices described below were identified by the workshop participants as those that could be used to maintain the amount of carbon in soils and were given the highest priority for implementation.

- **Maintain Soil Fertility:** Sustained inputs of new carbon to soils from primary production is essential for maintaining current levels of soil carbon. Interruption of these carbon inputs results in loss of soil carbon by the readjustment of the soil system to a lower equilibrium level of soil carbon. Maintaining soil fertility helps sustain primary production, which in turn helps to sustain the input of new carbon belowground and the sequestration of carbon in soils.

- **Concentrate Tropical Agriculture:** Concentrating or intensifying tropical agriculture is aimed at preventing tropical deforestation and the soil carbon loss associated with it, and thereby maintaining the existing stocks of soil carbon. Concentrating tropical agriculture is the practice of directing resources and management for use only on the best agricultural lands. The net result is that less land will be used to produce the same, if not more, volume of agricultural products. In achieving this, the need for slash-and-burn agriculture (deforestation) is diminished.

- **Preserve Natural Wetlands:** Inundated soils in wetlands contain a great deal of carbon that has a very long retention time if undrained. The practice of draining these systems, primarily for agrarian purposes, results in the rapid oxidation and loss of carbon to the atmosphere. Preserving wetlands insures the carbon storage function of these lands.

- **Increase Efficiency of Forest Product Use:** Increasing the efficiency of forest harvesting (by reducing waste) and increasing the life-span of forest products (including recycling) is aimed at reducing the demand for forest harvesting. Reducing forest harvesting, or increasing the interval between harvests, will help to maintain the large above- and belowground carbon stocks in the worlds forests.

RESTORING SOIL CARBON IN CARBON-DEPLETED SOILS: An opportunity exists to restore carbon in soils that are depleted in carbon due to mismanagement. Worldwide, there may be millions of hectares of carbon-depleted forest and agricultural land that could store additional carbon. Management practices that bring these once productive lands back into increased production will lead to increased carbon sequestration and storage both above- and belowground. Soils that are the most carbon depleted will require more inputs to restore them to their full carbon carrying capacity. The long-term objective of this strategy is to restore the soil carbon levels to what they were originally.

HIGH PRIORITY MANAGEMENT PRACTICES FOR RESTORING CARBON IN CARBON-DEPLETED SOILS

- Reforestation
- Improve Soil Fertility
- Use Municipal, Animal, Industrial and Food Processing Wastes as a Source of Low-Cost Fertilizer

Management Practices to Restore Carbon in Carbon-Depleted Soils

The management practices described below were identified as those that would be useful for restoring soil carbon to previous levels and were given the highest priority for implementation to restore carbon in carbon-depleted soils.

- **Reforestation:** Large-scale reforestation has the potential to sequester and store large amounts of new carbon both above- and belowground, particularly on carbon-depleted soils. Some deforested areas will regenerate naturally while others will only require new tree planting. Others will require intensive management and large inputs of resources.

- **Improve Soil Fertility:** Soils that are carbon depleted may also lack in soil nutrients, which may limit primary production. Improving the fertility of these soils to support vegetation is key to restoring carbon in these soils.

- **Use Municipal, Animal, Industrial and Food Processing Wastes:** Restoring carbon in carbon-depleted soils may be limited by the lack of plant nutrients needed for primary production or by the cost of fertilizer to replenish nutrients. Municipal, animal, industrial, and/or food processing wastes may be ideal sources of low-cost forest fertilizers. Using them in forests or in agriculture, particularly on marginal lands, can provide water and essential nutrients to vegetation, thereby promoting a higher level of primary production and above- and belowground carbon sequestration.

ENLARGING THE SIZE OF THE GLOBAL SOIL CARBON RESERVOIR: The objective of this strategy is to manage forested and agricultural systems in ways that increase their productivity and their allocation and storage of carbon belowground. Most of the opportunities to enlarge this pool may be in agriculture because agricultural systems are generally more intensely managed than forested systems. Workshop participants surmised that the marginal return, measured in terms of stored carbon, would probably be greater by implementing management practices aimed at "maintaining" and "restoring" storing soil carbon than by attempting to enlarge the global pool of soil carbon.

HIGH PRIORITY MANAGEMENT PRACTICES FOR ENLARGING THE GLOBAL POOL OF SOIL CARBON

- Conservation Tillage
- Improve Soil Fertility
- Concentrate Tropical Agriculture
- Minimize Dryland Fallowing

Management Practices for Enlarging the Global Soil Carbon Reservoir

The management practices described below were given the highest priority for implementation to enlarge the global reservoir of soil carbon.

- **Conservation Tillage:** In the context of enlarging global soil carbon stocks, widespread implementation of conservation tillage practices could lead to additional sequestration of carbon in soils. Implementing conservation tillage practices implies that the use of conventional tillage practices will decline, thus reducing the oxidative loss of soil carbon.

- **Improve Soil Fertility:** Lack of nutrients often limits primary production. Eliminating or reducing nutrient limitations will improve primary production leading to greater sequestration of carbon in soil.

- **Concentrate Tropical Agriculture:** By concentrating tropical agriculture, lands removed from shifting agriculture can be reforested or revegetated, leading to increased soil carbon stocks.

- **Minimize Dryland Fallowing:** Fallowing is the practice of leaving semi-arid agricultural lands bare in alternate years to accumulate sufficient soil moisture to grow a crop every other year. Dryland fallowing is a widely used agricultural practice. There is gathering evidence that this practice promotes the loss of soil organic carbon because the soil is usually kept bare by mechanical means. This stirring and mixing of the soil combined with increased soil temperatures, due to lack of cover, results in rapid and thorough oxidation of organic carbon. Use of cover crops or crop rotations may achieve the same soil water objectives and eliminate the need to fallow.

CONCLUSIONS

Two primary conclusions can be drawn from the workshop. First, that **steps should be taken to protect and preserve the size and integrity of the global reservoir of soil carbon** because continued losses of soil carbon to the atmosphere could exacerbate global warming and climatic change. Second, that **steps should be taken to manage soils and ecosystems to store additional carbon**. The latter is to be accomplished predominately by increasing net primary production. The workshop identified the major uncertainties related to carbon sequestration in soils and developed specific strategies for addressing the uncertainties and for managing soils to store carbon.

Major conclusions of the workshop participants:

- Soils are an important component of the global carbon cycle, containing a large pool of active, cycling carbon. As such, they are a very large potential source of atmospheric carbon, but they also represent a large potential sink for carbon, if managed properly.

- Uncertainties exist in the success of widespread implementation of soil management practices because of the potential for the occurrence of concomitant negative effects. At some locations the associated negative effects may outweigh the positive benefits. For instance, under certain circumstances some of these practices could lead to the emission of gases (e.g., nitrous oxide) that have a greater radiative forcing than carbon dioxide. In terms of global warming, this scenario would be counterproductive. The implementation of any new or altered management practices should be considered on a site-by-site or region-by-region basis prior to implementation, and should be evaluated in terms of the effect on carbon pools and fluxes.

- Three strategies for managing soil carbon are proposed: (1) managing soils to maintain current levels of soil carbon, (2) managing carbon depleted soils to restore carbon to former levels, and (3) managing soils to enhance the size of current soil carbon pools. For each of these a variety of opportunities exist for capturing atmospheric carbon, via photosynthesis, and storing it in soils and aboveground biomass.

- In addition to storing carbon assimilated from the atmosphere, managing soils to conserve carbon will have other benefits. These include: (1) increased soil water holding capacity, (2) increased nutrient availability, (3) improved soil physical properties, and (4) decreased soil erosion by wind and water. Together these should lead to (5) sustainable food and fiber production.

The consensus on the central workshop question "Can soils be used to store sufficient carbon to aid in mitigating global climate change?" is that we need more reliable information to provide a definite answer.

RESEARCH RECOMMENDATIONS

Throughout this workshop, the lack of sufficient, reliable, quantitative data and numerous areas of uncertainty related to soil carbon were identified. Research and data gathering in these areas will improve our quantification of global soil carbon and related processes. Here we list those topics thought to be critical for a more complete analysis of soils and global climatic change. This list, although not exhaustive, provides guidance for research in areas that could provide valuable information or tools for evaluating the role of soils in the global carbon cycle with a focus towards the potential of soils to sequester and store additional carbon from the atmosphere.

- **Define** soil carbon pools based upon lability and soil processes and determine the factors that control the partitioning of carbon into the respective pools.

- **Identify** and characterize the specific fractions of soil carbon that are manageable and practices that are effective for managing the various fraction.

- **Improve** estimates of global soil carbon by conducting large-scale statistically designed soil surveys coupled with intensive soil sampling and physical and chemical analysis.

- **Quantify** above- and belowground carbon pools and fluxes in specific ecosystems under steady state conditions for the purpose of developing general principles of ecosystem carbon dynamics from specific examples.

- **Characterize** and quantify the factors that control soil carbon fluxes.

- **Develop** soil carbon methods for characterization and quantifying the true size and lability of soil carbon pools.

- **Characterize** and quantify the role of abiotic soil factors in stabilizing soil carbon.

- **Quantify** the effects of land use and management, including agricultural and silvacultural, on soil carbon.

- **Conduct** experiments to characterize the effects of altered climatic conditions on terrestrial plant carbon fixation and allocation, focusing on the quantity and quality of carbon in detritus and in belowground allocation.

- **Develop** simulation models that accurately project how carbon fluxes (and thus pools and feedbacks to the atmosphere) will shift in specific ecosystems under a series of altered climate scenarios.

- **Quantify** the economics of implementing soil management practices that sequester and store carbon.

EPILOGUE

It was the general consensus of the workshop participants that because global warming and climatic change are international problems, a major global-scale effort is needed to grasp the full scope of these problems and to conduct the research and planning needed to develop global-scale solutions. As research is conducted on global climatic change and mitigation plans are formulated, it is important that the role of soils and other components of terrestrial ecosystems be considered because of the dynamic linkages between the components and climate.

The storage of carbon in soils is a very complex phenomenon. Although it is not fully characterized or understood, steps can be taken to use soils as a reservoir of carbon. The role of soils in the carbon cycle must be more fully understood to develop strategies to mitigate increases in atmospheric carbon dioxide, including strategies to manage the biosphere. Likewise, the effects of specific management practices on soil carbon cycling and storage must be more fully understood. The gaps in our knowledge of soils and ecosystems, and their response to climatic change, necessitate additional research before quantifiable projections of the role of soils in global climatic change can be made.

This workshop identified the major uncertainties in our understanding of the role of soils in global climate change and identified steps that can be taken to manage soils to optimize their carbon storage potential and sustain their productivity.

CITED REFERENCES

Grainger, A. 1990. Modeling the impact of alternative afforestation strategies to reduce carbon dioxide emissions. p. 93-104. In Tropical Forestry Response Options to Global Climate Change, Sao Paulo, January 1990, Conference Proceedings, U.S. Environmental Protection Agency, Washington, D.C.

Houghton, J.T., G.J. Jenkins, and J.J. Ephraums (eds.). 1990. Policymakers Summary. In Climate Change: The IPCC Scientific Assessment. Cambridge University Press, Cambridge, England.

Houghton, R.A. 1990. Projections of future deforestation and reforestation in the tropics. p. 87-92. In Tropical Forestry Response Options to Global Climate Change, Sao Paulo, January 1990, Conference Proceedings, U.S. Environmental Protection Agency, Washington, D.C.

Jenny, H. 1980. The Soil Resource: Origin and Behavior. Springer-Verlag, New York.

Mitchell, J.F.B. 1989. The "Greenhouse" Effect and Climate Change. Reviews of Geophysics 27:115-139.

U.S. Congress. 1991. Changing by degrees: Steps to reduce greenhouse gases. Office of Technology Assessment, OTA-0-482 Washington, D.C.

World Resources Institute. 1990. In Hammond, A.L. et al. (ed.) World resources 1990-91. A report by the World Resources Institute, Oxford University Press, Oxford, England

SEQUESTERING CARBON IN SOILS: A WORKSHOP TO EXPLORE THE POTENTIAL FOR MITIGATING GLOBAL CLIMATE CHANGE

1. INTRODUCTION

Long-term atmospheric chemistry data indicate that human activities have increased the concentration of a number of greenhouse gases due to fossil fuel combustion and land use changes, that may be enhancing the absorption the earth's long-wave black-body radiation (Houghton et al., 1990). This increased retention of solar energy through the "greenhouse" effect, may lead to global warming and changes in global climates through radiative forcing. Long-term earth surface temperature data indicates that the surface of the earth may have warmed as much as 0.3°C - 0.6°C in the last century (Houghton et al., 1990). This temperature increase is further substantiated by evidence of retreating glaciers and sea level rise. Because the extent, duration, and amplitude of global warming is largely unknown, the long-term effect on global climate is also unknown.

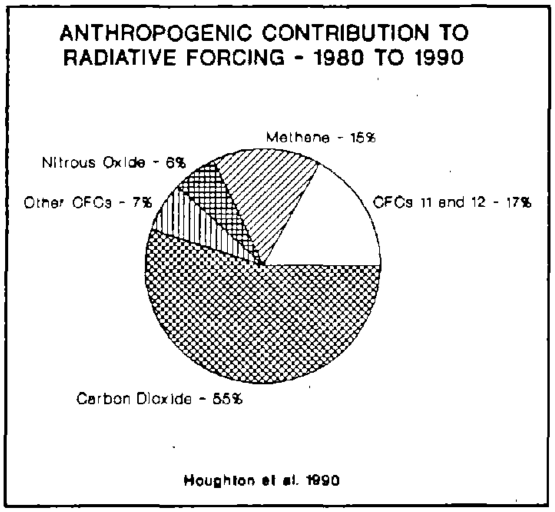


Figure 1

The global carbon cycle has a central role in global climatic change because two of the important greenhouse gases, carbon dioxide (CO_2) and methane (CH_4), are part of the actively cycling carbon. Deforestation and other land use practices release large amounts of non-fossil fuel carbon into the atmosphere, thus adding to the increase in greenhouse gases. Soils are an important component of the carbon cycle, providing a growth medium for plants and storing a large quantity of carbon belowground.

In response to concern over the possibility of global climatic change, the U.S. Environmental Protection Agency (EPA) and other federal agencies are gathering information and conducting research to determine the likelihood and potential extent of climate change, the effects of climatic change, and strategies to mitigate climatic change. In this report we present the findings and recommendations of a workshop that was convened to examine the role of soils in the global carbon cycle and to consider the potential of soils to mitigate global climate change by the sequestration of additional atmospheric carbon in soils.

2. WORKSHOP GOALS AND ORGANIZATION

The workshop on soils and climate change was co-sponsored by the Climate Change Division of EPA's Office of Policy Analysis, Washington, D.C., and the EPA's Environmental Research Laboratory in Corvallis, Oregon. The workshop was held February 27 and 28, 1990, on the campus of Oregon State University. More than 40 scientists from universities, and federal and private research organizations participated in the workshop, including internationally recognized soil and carbon cycling experts. The participants and their affiliations are listed in Appendix F.

Workshop Goals

The workshop was organized around a central question, "Can soils be used to store sufficient additional carbon to aid in mitigating global climate change?". To answer this question three workshop goals were stated at the outset:

(1) to provide the EPA with an informed scientific opinion as to whether or not carbon can be sequestered in soils on a global scale to the extent that soils can be used to reduce the rate of atmospheric carbon dioxide increases.

(2) to identify the major unknowns regarding the sequestration of additional atmospheric carbon in soils.

(3) to recommend research that should be pursued to eliminate knowledge gaps and uncertainties in this area.

To achieve these goals, the workshop was organized around three key areas:

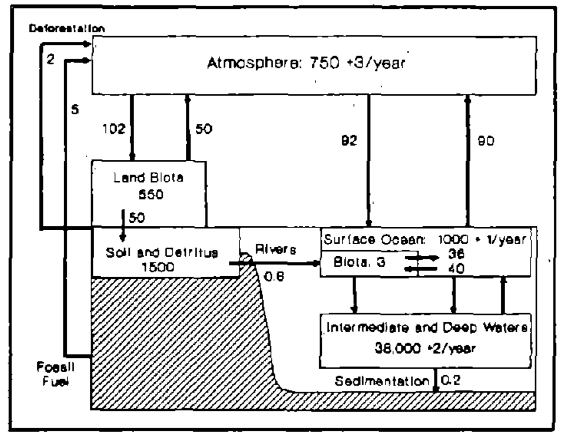
- the global carbon cycle
- soil carbon stocks
- managing soil carbon

Scientists were invited to speak in each of these areas and asked to highlight what is known, identify uncertainties and limitations, and make research recommendations. Agricultural and forestry practices were accentuated at the workshop because of the potential for using them or adapting them for managing soil carbon. Each of the presentations was followed by a period for questions and discussion. To facilitate additional scientific discussion, participants were organized into three small discussion groups and were provided with a set of questions to guide the discussions. One group focused their discussions on forested soils, one on soils in temperate agriculture, and one on soils in tropical agriculture. These groups met several times during the workshop. The workshop agenda is reproduced in Appendix A.

Workshop Report Objectives and Organization

The purpose of this report is to provide documentation and a synthesis of the information presented in the workshop. This report is written to be used as a source of information for policy makers and scientists. It includes a list of specific research topics that, if pursued, would reduce knowledge gaps and uncertainties in current soil carbon data and management practices.

This report is organized around the three focus areas: the global carbon cycle (Section 3), soil carbon stocks (Section 4), and managing soil carbon (Section 5). The material in these sections is a composite of the information presented and discussed at the workshop, including the small group discussions, and scientific information from the recent literature. Section 6 outlines and describes soil carbon management strategies developed at the workshop for conserving and sequestering carbon in soils and details specific management practices that the workshop participants determined would be important for achieving the soil management goals. Section 7 is a synthesis and summary of the workshop and includes the workshop conclusions. Section 8, the final section, lists areas (identified at the workshop) in which further research and data gathering would lead to improved quantification of global soil carbon and a better understanding of related processes.



Current estimates of global carbon pools and fluxes in petagrams of carbon including annual increases due to human activities. (source: Houghton et al. 1990)

3. THE GLOBAL CARBON CYCLE

Annually, the burning of fossil fuels releases an estimated 5 Pg (Pg = petagrams = 10^{15} grams) of carbon, primarily as carbon dioxide, to the atmosphere (Post et al., 1990). The burning of fossil fuels since the industrial revolution accounts for most of the increase in atmospheric carbon dioxide (Houghton et al., 1990). Other human activities, such as changes in land use and deforestation, also contribute an estimated 2 Pg of carbon to the atmosphere annually. At the same time other "greenhouse" gases (e.g., methane, nitrous oxide, chlorofluorocarbons) have been increasing in the atmosphere. Greenhouse gases transmit incoming solar radiation but partially absorb the earth's long-wave black-body radiation, thereby, retaining energy which warms the atmosphere in proportion to the concentration of greenhouse gases. If the increasing concentration of greenhouse gasses goes unchecked, it is likely that there will be an increase in the earth's mean annual surface temperature (Houghton et al., 1990). It is theorized that this warming may alter global climates causing a change in the timing and distribution of precipitation. In turn, the distribution of the earth's cycling carbon could be changed with the possibility of enormous amounts of carbon being released into the atmosphere from terrestrial pools because atmospheric carbon is linked to carbon in the biosphere through the carbon cycle. There is also linkage between cycling carbon and climate because of the relationship of primary productivity (photosynthesis) to temperature and precipitation.

Global Carbon Pools and Fluxes

At the global-scale, the pools of active, or cycling, carbon are very large (Figure 1). Recently, Post et al. (1990) characterized the global cycle in detail and reported that the atmosphere currently contains about 750 Pg of carbon, terrestrial systems contain 2,000 Pg, oceans 38,000 Pg, and that the geological store of recoverable carbon is about 4,000 Pg. The authors note, however, that there is considerable uncertainty in these numbers.

GLOBAL RESERVOIRS OF CARBON
(Petagrams of Carbon)

Vegetation	550
Soils	1,500
Atmosphere	750
Oceans	38,000
Recoverable Fossil Fuels	4,000

Source Post et al., 1990

An important feature of the carbon cycle is the exchange of carbon between pools. Annually, at the global-scale the natural exchanges of carbon are very large in comparison to the emission of carbon from fossil fuel burning. For example, green plants sequester an estimated 100 - 120 Pg of carbon through photosynthesis annually. At the same time through respiration they return about 50% of this carbon to the atmosphere. The other 50% fixed through photosynthesis and converted to plant biomass falls to the ground as litter or enters the soil by root mortality. Decomposition of plant residues and soil carbon releases 50 - 60 Pg of carbon back to the atmosphere. An estimated 100 - 115 Pg of carbon is exchanged between the atmosphere and oceans annually. As with the estimates of global carbon pools there are uncertainties in the estimates of carbon exchange and it is difficult to balance all the carbon fluxes.

Mitigation

As more carbon is injected into the atmosphere annually and less and less of it is being removed (either through photosynthesis or absorbed by the oceans), concern over the potential for climatic change grows. Plans to mitigate these gaseous increases are being developed. In addition to reducing emissions of carbon dioxide and other greenhouse gases, some components of the carbon cycle itself may provide a means to sequester atmospheric carbon to offset increasing carbon dioxide, primarily through photosynthesis. It has been proposed that large-scale reforestation could sequester a great deal of carbon dioxide over the next 5 or 6 decades, thus offsetting the magnitude of the annual increase in atmospheric carbon dioxide. In addition to sequestering carbon in aboveground biomass, a significant portion of the carbon fixed through photosynthesis will be allocated belowground where it is less susceptible to oxidation. The modeling work of Prentice and Fung (1990) indicates that terrestrial plants can sequester at least 2 Pg of carbon per year, thereby offsetting fossil fuel emissions. A portion of this will be sequestered in soils. Soils will have several functions in biosphere mitigation strategies: they will be a vegetation rooting medium, a source of nutrients, and a source of moisture.

Unknowns

The global carbon cycle is not fully understood (Tans et al., 1990) because of its dynamic nature and the magnitude of the pools and fluxes between pools. Even though there have been numerous studies and reports on the size of global carbon pools and fluxes, large uncertainties remain in the generally accepted estimates. One of the key scientific activities currently underway is the development of simulation models to project the effects of shifting carbon stocks and the interaction with temperature and climate.

4. SOIL CARBON POOLS

Of the 2,000 Pg of carbon in terrestrial systems (Post et al., 1990; Houghton and Skole, 1990) an estimated 1,500 Pg is in soils. This is roughly three times the amount of carbon in vegetation and two times the amount of carbon in the atmosphere. There is also an estimated 800 Pg of inorganic non-cycling, slowly accumulating carbon in carbonates in soils. Excluding non-cycling fossil carbon in the geologic reservoir, soils are the largest terrestrial reservoir of carbon.

Global Distribution of Soil Carbon

Not all soils contain the same amount of carbon. In fact, the variation in carbon density (the amount of carbon in the top meter of soil, or less if the soil is shallower, corrected for coarse fragments and soil bulk density) content can be quite high. Post et al. (1982) report that soil carbon densities can range from as low as 1.4 kg carbon m^{-2} to as high as 72.3 kg carbon m^{-2} [Table 1]. The lower value is representative of soils in warm dry deserts and the larger value is representative of wetland soils that have accumulated a great deal of carbon. These two ecosystems represent the extremes in soil carbon accumulation potential--soil carbon tends to accumulate under cool wet conditions but not under warm dry conditions. Soils have carbon carrying potential, or maximum amount of carbon that can accumulate, that is limited by climate and primary production.

If soils are to be used to sequester atmospheric carbon it is important to know what kinds of ecosystems store substantial amounts of carbon belowground. Again, the work of Post et al. (1982) is useful for characterizing where carbon in soils is distributed, although published reports by Schlesinger (1984) and Waring and Schlesinger (1985) could also be used. Post et al. (1982) report that combined, the worlds forests (tropical, temperate, and boreal) cover 30% of earth's land surface and hold approximately 33%, or 470 Pg, of the carbon held in soils. In contrast, 16% of the earth's land surface is deserts which combined contain 82 Pg of carbon, or about 6% of the global stock of soil carbon. Tundra and wetland soils cover 9% of the land and contain 28% of the carbon in soils (394 Pg). According to Post et al. (1982) there are 2.1 billion hectares of land under cultivation, that accounts for 168 Pg of soil carbon. We know that a portion of the carbon in these soils will be oxidized and lost to the atmosphere through common agricultural practices (Mann, 1986). On the other hand, through intensive management and implementation of practices that conserve soil carbon this trend may be reversed and agricultural soils may be a net sink for atmospheric carbon. Likewise, through reforestation or afforestation carbon will be sequestered in above- and belowground pools.

TABLE 1: DISTRIBUTION OF CARBON IN WORLD SOILS

Source: Post et al., 1982

Life-zone groups	Carbon Density ($kg\ m^{-2}$)	Area ($x10^{12}m^2$)	Percent of total area	Soil carbon ($x10^{15}g$)	Percent of total soil carbon
Tropical Forests					
Wet	19.1	4.1		78.3	
Moist	11.4	5.3		60.4	
Dry	9.9	2.4		23.8	
Very Dry	6.1	3.6		22.0	
Total		15.4	11.9	184.5	13.2
Temperate Forests					
Warm	7.1	8.6		61.1	
Cool	12.7	3.4		43.2	
Total		12.0	9.3	104.3	7.5
Boreal Forests					
Wet	19.3	6.9		133.2	
Moist	11.6	4.2		48.7	
Total		11.1	8.6	181.9	13.0
Tropical Woodland & Savanna	5.4	24.0	18.5	129.6	9.3
Temperate thorn steppe	7.6	3.9	3.0	29.6	2.1
Cool temperate steppe	13.3	9.0	6.9	119.7	8.6
Tropical desert bush	2.0	1.2	0.9	2.4	0.2
Desert					
Warm	1.4	14.0		19.6	
Cool	9.9	4.2		41.6	
Boreal	10.2	2.0		20.4	
Total		20.2	15.6	81.6	5.8
Tundra	21.8	8.8	6.8	191.8	13.7
Wetlands	72.3	2.8	2.2	202.4	14.5
Cultivated land	7.9	21.2	16.4	167.5	12.0
Grand Totals		129.6	100.0	1,395.3	100.0

Genesis of Soil Carbon

Post et al. (1990) distinguish two soil carbon pools. One is litter at the soil surface that is estimated to contain about 72 Pg of carbon. The other is referred to as soil organic matter, and contains about 1,300 Pg of carbon. The annual input to each of these pools is about 60 Pg of carbon. Because plant litter is at the soil surface, it is more susceptible to decomposition and accounts for about 42 Pg of the carbon that is returned to the atmosphere annually through decomposition. Only about 20 Pg of carbon per year are lost via decomposition from the larger soil organic matter pool. Globally, carbon in litter has a retention time or turnover time of about 1.75 years (size of pool/annual losses = 72 Pg/42 Pg) and carbon within the soil profile has a retention time of about 65 years (1,300 Pg/20 Pg). These numbers are average values because through carbon dating, ages of soil organic matter approaching 10,000 years have been reported (Martel and Paul, 1974). Carbon in wetland soils can have particularly long retention times of more than 10,000 years (Armentano, 1980) because inundation prevents rapid aerobic decomposition of organic deposits.

Fertile soils with climatic conditions appropriate for plant growth accumulate carbon. Soil organic matter (carbon) positively influences other soil characteristics such as consistency, water holding capacity, and size and distribution of water stable aggregates. The amount of carbon that accumulates is related to the inputs of carbon to the soil, either through litterfall or root turnover, soil moisture and maximum annual temperatures. Jenkinson et al. (1987) and Jenkinson (1991) have demonstrated that increasing the inputs of carbon to soils will increase the amount of carbon stabilized and retained in soil. Soils that are wet and cool tend to have higher soil carbon contents than soils that are moist and warm, or dry and warm, because litter and soil carbon decomposition proceed at faster rates at elevated temperatures. Inundated wetland soils have some of the highest carbon contents because decomposition rates are reduced due the anaerobic conditions created by water saturation. Even though the primary production of wetland systems can be quite low, under anoxic conditions decomposition rates are even lower. Consequently, carbon accumulates.

For many years there has been a been a debate in the scientific community regarding the legitimate or definable pools of soil carbon. It became apparent at the workshop that this debate has yet to be settled. In the simplest case there are two kinds of carbon in soils. Living carbon, which includes roots, microbes, insects, invertebrates, etc., accounts for about four percent of total soil carbon (Theng et al., 1989). The non-living or detrital soil carbon accounts for about 96 - 98% of soil carbon and consists of about 20% macroorganic matter and 80% humified (partially decomposed or altered) material that may less susceptible to oxidation because of its high carbon to nitrogen ratio.

Soil Carbon Accumulation Rates

One of the important issues in sequestering carbon in soils is whether or not the rates are sufficient to sequester enough atmospheric carbon to delay or prevent global warming. The rate of carbon accumulation in soils is a function of a variety of factors, but primary production--photosynthetic carbon fixation, is of paramount importance. Without primary production there will be no plant carbon to sequester belowground. Production is dependent upon favorable climatic conditions and fertile soils.

Initially, soils developing in newly formed parent material lack the biology, physical structure, and chemistry that are essential for significant primary production, consequently carbon accumulates slowly. As the soil becomes more organized, colonized and structured, productivity accelerates and so does the soil carbon accumulation rate. The rate eventually slows for most systems as they near their respective carbon carrying capacity. Therefore, the soils with the greatest potential carbon accumulation rates are likely to be those that are somewhat carbon depleted, but still retain the requisites (e.g., nutrients, biology, structure) for primary production. The extent of these soils may be great and therefore, they have the potential to sequester a substantial amount of atmospheric carbon in the short-term (50 to 250 years).

Alexander et al. (1989) reported soil carbon accumulation rates for forested soils in southeastern Alaska that range from 29 to 113 g carbon m^{-2} yr^{-1}. Schlesinger (1991 and this workshop) reported that the long-term soil carbon accumulation rates for newly formed land surfaces (e.g., mudflows, retreating glaciers) is 2.4 g carbon m^{-2} yr^{-1}. For soils that have lost some, but not all, of their native carbon, the accumulation or reaccumulation rate may be greater. Jenkinson (1991 and Appendix D) reports that carbon reaccumulation in soils that were carbon depleted by long-term continuous agriculture but were abandoned, allowing a mixed deciduous forest to naturally regenerate, have soil carbon accumulation rates on the order of 25 - 50 g carbon m^{-2} yr^{-1}. Ariel Lugo (this workshop) reported soil carbon accumulation rates in managed tropical systems as high as 120 g carbon m^{-2} yr^{-1}.

If a soil, having an initial carbon density of 8,000 g carbon m^{-2} was brought into agricultural production with conventional cultivation and loses, on average, 40 g carbon $m^{-2}yr^{-1}$, after 50 years the soil would have lost 2,000 g carbon m^{-2} (25% of the initial carbon). If after 50 years of conventional cultivation this soil is now managed using conservation tillage practices that instead of losing soil carbon, accumulate it at a rate of 10 g carbon $m^{-2}yr^{-1}$, it would take 200 years to reaccumulate the lost carbon. This assumes that the accumulation rate stays constant over the entire 200 years, which is not likely because accumulation rates tend to slow as the soil carbon carrying capacity is neared. This simple example emphasizes the fact that soil carbon is much easier to lose than it is to accumulate. In terms of carbon sequestration, it is therefore best to manage soils to minimize carbon losses rather than allow the carbon to be lost then to try to restore it.

The current amount of cropland is estimated to be 1.5 billion hectares (World Resources Institute, 1990) and provides an opportunity to implement management practices on a vast amount of currently managed land for carbon sequestration in soils. Additionally, degraded soils could also be managed to sequester additional carbon. Previous estimates of the amount of degraded land and the severity of degradation are highly uncertain. Efforts are underway, however, to obtain more reliable global estimates (Oldeman, 1990). When the amount and condition of this land is know, accurate estimates of the carbon sequestration potential can be made. UNEP (1986, UNEP is the United Nations Environment Program) estimated the amount of degraded land to be about 2 billion hectares, or 15% of the earth's land surface area. If both the land currently in cultivation and degraded lands were managed to accumulate carbon at 2.4 g carbon m^{-2} yr^{-1} they would accumulate only about 0.08 Pg carbon annually, or about three percent of the annual atmospheric increment (currently estimated to be 3 Pg carbon per year). If the average accumulation rate was 30 g carbon m^{-2} yr^{-1}, then the annual accumulation rate would be in excess of 1 Pg of carbon, or a third of the annual atmospheric increment. The feasibility of sequestering this amount of carbon in soils needs further evaluation.

Loss of Soil Carbon

Because soil carbon is susceptible to oxidation, soils are not permanent repositories for carbon. They are, however, stable reservoirs for carbon that is in equilibrium with ambient conditions. Changes in these conditions can lead to a shift in the amount of carbon stored, including loss to the atmosphere. Houghton et al. (1983) reported that land use changes in the past two centuries have released more carbon from terrestrial systems, including soils, than fossil fuel burning during the same period. These land use changes include forest harvesting, conversion of forests to agriculture, and expansion of agriculture to meet growing world food and fiber demands. One of the concerns associated with global warming is that even a slight increase in soil temperature could release a great deal of carbon to the atmosphere.

Soil carbon levels are maintained by continuous inputs of new carbon. Tillage practices, such as plowing, accelerate organic matter oxidation through the mixing and stirring of the soil. There is rapid loss of soil carbon in the first 20 to 30 years of cultivation, with losses of soil carbon ranging from 30 to 50% in the uppermost soil horizons and somewhat less in the lower horizons (Schlesinger, 1985; Balesdent et al., 1988). Mann (1986) also reported the rapid initial loss of soil carbon with cultivation, and also reported that the extent of loss is related to the starting levels of carbon. Soils initially high in carbon, lost at least 20% of their carbon during cultivation, while soils very low in carbon actually gained some with cultivation. Soil carbon is also lost by erosional processes. It has been estimated (this workshop) that up to 50% of eroded soil carbon is oxidized.

There may be natural limits to the amount of carbon that can be lost from soils. This limit may be due to increases in the carbon to nitrogen ratio (C/N) of the organic residues. Organic matter with high C/N ratios may be a poor quality substrate for decomposer organisms (limited nitrogen availability). Substrate quality may also be related to the presence of specific organic molecules, such as phenolics, or to the presence of toxic metals such as aluminum that decrease the quality of the material.

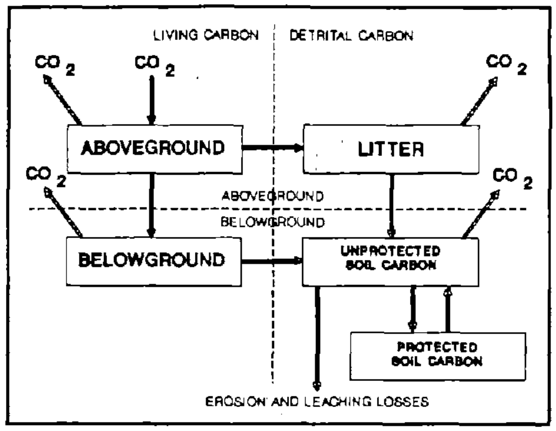
Conceptualizing and Quantifying Soil Carbon Pools

To predict how carbon cycles through soils it is essential to be able to characterize the various forms of soil carbon. There is a real need to better understand the dynamic nature (residence times) of soil carbon and the factors that control the partitioning between forms. For decades soil scientists have tried to characterize various carbon fractions and have generally relied upon a host of extraction methods to quantify these fractions (Stevenson and Elliot, 1989). For some applications the extractable forms of carbon are useful but they are not useful for describing the dynamic character of soil carbon.

A number of conceptual models have been developed to depict the dynamic properties of soil carbon. Parton (Parton et al., 1987 and this workshop) designates three pools of soil carbon with increasing resistance to biological decomposition. One is the "active" pool with a short turnover time (1 to 5 years). Another is the "slow" pool with intermediate turnover times (20 - 40 years). Third is the "passive" pool with the longest turnover times (200 to 1,500 years). Similarly, Michael Beare (this workshop) has proposed three soil carbon pools; an "active unprotected" pool, an "active protected" pool, and a "passive" pool. The two active pools are associated with soil aggregation with the unprotected pool of carbon being more labile than the other two pools.

John Duxbury (this workshop) proposed four pools. First is an "active" pool, that is readily oxidizable and is controlled by residue inputs and climate. Second is a pool of "slowly oxidized carbon" that is associated with soil macroaggregates. Because tillage affects the size distribution of aggregates--tending to decrease the number of macroaggregates, this pool can be affected by management. Third is a pool of "very slowly oxidized carbon". This is the pool of carbon associated with soil microaggregates and is not likely to be affected by management unless management somehow completely destroys soil structure. Fourth, is the "recalcitrant" pool. This pool of carbon is not accessible to decomposers and is either intercalated between clay platelets or adsorbed on platelet surfaces. Because this fraction relies upon physico-chemical interactions, it is not easily managed.

There is some uncertainty associated with operationally defined soil carbon pools. Even though there is evidence to support each of the conceptual models of soil carbon proposed above, direct methods for quantifying these pools are still being developed. It was generally agreed that there are at least two distinct pools of soil carbon, protected (from oxidation) and unprotected and that further delineations are possible. It was also agreed that efforts need to be made to arrive at a widely acceptable and applicable definition of soil carbon pools that reflects the true dynamic nature of soil carbon and that these pools must be related to the processes that are responsible for soil carbon activity. Methods to measure these pools need to be developed concomitantly.



Simplified conceptual model of carbon pools and fluxes in terrestrial systems.

Forecasting Soil Carbon Dynamics

It has been recognized for sometime, and was reiterated at the workshop, that to successfully model the flow of carbon in soils, the dynamic nature of soil carbon has to be reflected in the designated carbon pools or fractions. Simulation models of soil carbon dynamics under various climatic and management regimes can provide very useful information. The usefulness of the forecasts will depend upon the amount of realism included in the model. Equally important is the partitioning and retention time of the various carbon pools from which and into which carbon flows. Several mathematical models have been developed for predicting the behavior of soil carbon. These include the models of van Veen et al. (1984), Jenkinson et al. (1987), and Parton et al. (1988). Each of these was developed for agricultural applications and has been used successfully. Bill Parton (this workshop) used his CENTURY simulation model to simulate the effects of different agricultural management practices on soil carbon demonstrating its utility as a heuristic tool. There is a need for the development of a model of soil carbon dynamics in tropical, temperate, and boreal forests.

Unknowns

Because of the magnitude and diverse nature of soils there remains some uncertainty in the estimates of global soil carbon. It is unlikely that these uncertainties will be reduced or eliminated without collection of additional data. One of the weaknesses of existing soil carbon databases is the lack of information on soil bulk density and the amount of coarse soil fragments (stones etc.). Without these, it is not possible to accurately calculate soil carbon pool sizes (Schlesinger, 1985).

At steady-state the exchange of carbon between pools is balanced--e.g., terrestrial fixation is equal to terrestrial oxidation. However, with the injection of large amounts of carbon into the atmosphere from fossil fuel burning and deforestation, the exchange of carbon between pools is unbalanced with yet unknown consequences. Because of the dynamic nature of the carbon cycle, the system will readjust to achieve a new balance. Elevated atmospheric CO_2 can cause greater net primary production, thereby sequestering, through photosynthesis, additional atmospheric carbon. Because of their size, the oceans are a likely sink for some of the fossil fuel CO_2. A recent analysis by Tans et al. (1990), however, suggests that the oceans are not as large of sinks as once believed and that a larger amount of CO_2 is absorbed instead by terrestrial ecosystems including plants and soils. The magnitude of the carbon that is unaccounted for is about 2 - 3.4 Pg (Tans et. al., 1990) representing about 4% of terrestrial net annual primary production (62 Pg/2.7 Pg) and about 3% of the annual exchange of carbon between the oceans (100 Pg/2.7 Pg) and the atmosphere. If terrestrial systems in northern temperate regions are the sink for this missing carbon, as suggested by Tans et al. (1990) then it seems that would be possible to locate the increased carbon sequestration in these areas. But as Post et al. (1990) point out, current methods of estimating global carbon pools and fluxes cannot detect such small annual fluxes. So it is unlikely that the sink for this carbon will be explicitly identified. It seems, however, that the long-term accumulation of 2 - 3.4 Pg per year over the past 100 years should be simple to locate.

In general, soil carbon accumulates slowly, but because of past management, soils have lost large amounts of carbon. If soil temperatures warm appreciably the net effect is likely to be the efflux of carbon from the soil. The amount of carbon released into the atmosphere will depend upon the extent of warming and the distribution of precipitation. Modeling is one tool that can be used to project the effects of various climate change scenarios on the sequestration of carbon in soils. There is a need to identify soil carbon pools that reflect the dynamic nature (retention time) of soil carbon and to develop direct methods for measuring these pools. If these can be accomplished, the predictive capability of currently existing models will be enhanced.

5. MANAGING SOIL CARBON

Managing the terrestrial biosphere to sequester additional atmospheric carbon is a potential measure to aid in mitigating global warming and climate change. Because soils are the largest terrestrial reservoir of cycling carbon, a component of the terrestrial biosphere, and are a potential sink for atmospheric carbon, a large part of this workshop was used to consider how soil management could lead to increased carbon sequestration in soils.

TABLE 2: SOIL CONDITIONS AND MANAGEMENT PRACTICES THAT PROMOTE CARBON ACCUMULATION IN SOILS

Soil Change	Practice	Applications
Cooler soil	Mulch, shade	All soils
Wetter soil	Irrigation	Dry regions
Increase Fertility	Fertilizer	Most soils
Raise subsoil pH	Deep liming	Acid subsoils
Reduced aeration	Limited tillage	All soils

(source S.W. Buol and UNEP)

Workshop participants agreed that soil management affects the amount of carbon sequestered in soils. In general, past management was not aimed at carbon sequestration but often capitalized on the native fertility of soils. This type of land use, or management, has led to the loss of massive amounts of soil carbon in the last century (Houghton et al., 1983). Houghton and Skole (1990) report that between 90 and 120 Pg of carbon has been lost to the atmosphere for the interval between 1850 and 1980 just from changes in land use--a significant portion of this coming from soils. Data was presented at the workshop demonstrated that with proper management the carbon content of many soils can be increased. An important observation is that management plays an important role in determining whether a soil will be a source of atmospheric carbon or a sink for atmospheric carbon.

Carbon Sequestration in Soils

The objectives of managing soils to sequester carbon are to increase the amount of carbon entering the soil and to decrease the amount leaving either through decomposition or erosion. If soils in wet cool climates accumulate carbon then it follows that management practices that produce wetter or cooler soils will promote the accumulation of carbon. Stan Buol (see presentation summary in Appendix B) presented a number of soil conditions that promote the accumulation of carbon and management practices that can be used to bring about the desired changes [Table 2]. Buol's list of soil conditions that favor carbon accumulation are shown in the accompanying table.

Carbon Carrying Capacity

Every soil has a carbon carrying capacity that is determined by soil characteristics, vegetation, and climate. If left undisturbed in a stable climate, soils will realize their carbon carrying capacity. If disturbed, they are likely to loose carbon rapidly. Worldwide, a large portion of the earth's lands have been degraded resulting in the loss of soil carbon (Oldeman et al., 1990). With time and the proper inputs, the carbon carrying capacity in these soils may once again be realized. It is also possible to increase the capacity of some soils to store carbon. Returning soils to their native carbon carrying capacity and then increasing that storage capacity may create considerable sinks for atmospheric carbon.

Decomposition

Decomposition is a microbially mediated process that breaks down plant residues and produces CO_2 as a waste product. Plant residues are the substrate, or energy source, that fuels decomposition. Without substrate soil microbial biomass decreases rapidly. The quality of the substrate is also important to decomposing organisms. High C/N ratios, or the presence of phenolic organic compounds may be indicators of poor substrate quality. Changes in the composition of the atmosphere, principally CO_2, may have direct effects on the quality of plant residues, and indirectly affect the decomposition of the residue by microbes.

In addition to substrate quantity and quality affecting decomposition, soil temperature and moisture content also constrain decomposition. Decomposition is slow in cool wet (low available oxygen supplies for microbial respiration) soils and rapid in warm, moist, aerobic soils. In warm and very dry climates decomposition is slow because soil microbial activity is limited by droughty conditions.

Temperature Effects

Temperature is an important environmental control on soil carbon. As temperature goes up so does the rate of decomposition. That is why cooler soils tend to have more carbon. It was reported at the workshop (S.W. Buol) that the crucial element for carbon sequestration belowground is the maximum temperature and not the mean. To manage soils for maximum carbon storage extremely high temperatures should be avoided. Mulching or using vegetation to shade soils are effective methods for reducing extreme soil temperatures. In terms of storing soil carbon, dryland fallowing--the practice of leaving semi-arid agricultural lands bare in alternate years to accumulate sufficient soil moisture to grow a crop every other year, should also be avoided because during the fallow years the temperatures of the bare soil can be very high. The use of cover crops or crop rotations may simultaneously achieve the same soil water objectives and reduce soil temperatures.

Soil Fertility

Soil fertility is essential for primary production and is therefore key to sequestering carbon in soils. To sequester carbon in soils fertility problems need to be identified and corrected. Soils that have lost carbon or that are naturally low in fertility have the potential to store carbon through improved fertility. While this is a general guideline there are circumstances that improving soil fertility could lead to increased emission of greenhouse gases. Increased nitrous oxide (N_2O) emissions from microbially mediated soil processes (nitrification and denitirification) may result from the application of nitrogen fertilizers (Bouwman, 1990; van Breemen and Feijtel, 1990). Per molecule, the radiative forcing effect of N_2O is about 200 times greater than CO_2 (U.S. Congress, 1991).

Another fertilization issue was raised by Dale Johnson in his presentation. It concerns the long-term effect of fertilization and carbon sequestration. Forests tend to be nitrogen limited, i.e., there is a measurable response to nitrogen fertilization, yet the response is short-lived. That is, for several years following nitrogen fertilization forests are more productive but their productivity soon returns to that prior to fertilization. This is because nitrogen is lost from the system either through volatilization or leaching as nitrate. Fertilization with other nutrients such as phosphorous, potassium, calcium, or magnesium should have a much longer lasting effect on system productivity because these nutrients are relatively immobile. In forested systems these nutrients are more likely to have a positive effect on soil carbon because they cycle in place. Nitrogen in organic forms, either from municipal wastes or from nitrogen fixing plants, may have a more permanent effect because the nitrogen is in a form which is less slowly released and less likely to be lost from the system. It is also likely that nitrogen fertilization could stimulate soil microbes and promote the decomposition and loss of soil carbon.

Soil Aggregation

The degree of aggregation of soil particles into larger particles or aggregates, and the stability, of these aggregates are becoming important indicators of agricultural soil condition (Beare, this workshop). Macroaggregates are associated with greater soil carbon contents. Loss of macroaggregates and an increase in less stable microaggregates are indicative of soils that have been degraded through cultivation. Aggregation is not solely a function of carbon content. Other factors such as soil particle size distribution and clay mineralogy also relate to aggregate formation and stability. Management practices that result in improved aggregate stability are likely to be those that also promote the accumulation of carbon in soils. Michael Beare (this workshop) also showed that inhibiting soil-building fungi with fungicides decreased the amount of water stable aggregates. This emphasizes the need for the judicious use of chemicals and fertilizers because of negative effects that could reduce carbon sequestration in soils.

Agricultural Systems: Temperate and Tropical

The amount of organic carbon in soils is a function of the quantity and quality of carbon inputs and subsequent losses through decomposition and erosion. Soil carbon is also a function of soil chemical and physical properties. Increasing the inputs of carbon to soils can increase the amount of carbon sequestered in soils. Minimizing soil mixing and warming will slow decomposition.

Converstion of native prairie soils and forested soils to conventional agriculture significantly depletes soil carbon (Jenny, 1980; Coleman et al., 1984; Mann, 1986). Managing agricultural soils to conserve and store carbon requires the use of conservation tillage practices to minimize soil disturbances, and the incorporation of crop residues into the soil to increase carbon inputs to the soil. Soil temperature is positively related to decomposition. The use of mulches or cover crops reduce soil temperatures, thereby reducing soil carbon losses.

In general, soils have not been managed to retain or conserve carbon. Economics, as measured by crop yields and forest productivity, has been the common metric driving agricultural and forest system management, but soils are an important, but often overlooked, component in the production equation. In addition to being an important carbon reservoir, organic carbon in soils is important for maintaining the productivity of soils. Organic carbon contributes to soil productivity by promoting soil aggregation; absorbing and holding water; serving as a natural reservoir of plant nutrients; minimizing wind and water erosion; and providing exchange sites for plant nutrients.

Forested Systems: Temperate and Tropical

Historically, forests have not been managed to store soil carbon. There are mixed reports in the literature on the effects of tree harvesting on soil carbon. In general, when forests are harvested and the inputs of carbon from vegetation stop, soil carbon decreases (Edwards and Ross-Todd, 1983; Houghton et al., 1983). There is usually a lag between harvesting and a measurable decrease in soil carbon. Initially, there may be an increase in microbial biomass associated with the nutrient inputs from slash but total carbon decreases.

Slash-and-burn agriculture (shifting cultivation) and the conversion of forests to agriculture dramatically alter the inputs of carbon to soil. In slash-and-burn agriculture, cleared lands are farmed for several years then abandoned. Eventually these lands naturally return to forests and the net effect on soil carbon is usually small (Nair, 1984). With increasing world population there increased pressure to extend the period of time that these systems are kept in the cultivation part of the cycle because the per capita area of land available is decreasing and can no longer support the number of people participating in shifting cultivation (U.S. Congress, 1991). Increasing the frequency and duration of cultivation, the greater the net loss of soil carbon. Long-term conversion of forests to conventional agriculture, as done in the Southeastern U.S. (Delcourt and Harris, 1980), can result in the depletion of soil carbon. If cleared lands are turned into pastures the carbon content of the soils may increase because grasses distribute carbon deeper into soils because of their rooting habit. With the loss of the massive amounts of carbon in aboveground biomass from tree harvesting the net carbon storage in the system is decreased.

When removing forest slash by burning, a portion of the material is converted to charcoal. Charcoal is found in many soils and is evidence of past fires (Sanford et al., 1985). Shiffman and Johnson (1989) report that charcoal is a very stable form of carbon and may remain unoxidized for thousands of years. They also estimate that the forest floor in forest plantations where the slash is burned after harvesting can be 30% charcoal. Burning slash is not always the best management practice because hot burns can damage the soil and slow forest regeneration. Workshop participants also noted that fine particles of carbon can be translocated by the movement of soil water deep into soil profiles.

Although forest management is markedly different than agricultural management, the principles of minimizing soil disturbance and taking steps to lower soil temperatures are still applicable for conserving carbon in forested soils. The removal of forest cover results in increased oxidation of soil carbon through increased soil temperatures, particularly in large exposed clear-cuts. Soil disturbances associated with forest harvesting also contributes to the net loss of soil carbon. Implementing management practices that minimize soil disturbance during forest harvesting and providing soil mulches following harvesting will conserve soil carbon in forested soils.

Forest fertilization is one practice that could increase the amount of primary production in forests that could translate into increased belowground carbon sequestration. Forests are often growing with some nutrient limitations, such as nitrogen, and will respond to inputs of limiting nutrients. For nitrogen the response may be transient because nitrogen can be lost through leaching or volatilization. The effects of applying other nutrients such as phosphorous or potassium should be long-lasting because these nutrients are relatively immobile and remain in the forest system. A potential source of low-cost forest fertilizer may be municipal, animal, industrial, or food processing wastes.

Agroforestry is the deliberate mixture of trees with crop and animal production systems with the objective that the net benefit of combining these two systems will be greater than if the systems were operated independently (Nair, 1984). The losses of soil carbon from agroforestry may be less than from conventional tillage in the tropics. Shading of crops is one advantage of combining agriculture and forestry because it lowers temperatures, thus reducing the potential of soil organic matter decomposition.

Unknowns

There are a variety of management options in both agriculture and forestry that can conserve soil carbon and may lead to increased belowground carbon sequestration. It is important to evaluate each management application in terms of carbon benefit prior to implementation. For instance, conservation tillage can lead to increased soil carbon levels in soils that have been managed with conventional tillage in the temperate region. However, if the total carbon cost of conservation tillage is measured, including the carbon costs of manufacturing and shipping the additional herbicides that will be needed for weed control, is conservation tillage leading to more sequestered carbon? Questions like this need to answered. Also what is likely to be the long-term effect of increased carbon inputs to soils? Will the microbial biomass sequester essential nutrients when they are needed by crops? Will yields drop?

Managing soils to store carbon is not necessarily a "no regrets" environmental policy and will not be accomplished without some costs. There are potential negative consequences that should be considered like the potential release of nitrous oxide. The release of other gaseous decomposition products from mulching, such as ethylene, may affect seed germination. There will be societal costs as well. Will people be willing to pay more for food and wood products because production costs have increased? If society is unwilling to bear those costs then managing systems to store carbon is not likely to succeed.

6. STRATEGIES FOR MANAGING SOIL CARBON AT THE GLOBAL SCALE

Based upon the size of the soil carbon reservoir and the ease with which carbon can be lost from soils, there was a workshop consensus that a proactive effort is needed to protect and preserve this very large pool of carbon. Workshop participants also determined that soils could store additional carbon, but they could not definitively conclude whether or not the storage of new carbon in soils would be sufficient to offset atmospheric increases in carbon or to mitigate global warming. It was debated and finally concluded that soils should be managed to optimize carbon sequestration and storage.

SOIL CARBON MANAGEMENT STRATEGIES

- Manage to MAINTAIN the global soil carbon pool
- Manage to RESTORE carbon to carbon-depleted soils
- Manage to ENLARGE the global soil carbon pool

It is important to distinguish between maintaining soil carbon stocks and managing soils to sequester additional carbon. Maintaining the integrity and size of the soil carbon pool is primarily to prevent soils from being a net source of atmospheric carbon. Taking steps to preserve soil carbon implicitly acknowledges that it is more difficult to restore or raise soil carbon levels..

Workshop participants identified three general soil carbon management strategies to optimize carbon sequestration and storage: (1) maintain the global pool of soil carbon, (2) restore carbon in carbon-depleted soils, and (3) enlarge the size of the global soil carbon reservoir. These are described below and followed by a section describing specific management practices that the workshop participants determined would be important for achieving the soil management goals. Three lists of management practices were developed, one for each of the soil carbon management strategies. The practices were ranked by the workshop participants to delineate the perceived benefit of implementing these practices. These practices are primarily intended for use in managed forest and agricultural systems but may be applicable to other systems. At the time of the workshop, data were not available to quantify the amount of carbon that could be sequestered by implementing these practices.

MAINTAINING THE GLOBAL POOL OF SOIL CARBON

Because soils are the largest terrestrial pool of active carbon and because a large portion of this carbon is potentially released to the atmosphere through human activities, workshop participants recommended that management practices be implemented to preserve the size and integrity of the pool. Managing soils to maintain their current carbon levels recognizes that soil carbon is labile and is lost to the atmosphere relatively easily when the soil is mixed and stirred as in conventional agricultural systems. It also recognizes that it takes more time to raise soil carbon levels than it does to lose soil carbon. Workshop participants concluded that it is better to protect soil carbon before it is lost, than it is to allow it to be lost and then try to restore it. A significant loss of soil carbon to the atmosphere could exacerbate global warming.

Management Practices to Maintain Soil Carbon Levels

The management practices described below were identified by the workshop participants as those that could be used to maintain the amount of carbon in soils.

- **Maintain Soil Fertility:** Sustained inputs of carbon to soils from primary production are essential for maintaining current levels of soil carbon. Interruption of these carbon inputs results in loss of soil carbon by the readjustment of the soil system to a lower equilibrium level of soil carbon. Maintaining soil fertility helps sustain primary production, which in turn helps to sustain the input of carbon belowground and the sequestration of carbon in soils. [High Priority]

- **Concentrate Tropical Agriculture:** Concentrating or intensifying tropical agriculture is aimed at preventing tropical deforestation and the soil carbon loss associated with it, and thereby maintaining the existing stocks of soil carbon. Concentrating tropical agriculture is the practice of directing resources and management for use only on the best agricultural lands. The intended outcome is that less land will be needed to produce the same, if not more, volume of agricultural products. In achieving this, the need for slash-and-burn agriculture (deforestation) is diminished and the carbon losses associated with it. [High Priority]

- **Preserve Natural Wetlands:** The inundated soils in wetlands contain a great deal of carbon that has a very long retention time if undrained. The practice of draining these systems, primarily for agrarian purposes, results in the rapid oxidation and loss of carbon to the atmosphere. Preserving wetlands insures the carbon storage function of these lands. [High Priority]

- **Increase Efficiency of Forest Product Use:** Increasing the efficiency of forest harvesting (by reducing waste) and increasing the life-span of forest products (including recycling) is aimed at reducing the demand for forest harvesting. Reducing forest harvesting, or increasing the interval between harvests, will help to maintain the large above- and belowground carbon stocks in the world's forests. [High Priority]

- **Conservation Tillage:** Conservation tillage is the agricultural practice of retaining crop residues on-site and reducing the number or severity of soil physical manipulations used to prepare seedbeds, control weeds, and apply fertilizer, thereby diminishing the loss of soil carbon as compared to conventional tillage practices that result in the loss of soil carbon. Conservation tillage includes the practices of either minimum tillage or no-tillage and farming along the contour of the land. [Medium Priority]

Agricultural and Forestry Practices to Maintain Soil Carbon

Management Practice	Priority[a]
Maintain Soil Fertility	H
Concentrate Tropical Agriculture	H
Preserve Natural Wetlands	H
Increase Efficiency of Forest Product Use	H
Retain Forest Slash on Site	M
Minimize Site Disturbance	M
Use Prescribed Burns to Maximize C Storage	M
Control Erosion	M
Mulching	M
Leave Crop Residues	M
Minimum Tillage	M
Incorporate Crop Residues	L

[a]Relative Priority: H = High, M = Medium, L = Low

- **Retain Forest Slash on Site:** Forest harvest residues are an important source of nutrients for successive rotations as well as an important post-harvest source of soil carbon. Often these residues are either removed or burned to expedite and reduce the cost of replanting. Removing slash removes nutrients that help to get the next rotation of trees established. Burning may cause nitrogen to be lost from the system by volatilization. If hot enough, burning can damage the soil resulting in future decreases in system productivity. Burning may also leave the soil bare, making it more susceptible to erosion, particularly in humid regions on steep slopes. Leaving residues on site may make it more difficult and more expensive to replant, but because of increased nutrient availability, lower soil temperatures, and increased water availability, rotations may become established more quickly and be more productive while conserving soil carbon. [Medium Priority]

- **Minimize Site Disturbance:** Extensive use of ground systems during forest harvesting may compact or disrupt large portions of the soil in the harvest areas. Likewise, yarding or skidding logs to landings can compact and expose the mineral soil. This can reduce the productivity of the site and promote the loss of soil carbon by oxidation or through erosion. Harvest and management practices that minimize or eliminate site disturbance will help maintain the productivity of the forest system and conserve soil carbon. [Medium Priority]

- **Use Prescribed Burning to Maintain Carbon Storage in Soils:** Burning has been used for centuries as an effective method for removing slash following a forest harvest or in shifting agriculture. Hot slash burns (i.e., hot dry, windy weather with dry slash) may severely damage the soil and affect the productivity of the system. These burns can even combust soil carbon and should be avoided. If burning is required, lighter burns (i.e., in cool wet weather) will be less damaging overall to the system and make it easier for the ecosystem to transition through harvesting to a new forest. Changing the way slash is burned may, in some situations, increase rather than decrease, the potential for a site to sequester and store carbon. Burning will convert some of the slash to charcoal, effectively sequestering the carbon for thousands of years. [Medium Priority]

- **Control Erosion:** Controlling soil erosion is intended to protect the soil resource. The surface layer of soil or topsoil is generally more fertile and has better water holding characteristics than the lower soil horizons. Because of its proximity to wind and rain, topsoil is the most likely part of the soil to be physically eroded. Physical loss or degradation of the soil resource diminishes primary production and consequently, carbon sequestration belowground. [Medium Priority]

- **Mulching:** The rate of soil organic matter decomposition is positively related to soil temperature. Mulching or using plant residues to cover the soil reduces extreme soil temperatures, thereby slowing decomposition, resulting in the retention of more carbon in the soil. [Medium Priority]

- **Leave Crop Residues:** Crop residues are an important source of carbon and nutrients in agricultural systems. Leaving crop residues helps to maintain soil carbon levels by maintaining the input of carbon to the soil and by serving as a mulch that reduces soil temperatures. [Medium Priority]

- **Incorporate Crop Residues:** Incorporating crop residues into the soil slows its decomposition and insures that more of the residue decomposition products remain in the soil, thereby helping to maintain soil carbon levels in agricultural soils. Residue incorporation improves soil water holding and infiltration characteristics, and in the tropics, prevents insects from removing the residue. [Low Priority]

RESTORING SOIL CARBON IN CARBON-DEPLETED SOILS

An opportunity exists to restore carbon in soils that are depleted in carbon due to management. Worldwide, there may be millions of hectares of unproductive forest land or abandoned agricultural lands that could store additional carbon. Management practices that bring these once productive lands back into primary production will lead to increased carbon sequestration above- and belowground. Soils that are the most carbon depleted will require more inputs to bring back their carbon sequestration potential. The long-term objective of this strategy is to restore soil carbon to previous levels.

Management Practices to Restore Carbon in Carbon-Depleted Soils

It was the consensus of the workshop participants that soils somewhat depleted in carbon offer the greatest potential for sequestering additional carbon because their carbon accumulation rates are much faster than soils approaching their carbon carrying capacity. Worldwide, the extent of soils that have lost carbon appears to be great (Oldeman et al., 1990). The management practices described below were identified as those that would be useful for restoring soil carbon to previous levels. The amount of carbon that can be sequestered by implementing these is, however, currently unknown.

- **Reforestation:** Large-scale reforestation has the potential to sequester and store large amounts of new carbon both above- and belowground, particularly on carbon-depleted soils. Some deforested areas will regenerate naturally while others will only require new tree planting. Others will require intensive management and large inputs of resources. [High Priority]

- **Improve Soil Fertility:** Soils that are carbon depleted are also likely to lack some other soil nutrients, which may limit primary production. Improving the fertility of these soils to support vegetation is key to restoring carbon in these soils. [High Priority]

- **Use Municipal, Animal, Industrial and Food Processing Wastes:** Restoring carbon in carbon-depleted soils may be limited by the lack of plant nutrients needed for primary production or by the cost of fertilizer to replenish nutrients. Municipal, animal, industrial, and/or food processing wastes may be ideal sources of low-cost forest fertilizers. Using them in forests or in agriculture, particularly on marginal lands, can provide water and essential nutrients to vegetation, thereby promoting a higher level of primary production and above- and belowground carbon sequestration. [High Priority]

Agricultural and Forestry Practices for Restoring Carbon in Carbon-Depleted Soil

Management Practice	**Priority**[a]
Reforestation	H
Maintain or Improve Soil Fertility	H
Use Municipal, Animal, Industrial and Food Processing Wastes as a Source of Low-Cost Fertilizer	H
Concentrate Tropical Agriculture	M
Remove Marginal Lands From Intensive Agricultural Production	M
Control Erosion	M
Urban Forestry	L

[a]Relative Priority: H = High, M = Medium, L = Low

- **Concentrate Tropical Agriculture:** Concentrating or intensifying tropical agriculture is aimed at preventing tropical deforestation and the soil carbon loss associated with it, and thereby maintaining the existing stocks of soil carbon. Concentrating tropical agriculture is the practice of directing resources and management for use only on the best agricultural lands. The intended outcome is that less land will be needed to produce the same, if not more, volume of agricultural products. In achieving this, the need for slash-and-burn agriculture (deforestation) is diminished and the carbon losses associated with it. The low-productivity lands removed from shifting agriculture by concentrating tropical agriculture can be reforested or revegetated, thus sequestering carbon in biomass and initiating the natural process of restoring soil carbon. [Medium Priority]

- **Remove Marginal Lands from Intensive Agricultural Production:** Marginal lands are usually steep and prone to erosion. They also tend to be naturally infertile and are not well suited for agricultural production. With low-cost fuel and fertilizer they have been brought into agricultural production, but cultivation of these lands has resulted in depletion of soil carbon stocks. By removing these lands from intensive agricultural production, they can be reforested or revegetated to sequester carbon in above- and belowground biomass and restore soil carbon to previous or near previous levels. [Medium Priority]

- **Control Erosion:** Physical loss or degradation of the soil resource diminishes primary production and consequently, carbon sequestration belowground. By controlling soil erosion and preventing loss of the soil resource, they can be used to support vegetation and sequester carbon belowground. [Medium Priority]

- **Urban Forestry:** An opportunity exists, albeit small, in urban areas to use small forests and individual trees to capture and store carbon in above and belowground biomass and as soil carbon. The objective is to restore soil carbon that has been lost because of the urban land use. Additional societal benefits of urban forestry include: recreation, lower urban temperatures, and air purification. Lower urban temperatures during the summer months will reduce air-conditioning usage, thereby conserving the carbon that would otherwise be used to run urban air-conditioners. [Low Priority]

ENLARGING THE SIZE OF THE GLOBAL SOIL CARBON RESERVOIR

The objective of this strategy is to manage forested and agricultural systems in ways that increase their productivity and their allocation and storage of carbon belowground. The essential aim of this strategy is to increase the carbon carrying capacity of soils. Most of the opportunities to enlarge this pool may be in agriculture because agricultural systems are generally more intensely managed than forested systems. Workshop participants surmised that the marginal return, measured in terms of stored carbon, would probably be greater by implementing management practices aimed at "maintaining" and "restoring" soil carbon than by attempting to enlarge the global pool of soil carbon.

Agricultural and Forestry Practices for Enlarging the Global Pool of Soil Carbon

Management Practice	Priority[a]
Minimum Tillage	H
Improve Soil Fertility	H
Concentrate Tropical Agriculture	H
Minimize Dryland Fallowing	H
Retain Forest Slash on Site	M
Leave Crop Residues	M
Incorporate Crop Residues	M
Remove Marginal Lands From Intensive Agricultural Production	M
Use Municipal, Animal, Industrial and Food Processing Wastes as a Source of Low-Cost Fertilizer	M
Mulching	M
Control Erosion	L

[a]Relative Priority: H = High, M = Medium, L = Low

Management Practices for Enlarging the Global Soil Carbon Reservoir

- **Conservation Tillage:** In the context of enlarging global soil carbon stocks, widespread implementation of conservation tillage practices could lead to additional sequestration of carbon in soils. Implementing conservation tillage practices implies that the use conventional tillage practices will decline, thus reducing the oxidative loss of soil carbon. [High Priority]

- **Improve Soil Fertility:** Lack of nutrients often limits primary production. Eliminating or reducing nutrient limitations will improve primary production leading to greater sequestration of carbon in soil. [High Priority]

- **Concentrate Tropical Agriculture:** By concentrating tropical agriculture, lands removed from shifting agriculture can be reforested or revegetated, leading to increased soil carbon stocks. [High Priority]

- **Minimize Dryland Fallowing:** Fallowing is the practice of leaving semi-arid agricultural lands bare in alternate years to accumulate sufficient soil moisture to grow a crop every other year. Dryland fallowing is a widely used agricultural practice. There is gathering evidence that this practice promotes the loss of soil organic carbon because the soil is usually kept bare by mechanical means. This stirring and mixing of the soil combined with increased soil temperatures, due to lack of cover, results in rapid and thorough oxidation of organic carbon. Use of cover crops or crop rotations may achieve the same soil water objectives and eliminate the need to fallow. [High Priority]

- **Retain Forest Slash on Site:** In the context of enlarging stocks of soil carbon, retaining forest slash on site following forest harvesting is aimed at retaining nutrients and water to promote the re-establishment of new forest vegetation as quickly as possible. If the cycle of burning or removing residues is interrupted, soil carbon stocks will not only be maintained but potentially increased. [Medium Priority]

- **Leave Crop Residues:** Crop residues are an important source of carbon and nutrients in agricultural systems. Leaving crop residues may help to increase soil carbon levels by increasing the input of carbon to the soil and by serving as a mulch that reduces soil temperatures. This is an important component of conservation tillage. [Medium Priority]

- **Incorporate Crop Residues:** Incorporating crop residues into the soil slows its decomposition and insures that more of the residue decomposition products remain in the soil thereby help to maintain soil carbon levels in agricultural soils. Residue incorporation improves soil water holding and infiltration characteristics, and in the tropics, prevents insects from removing the residue. [Medium Priority]

- **Remove Marginal Lands from Intensive Agricultural Production:** Marginal lands are usually steep and prone to erosion. They also tend to be naturally infertile and are not well suited for agricultural production. With low-cost fuel and fertilizer they have been brought into agricultural production, but cultivation of these lands has resulted in depletion of soil carbon stocks. By removing these lands from intensive agricultural production, they can be reforested or revegetated to sequester carbon in above- and belowground biomass, restore soil carbon to previous or near previous levels and potentially increase global soil carbon stocks. [Medium Priority]

- **Use Municipal, Animal, Industrial and Food Processing Wastes:** Restoring carbon in carbon-depleted soils may be limited by the lack of plant nutrients needed for primary production or by the cost of fertilizer to replenish nutrients. Municipal, animal, industrial, and/or food processing wastes may be ideal sources of low-cost forest fertilizers. Using them in forests or in agriculture, particularly on marginal lands, can provide water and essential nutrients to vegetation, thereby promoting a higher level of primary production and above- and belowground carbon sequestration. [Medium Priority]

- **Mulching:** The rate of soil organic matter decomposition is positively related to soil temperature. Mulching or using plant residues to covering the soil reduces extreme soil temperatures, thereby slowing decomposition, resulting in the retention of more carbon in the soil. [Medium Priority]

- **Control Erosion:** Controlling soil erosion is intended to protect the soil resource. The surface layer of soil or topsoil is generally more fertile and has better water holding characteristics than the lower soil horizons. Because of its proximity to wind and rain, topsoil is the most likely part of the soil to be physically eroded. Physical loss or degradation of the soil resource diminishes primary production and consequently, carbon sequestration belowground. [Low Priority]

7. WORKSHOP SUMMARY AND CONCLUSIONS

This workshop was an excellent forum for a scientific debate on the potential of soils to sequester additional carbon from the atmosphere. Two primary conclusions can be drawn from the workshop. First, that **steps should be taken to protect and preserve the size and integrity of the global reservoir of soil carbon** because continued losses of soil carbon to the atmosphere could exacerbate global warming and climatic change. Second, that **steps should be taken to manage soils and ecosystems to store additional carbon.** The latter being accomplished predominately by increasing net primary production. The major uncertainties related to carbon sequestration in soils and specific strategies for addressing these uncertainties and for managing soils to store carbon were also identified at this workshop.

Major conclusions of the workshop participants:

- Soils are an important component of the global carbon cycle, containing a large pool of active, cycling carbon. As such, they are a very large potential source of atmospheric carbon, but they also represent a large potential sink for carbon, if managed properly.

- Uncertainties exist in the success of widespread implementation of soil management practices because of the potential for the occurrence of concomitant negative effects. At some locations the associated negative effects may outweigh the positive benefits. For instance, under certain circumstances some of these practices could lead to the emission of gases (e.g., nitrous oxide) that have a greater radiative forcing than carbon dioxide. In terms of global warming, this scenario would be counterproductive. The implementation of any new or altered management practices should be considered on a site-by-site or region-by-region basis prior to implementation, and should be evaluated in terms of the effect on carbon pools and fluxes.

- Three strategies for managing soil carbon are proposed: (1) **manage soils to maintain current levels of soil carbon**, (2) **manage carbon depleted soils to restore carbon to former levels**, and (3) **manage soils to enhance the size of current soil carbon pools.** For each of these a variety of opportunities exist for capturing atmospheric carbon, via photosynthesis, and storing it in soils and aboveground biomass.

- In addition to storing carbon assimilated from the atmosphere, managing soils to conserve carbon will have other benefits. These include: (1) increased soil water holding capacity, (2) increased nutrient availability, (3) improved soil physical properties, and (4) decreased soil erosion by wind and water. Together these should lead to (5) increased food and fiber production. Managing soils to conserve carbon will help to produce more sustainable forest and agricultural systems.

The consensus on the initial workshop question "Can soils be used to store sufficient carbon to aid in mitigating global climate change?" is that we need more reliable information to provide a definite answer.

8. RESEARCH RECOMMENDATIONS

Throughout this workshop, the lack of sufficient, reliable, quantitative data, and numerous areas of uncertainty related to soil carbon were identified. Research and data gathering in identified areas will improve our quantification of global soil carbon and related processes. Here we list those topics thought to be critical for a more complete analysis of the relationship between soils and global climatic change. This list, although not exhaustive, provides guidance for research in areas that could provide valuable information or tools for evaluating the role of soils in the global carbon cycle with a focus on the potential of soils to sequester and store additional carbon from the atmosphere to mitigate the effects of global warming.

- **Define** soil carbon pools based upon lability and soil processes, and determine the factors that control the partitioning of carbon into the respective pools.

- **Identify** and characterize the specific fractions of soil carbon that are manageable and practices that are effective for managing them.

- **Improve** estimates of global soil carbon by conducting large-scale statistically designed soil surveys coupled with intensive soil sampling and physical and chemical analysis.

- **Quantify** above- and belowground carbon pools and fluxes in specific ecosystems for the purpose of developing general principles of ecosystem carbon dynamics from specific examples.

- **Characterize** and quantify the factors that control soil carbon fluxes.

- **Develop** soil carbon methods for characterizing and quantifying the true size and lability of soil carbon pools.

- **Characterize** and quantify the role of abiotic soil factors in stabilizing soil carbon.

- **Quantify** the effects of land use and management, including agricultural and forestry, on soil carbon.

- **Conduct** experiments to characterize the effects of altered climatic conditions on terrestrial plant carbon fixation and allocation, focusing on the quantity and quality of carbon in detritus and in belowground allocation.

- **Develop** simulation models that accurately project how carbon fluxes (and thus pools and feedbacks to the atmosphere) will shift in specific ecosystems under a series of altered climate scenarios.

- **Quantify** the economics of implementing soil management practices that sequester and store carbon.

LITERATURE CITED

Alexander, E.B., E. Kissinger, R.H. Huecker, and P. Cullen. 1989. Soils of southeast Alaska as sinks for organic carbon fixed from atmospheric carbon-dioxide. p.203-210. In E.B. Alexander (ed.) Proceedings of Watershed '89: A conference on the stewardship of soil, air, and water resources. USDA Forest Service, Alaska Region, R10-MB-77

Armentano, T.V. (ed.). 1980. The role of organic soils in the world carbon cycle--problem analysis and research needs. Report to the U.S. Department of Energy No.CONF-7905135. The Institute of Ecology, Indianapolis, Indiana.

Balesdent, J., G.H. Wager, and A. Mariotti. 1988. Soil organic matter turnover in long-term field experiments as revealed by carbon-13 natural abundance. Soil Sci. Soc. Amer. J. 52:118-124.

Bouwman, A.F. 1990. Exchange of greenhouse gases between terrestrial ecosystems and the atmosphere. p.62-127. In A.F. Bouwman (ed.) Soils and the greenhouse effect: Proceedings of the international conference on soils and the greenhouse effect, John Wiley and Sons, New York.

Coleman, D.C., C.V. Cole, and E.T. Elliott. 1984. Decomposition, organic matter turnover and nutrient dynamics in agroecosystems. p. 83-104. In R. Lowrance, B.R. Stinner, and G.J. House (eds.). John Wiley and Sons, New York.

Delcourt, H.R., and W.F. Harris. 1980. Carbon budget of the southeastern U.S. biota: Analysis of historical change in trend from source to sink. Science 210:321-323.

Edwards, N.T., and B.M. Ross-Todd. 1983. Soil carbon dynamics in a mixed deciuous forest following clear-cutting with and without residue removal. Soil Sci. Soc. Am. J. 47:1014-1021.

Houghton, J.T., G.J. Jenkins, and J.J. Ephraums (eds.). 1990. Policymakers Summary. p.x-xxxiii. In Climate Change: The IPCC Scientific Assessment. Cambridge University Press, Cambridge, England.

Houghton, R.A., J.E. Hobbie, J.M. Melillo, B. More, B.J. Peterson, G.R. Shaver, and G.M. Woodwell. 1983. Changes in the carbon content of terrestrial biota and soils between 1860 and 1980: A net release of CO_2 to the atmosphere. Ecological Monographs 53:235-262.

Houghton, R.A., and D.L. Skole. 1990. The long-term flux of carbon between terrestrial ecosystems and the atmosphere as a result of changes in land use. Research Project of the Month - July. Carbon Dioxide Research Program, Office of Health and Environmental Research, U.S. Department of Energy.

Jenkinson, D.S., P.B.S. Hart, J.H. Rayner, and L.C. Parry. 1987. Modelling the turnover of organic matter in long-term experiments at Rothamsted. INTECOL Bulletin 15:1-8.

Jenkinson, D.S. 1991. The Rothamsted long-term experiments: are they still of use? Agron. J. 83:2-10.

Jenny, H. 1980. The Soil Resource: Origin and Behavior. Springer-Verlag, New York.

Mann, L.K. 1986. Changes in soil carbon storage after cultivation. Soil Sci. 142:279-288.

Martel, Y.A., and E.A. Paul. 1974. The use of radiocarbon dating of organic matter in the study of soil genesis. Soil Sci. Soc. Amer. J. 38:501-506.

Nair, P.K.R. 1984. Soil productivity aspects of agroforestry. International Council for Research in Agroforestry, Nairobi, Kenya.

Oldeman, L.R., R.T.A. Hakkeling, and W.G. Sombroek. 1990. World map of the status of human-induced soil degradation: An explanatory note. International Soil Reference and Information Center, Wageningen, The Netherlands.

Parton, W.J., D.S. Schimel, C.V. Cole, and D.S. Ojima. 1987. Analysis of factors controlling soil organic matter levels in great plains grasslands. Soil Sci. Soc. Am. J. 51:1173-1179.

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

Post, W.M., W.R. Emanuel, P.J. Zinke, and A.G. Stangenberger. 1982. Soil carbon pools and world life zones. Nature 298:156-159.

Post, W.M., T.-H. Peng, W.R. Emanuel, A.W. King, V.H. Dale, and D.L. DeAngelis. 1990. The global carbon cycle. American Scientist 78:310-326.

Schlesinger, W.H. 1984. Soil organic matter: a source of atmospheric CO_2. 1984. p. 111-127. In G.M. Woodwell (ed.) The role of terrestrial vegetation in the global carbon cycle: Measurement by remote sensing. SCOPE 1984. John Wiley & Sons Ltd.

Schlesinger., W.H. 1985. Changes in soil carbon storage and associated properties with disturbance and recovery. p.194-220. In J.R. Trabalka and D.E. Reichle (eds.) The changing carbon cycle: A global analysis. Springer-Verlag, New York.

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

Stevenson, F.J., and E.T. Elliot. 1989. Methodologies for assessing the quantity and quality of soil organic matter. In D.C. Coleman, J.M. Oades, and G. Uehara (eds.) Dynamics of soil organic matter in tropical ecosystems. University of Hawaii Press, Honolulu, Hawaii.

Sanford, R.L., J. Saldarriaga, K.E. Clark, C. Uhl, and R. Herrera. 1985. Amazon rain-forest fires. Science 227:53-55.

Schiffman, P.M., and W.C. Johnson. 1989. Phytomass and detrital carbon storage during forest regrowth in the southeastern United States Piedmont. Can. J. For. Res. 19:69-78.

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

Theng, B.K.G., K.R. Tate, and P. Sollins. 1989. Constituents of organic matter in temperate and tropical soils. In D.C. Coleman, J.M. Oades, and G. Uehara (eds.) Dynamics of soil organic matter in tropical ecosystems. University of Hawaii Press, Honolulu, Hawaii.

UNEP. 1986. Farming systems principals for improved food production and the control of soil degradation in arid and semi-arid tropics. ICRISAT, Hyderabad, India.

U.S. Congress. 1991. Changing by degrees: Steps to reduce greenhouse gases. Office of Technology Assessment, OTA-0-482 Washington, D.C.

Van Breemen, N. and T.C.J. Feijtel. 1990. Soil processes and properties involved in the production of greenhouse gases, with special relevance to soil taxonomic systems. p.195-223. In A.F. Bouwman (ed.) Soils and the greenhouse effect: Proceedings of the international conference on soils and the greeenhouse effect, John Wiley and Sons, New York.

Van Veen, J.A., J.N. Ladd, M.J. Frissel. 1984. Modelling C and N turnover through the microbial biomass in soil. Plant and Soil 76:257-274.

Waring, R.H., and W.H. Schlesinger. 1985. Forest ecosystems: Concepts and management. Academic Press Inc., San Diego, California.

APPENDIX A: WORKSHOP AGENDA

SEQUESTERING CARBON IN SOILS: A WORKSHOP TO EXPLORE THE POTENTIAL FOR MITIGATING GLOBAL CLIMATE CHANGE

Final Agenda

Time — Monday, February 26, 1990

0830 **Agriculture and Forestry Field Tour** - Meet at Nendel's Inn Parking Lot

1700 **Return to EPA Laboratory**

Tuesday, February 27, 1990

Room 211 - Oregon State University Memorial Union

0830 **Welcome**

Tom Murphy, Director
EPA Environmental Research Laboratory
Corvallis, OR

0840 **Workshop Objectives and Procedures**

Mark Johnson
EPA Environmental Research Laboratory
Corvallis, OR

0850 **Introductions**

Plenary Session #1 - Carbon Cycles

0915 **Soil Genesis and the Carbon Cycle**

Stan Buol
Department of Soil Science
North Carolina State University
Raleigh, NC

0940 **Perspectives on the Global Carbon Cycle**

William Schlesinger
Department of Botany
Duke University
Durham, NC

1005 **Perspectives on the Terrestrial Carbon Cycle**

Richard Houghton
The Ecosystems Center
Marine Biological Laboratory
Woods Hole, MA

Time

1030 BREAK

1045 Small Working Groups - Session #1

1145 Small Working Group Reports

1200 Lunch

Plenary Session #2 - Soil Carbon

1300 Soil Carbon in Forested Ecosystems #1

Ariel Lugo
Institute of Tropical Forestry
Rio Piedras, PR

1325 Soil Carbon in Forested Ecosystems #2

Phil Sollins
Department of Forest Science
Forest Sciences Laboratory
Oregon State University
Corvallis, OR

1350 Soil Carbon in Agroecosystems #1

John Duxbury
Department of Agronomy
Cornell University
Ithaca, NY

1415 Soil Carbon in Agroecosystems #2

Michael Beare
Institute of Ecology
University of Georgia
Athens, GA

1440 Soil Carbon in other Ecosystems

Mac Post
Environmental Sciences Division
Oak Ridge National Laboratory
Oak Ridge, TN

1505 BREAK

1520 Small Working Groups - Session #2

1645 Small Working Group Reports

1700 ADJOURN

Time

Workshop Banquet

Peavey Lodge, OSU Peavey Arboretum

1900 **DINNER**

2030 **"The Role of Scientists in Developing Environmental Policy"**

David Bella, Professor
Department of Civil Engineering
Oregon State University
Corvallis, OR

2300 **ADJOURN**

Wednesday, February 28, 1990

Room 211 - Oregon State University Memorial Union

Plenary Session #3 - Managing Soil Carbon

0830 **Introductory Remarks**

Mark Johnson

0845 **Managing Soil Carbon in Tropical Agroecosystems**

Rattan Lal
Department of Agronomy
The Ohio State University
Columbus, OH

0910 **Managing Soil Carbon in Agroecosystems #1**

William Parton
Natural Resource Ecology Laboratory
Colorado State University
Fort Collins, CO

0935 **Managing Soil Carbon in Agroecosystems #2**

Paul Rassmussen
USDA-ARS and Oregon State University
Columbia Basin Agricultural Research Center
Pendleton, OR

1000 **BREAK**

Time

1015 Managing Carbon in Forested Ecosystems

Kermit Cromack
Department of Forest Science
Forest Sciences Laboratory
Oregon State University
Corvallis, OR

1040 Managing Soil Carbon in Forested Ecosystems

Dale Johnson
Desert Research Institute
University of Nevada
Biological Sciences Center
Reno, NV

1105 Small Working Groups - Session #3

1200 LUNCH

1300 Small Working Groups - Session #4

1430 Small Working Group Reports

1500 Group Discussion

1600 ADJOURN

APPENDIX B: PRESENTATION SUMMARIES

This section contains short summaries of each of the scientific presentations. These summaries highlight the salient points that each speaker made. They were compiled by designated rapporteurs or by the presenter. Several presenters submitted written papers to further document their presentations. The submitted papers follow in Appendix C.

Stan Buol, Department of Soil Science, North Carolina State University, Raleigh, NC

1. From a soil genesis perspective, the two forms of soil carbon of interest are the carbonate form (which is not discussed here) and organic carbon (OC) in the soil. The difference between soil and geologic material is the contribution of living things. Organic matter is greatly influenced by the type of mineral material that it is growing in.

2. The most difficult and unknown questions are just what is soil carbon, what is its composition, and how does it vary in behavior throughout the world? Most of the soil carbon research to date has looked at how to extract carbon. This research does not address how it behaves in the field because some forms of carbon may provide no energy for microbial respiration.

3. A simplified view of soil carbon is that some of the carbon is leached, some is oxidized to CO_2, and some goes through humification reactions. Carbon dissolved in groundwater is readily observable in sandy, humid areas where there are black rivers (i.e., Rio Negro, Brazil). This leaching is part of the podzolization process which forms spodic horizons, but some of the carbon is leached completed out of the soil. Organic matter near the surface oxidizes rapidly to CO_2. Organic matter in the soil undergoes a series of reactions in the humification chain. In the process some carbon is released as CO_2 and some is stored. Carbon can remain in soil from hundreds to thousands of years.

4. Data from the US Department of Agriculture - Soil Conservation Service, National Soil Survey Laboratory was used to assess what the impact of global warming would be on soil. The organic carbon of the upper 30 cm of soil was grouped by Soil Taxonomy family temperature classes. It was found that for the same mean annual soil temperature, soils that had less than a 5°C difference in winter and summer soil temperature at 50 cm depth ("iso") tended to have more carbon. It appears that the crucial element for carbon storage is the maximum temperature and not the mean. Thus, to manage soil for maximum carbon storage, extremely high soil temperatures should be avoided.

5. If soil temperatures in the temperate zone increases by 3°C, soil carbon contents would decrease by about 11%. Using this 11% value and applying it to all soils in the temperate zone, indicates that this level of soil warming would increase the amount of atmospheric CO_2 by about 8%.

6. Nearly all soils could increase carbon storage if high temperatures were controlled through practices such as mulching or shading. The wetlands throughout the world show that wet soils store high amounts of carbon. A more cost-effective way to store carbon than creating wetlands would be to irrigate dry land. Increased fertility gives high rates of production of organic matter. Most soils have some limiting nutrient that could be corrected. There are extensive areas of acid soils that could have increased soil carbon if subsoil pH was higher which would give deeper routing and greater organic matter production. Soils with restrictive subsoil hardpans could be physically manipulated to allow deeper rooting and greater primary production. Planting deep rooting, aluminum tolerant cultivars in acid soils would promote carbon storage by increasing root biomass and production. Limiting tillage would increase carbon in nearly all soils because tillage promotes aeration which speeds up organic matter decomposition.

7. Soils that have lost carbon (C depleted/degraded) and soils naturally low in fertility have the potential for storing more carbon. An important point is that the carbon content of soils can be increased, but is society willing to pay the costs involved? Irrigating, fertilizing, or breaking up hardpans can be expensive practices.

William Schlesinger, Department of Botany, Duke University, Durham, NC

1. Soils are a large carbon pool; about twice the atmospheric pool and almost three times the pool in biomass; deserts represent an additional large pool of carbon in carbonates.

2. Carbon pools: All numbers for pools will be in units of Pg of carbon (Pg = Petagrams = 10^{15} grams).

   - Terrestrial organic carbon in soil --> 1400 Pg. Of this about 50 Pg is in litter, with a low proportion in the tropics but a high relative proportion in tundra.

   - Desert soils contain an additional 800 Pg, as $CaCO_3$ in the top meter of soil.

   - Terrestrial Biomass --> 560 Pg; Atmosphere --> 700 Pg; Oceans --> 38,000 Pg.

3. Carbon fluxes: fluxes are in units of Pg/yr.

   - Fossil Fuel burning --flux to atmosphere of ca 5 Pg/yr.

   - Biomass net primary productivity -- approx. 120 Pg/yr, about 60 Pg of this transferred annually to soil, mostly as litter balance returned to atmosphere via respiration.

   - Air to ocean transfer 100-120 Pg/yr.

4. Turnover rates:

   - Atmosphere --> 700 Pg/(120 Pg + 120 Pg) is about 3 years.

   - Biomass --> 560 Pg/(120 Pg) is about 5 years. (This is an average of extremes; some material lasts a week or less while some trees are thousands of years old.

   - Soil --> 1400 Pg/60 Pg roughly 20 years. Again, this is the weighted average life of carbon in the soil; some material decomposes in hours to days whereas humins can be thousands of years old. This may be an over-estimate of soil carbon turnover because it under-represents root turnover.

   - Carbonate turnover -> 3800 years. This number was arrived at by taking a known age layer in a desert soil (Mojave desert) and dividing the carbon pool of the soil above that layer by age at the layer. This results in an accumulation rate of 3 g carbon/m^2/yr in $CaCO_3$. This rate, coupled with relevant desert area, converts to an annualized global flux of carbon to desert carbonates of 0.023 Pg/yr.

5. Accretion of Soil Organic Carbon

   - Computation of the net organic accretion is more difficult than for carbonates, since there is significant efflux of carbon from the soil after decomposition. The real question -- is there any long-term net storage and if so, what is the rate?

   - Using chronosequence data (volcanic, beach or glacial retreat, etc.) to estimate, for soil systems of known age, changes in carbon pools with soil age. Soil ages are as low as 100 years, as high as 10,000 years.

   - Estimated rates computed as soil pool/age; this was recognized as an imperfect approach, because in very old systems the pool is essentially constant so the value asymptotically approaches zero. The point is to compare young versus not-so-young soils to estimate accretion in older soils.

   - Key result is that young soils accumulate large amounts of carbon - 20 to 30 g/m^2/yr during their first 100 or so years. From this data it appears that the carbon accumulation rate drops sharply with age, to an average steady-state rate of about 2 g/m^2/yr for 10,000 year old forest.

- If 2 g carbon/m^2 is accumulated annually in soils of mature, unmanaged forests, that translates to about 0.40 Pg carbon/yr globally. This a soft number, intended to give a sense of the magnitude soil carbon accretion relative to other fluxes. This value is an order of magnitude smaller than the flux from fossil fuel burning, but well above the rate for carbonate accretion in deserts.

- The rate of accumulation in soils is of about equal magnitude with the removal of carbon from terrestrial systems as dissolved organic carbon (DOC) 0.4 Pg/yr. Therefore, additional storage of carbon in soils appears to be diminishingly small -- in the noise. As a final note on the flux from the soil, recent estimates of the annual accumulation of terrestrial organic carbon in ocean sediments at 0.1 or 0.15 Pg carbon/yr. It appears that much of the refractory material lost from the soil as DOC is in fact turned over [oxidized] in the ocean before it can be sedimented.

Richard Houghton, The Woods Hole Research Center, Woods Hole, MA

1. Recent geophysical modeling indicates that temperate/boreal (terrestrial) regions of the earth are accumulating carbon. If this is true, how can we find and document it? The storage of this much carbon ought to be obvious (e.g., enlargement of tree rings) but this carbon hasn't been found and doesn't appear to be in trees; could it be accumulating in soils? If so, how do we find and document it?

2. Documenting changes in landuse, is essentially a big bookkeeping effort--tracking all of the carbon in the system. System carbon drops appreciably at time of disturbance/cutting/burning along with (more slowly) oxidation of carbon in slash, wood, and soil over time. If there is regrowth, there is subsequent re-accumulation of carbon in terrestrial systems with time, but if land converted to agriculture or if land simply abandoned, there will be large long-term losses of carbon from the terrestrial system.

3. In the tropics, in 1980, deforestation was about an order of magnitude greater than reforestation. At the present time annual net carbon release from the tropics is estimated at between 1 and 3 Pg carbon/yr. Soil carbon losses contribute about 15-20% of total system loss; the biggest loss term is slash and stumps.

4. If the total exploitable biomass pool in the tropics is somewhere between 100 and 300 Pg, deforestation at current levels could release up 5 Pg carbon/yr until we run out of forest. If deforestation stops immediately and is followed by natural reforestation or by managed reforestation with controlled cutting in the future, then carbon would be withdrawn from the atmosphere and stored in soils and biomass. The rate could be as high as 3 Pg carbon/yr. Up to about 100 Pg of carbon could be stored. This is less total carbon storage than was initially stored in these forests. This is because not all land is regarded as available for reforestation and some will be supporting intensive agriculture. The actual potential for carbon sequestering is highly uncertain - how extensive would forests become; how well would forest come back on degraded lands?

5. Since the 1850s temperate and boreal zones have contributed significant amounts of carbon to the atmosphere during exploitation of North America and development of the industrial era, but tropics have dominated more recent fluxes to the atmosphere.

6. Previous data described what we "know" based on land use and related data about human use of the land. Geophysical work presents additional data about where carbon has been coming from and going to. Glacial ice bubbles can be used to characterize carbon content of atmosphere for past 100 to 1000+ years. Geophysical models (ocean and atmospheric circulation and gas exchange) of how much carbon we think the oceans are capable of removing from the atmosphere, coupled with gas bubble data, let us run models backwards to calculate "missing" sources/sinks of carbon. Results appear to be very different for the recent period (since 1950), land use data indicate large net release of carbon from the land while ocean models show much smaller net release.

7. Recent modeling suggests that atmospheric carbon levels in the north temperate zone are not as high as they "should" be, and suggest that this results from a substantial net flux into temperate/boreal terrestrial systems. There appears to be less uptake of CO_2 by the oceans and more transfer to the land than previously believed, with an unknown temperate terrestrial sink of roughly 2 Pg/yr. What does this mean? Have subtle changes in temperature or moisture changed carbon storage? Is elevated pCO_2 resulting in increased primary production? Are soils behaving differently (i.e., is carbon storage changing) from where they were a few to several decades ago? Where/how would you look for and assess such possible changes?

Ariel Lugo, Institute of Tropical Forestry, Rio Piedras, PR

1. One needs to put things in perspective, in terms of vegetative and soil organic carbon. Wetlands and grasslands store the most soil carbon; tropical forests store more than boreal forests but a little less than temperate forests in terms of overall soil carbon storage.

2. In another broad view, one can look at soil carbon in relationship to the ratio of temperature and precipitation, which is an indicator of moisture availability. If one considers the tropics, which is more climatically diverse than both temperate and boreal systems together, [62 Holdridge Life Zones in the tropics vs. 120 in the world], then reduce this variability to six groupings, of dry, wet, and moist for tropical, subtropical areas: total carbon shows a nice linear decrease with increasing ratio of temperature/precipitation (T/P) (an indicator of moisture availability) whereas relationships for soil carbon and vegetation carbon are curvilinear, generally decreasing with higher T/P ratios, except for an increase in vegetation carbon between T/P ratios of 0.8 to 1.3.

3. Within tropical forests the greatest amounts of soil carbon are in subtropical and tropical wet and rain forests, those forests which are actually disturbed the least. If one looks at the actual data set, however, with individual data points for soil pits with bulk density, there is lots of scatter: with climate (different T/P ratios), soil carbon can change dramatically but within climates. There is substantial variation within life zone associations.

4. Site topography has an impact on the accumulation of soil carbon.

5. Another factor affecting soil carbon is land use and age. For example, consider pasture sites in Costa Rica (wet life zone) and Venezuela (moist life zone-Western grasslands). In both countries, the pastures had greater amounts of soil carbon than did nearby mature forests.

6. Succession is another factor that affects soil carbon. Chronosequence data for the subtropical wet forest in Puerto Rico and the subtropical moist forest on St. John, US Virgin Islands show in both instances, that the mature forest had greater soil carbon contents than did younger forest.

7. Historical land use affects soil carbon. For example, soil carbon almost doubled, from 37-64 and from 34-60 tons/ha, respectively in moist and wet life zones, from 1950-1960 on plots abandoned following agriculture. On the other hand, in 1980, coffee shade agriculture (a type of agriculture that uses mature trees to shade coffee plants) had 10 tons more or almost 20 tons/ha less soil carbon, depending on whether paired plots were in moist or wet life zones.

8. In another study following 40 years of agriculture, we found changes in organic carbon, small changes in bulk density, and large changes in organic carbon storage (tons/ha). The annual rate of soil carbon accumulation ranged from 20-120 g carbon/m^2/yr rate. These rates are at least 10 times the soil carbon accumulation rate of 2 g/m^2/yr mentioned by Schlesinger earlier. These rates indicate that nature is very responsive to changes in land use on a short-term basis. This means that management effects on soil carbon can be dramatic.

9. In Costa Rica and Venezuela, using paired forest/agriculture sites, we found: 1) no relationship between soil texture with soil carbon, 2) no difference between mature forest and agricultural sites, and 3) Venezuela soils had 2-3 times as much soil carbon as paired Costa Rica soils. This is due primarily to the mineralogy and high clay content of the Venezuelan soils.

10. It's important to collect and report soil bulk density data along with soil carbon data. Similarly, it's not a good idea to infer or extrapolate bulk densities from another sites.

11. How can management play a role in increasing soil carbon storage? In answering this, I want to emphasize the role of managed forest plantations. For example, at a site in the Luquillo Experimental Forest in Puerto Rico, where 10 different tree species are planted in small plots, 23 yrs old, on the same soil, organic matter percent (in top 10 cm) varied from 5.6 to 10, representing accumulations of 46 to 70 t carbon/ha. Litter

production is a function of species.

12 Litter is not the only factor contributing to the observed differences between soil carbon in plantations and natural forests. For paired plantation/natural forest sites we found that they tended to have similar levels of same soil carbon in plantations and natural forest. Plantations have greatest amounts of carbon in the litter, natural forests have greater amounts in the roots, and plantations are way ahead of natural forest in aboveground biomass.

We then investigated the root vs. litter mass question in more detail. Over a 12-year period, a pine forest accumulated much more litter biomass than did a paired secondary forest site. But for fine root biomass, the relationship was inverted: secondary forest had much higher root biomass than did the paired plantation site. When the total primary productivity was calculated, the result was the same: 19 tons/ha/yr. However, the nature of prevalent soil inputs was very different: via litter for plantations and via roots for natural forest.

13. In summary, we need a hierarchial approach to answer the question of whether soils can be manipulated to store more carbon. I believe that we can store addition carbon in soils via management practices to control aboveground vegetation, such as encouraging forest succession and other things. But, consider the task ahead. If one considers the amount of degraded lands with potential for forest replenishment, the total is 758 million ha--the tropics have an overall total of 2 billion ha of damaged lands that have below-par levels of carbon above- and below-ground. These damaged lands represent the opportunity we have for manipulating succession or applying management to increase storage of carbon, both in above-ground vegetation and below-ground.

14. Tools for storing carbon in soils:

- Encourage forest succession, (i.e. greatest gains will be made in allowing/encouraging succession on degraded sites, not in trying to improve carbon status of mature forests).
- Use pastures on highly degraded lands.
- Use plantations carefully, (i.e. there is great diversity on how species respond: some put more carbon in roots, others in litter; this allows one flexibility in technique to develop different management strategies for particular sites).
- Use cultivation techniques that preserve/encourage soil structure.
- Add or retain organic matter in agricultural fields, (there is a lot of "old literature" from Puerto Rico, indicating that leaving straw in the fields from sugar cane improves soil carbon).
- Recycle sewage through forest and degraded lands that have nutrient limitations.
- Use plants with high root production.
- Preserve wetlands and grasslands.
- Manage landscapes. Think more about a complete landscape focus at watershed scales rather than becoming entangled in the issues of hierarchies and long time scales--long-term calculations may be correct for certain values but inaccurate in terms of (shorter scale) management objectives.

Phil Sollins, Department of Forest Science, Oregon State University, Corvallis, OR

1. Estimates of tree root turnover are suspect and may be misleading.

2. Erosion and leaching losses of soil carbon are comparable to greater than the soil carbon accumulation rates. We have little data on soil carbon accumulation, little for losses of soil carbon lost through erosion, and even less for carbon losses through leaching.

   A major unanswered question: Is the leaching of soil organic carbon a net sink of atmospheric carbon, or is it mainly metabolized and degassed as CO_2?

3. Soil physical structure is an important factor that influences the accumulation or loss of soil carbon. Physical structure affect soil thermal properties and water holding capacity. At the same time, soil mineralogy has a large affect on physical structure.

4. The pools of soil carbon are important, but the rates of change of these pools are even more important. Based upon the compiled chronosequence data of Schlesinger, and other data, potential soil carbon loss rates appear to be much larger than soil carbon accumulation rates. We can conclude that it's easier to lose carbon from soils than it is to accumulate soil carbon.

5. When measuring soil carbon concentrations it is essential to obtain good estimates of soil bulk density. It's also essential that measures of coarse fragments be made, particularly in forested soils where coarse fragments often account for more 30% of the soil volume. Without these data, it's not possible to make good estimates of soil carbon pools.

John Duxbury, Department of Agronomy, Cornell University, Ithaca, NY

1. The soil organic carbon pool size is somewhere between 1400-1500 Pg. The loss of soil organic carbon due to agriculture is between 10-100 Pg, or somewhere between 0.7 - 7% of the global soil carbon pool. There is some uncertainty in these numbers because the data, particularly in agricultural systems are poor. Methods generally used are poor and not standardized.

2. Ways to improve the data:

   - Need to sample deeper into the soil (it isn't sufficient to just sample the plow layer) - sample at least one meter, if not more.

   - When reporting changes in soil carbon, the same amount of soil needs to be compared. Thus, need to measure and correct for bulk density variation and for stones/large fragments in the soil.

   - Correct for soil erosion (how much material has been physically removed?).

3. Instead of talking about various extractable soil carbon pools (e.g., humic or fulvic acids) we now talk about soil carbon dynamics (e.g., a range of turn-over rates). I suggest four pools of soil carbon based upon carbon dynamics.

   Active or Labile Pool--Readily Oxidizable

   - Controlling factors include: residue inputs and the climate; type of soil is not important to this pool of soil carbon.

   - Agronomic factors: cropping systems that affect residue inputs--management can affect the size of this pool

   Slowly Oxidized Pool--Macroaggregates

   - Controlling factors include: soil aggregation and mineralogy.

   - Agronomic factors: because this pool is related to the degree of aggregation, tillage is most important--management can affect the size of this pool

   Very Slow Pool--Microaggregates

   - Controlling factors include: soil aggregation and mineralogy.

   - Agronomic factors: it is unclear whether or not management will affect the size of this pool because it probably involves mostly microaggregate structure which is not likely altered by tillage.

   Passive, Recalcitrant Pool

   This pool may not actually exist, but there is some evidence that organic compounds can become trapped between clay plates and be unavailable or unaccessible to decomposers.

   - Controlling factors include: clay mineralogy

   - Agronomic factors: none

4. Evidence for and measurement of the dynamic carbon pools:

Active Pool

- Evidence based upon measurements of ^{14}C labeled residue decomposition rates.

- Residue decomposition follows the same decay pattern (curve) in all environments as long as we normalize the time scale. The rates at a given site are, however, affected by factors such as temperature and moisture. The decomposition processes are probably the same all around the world.

- The residue decomposition process appears to have two phases. The first is a rapid decay phase (about two thirds of the carbon in the residue is lost in this initial phase) and the second phase follows first order kinetics ($C_t = C_o e^{-kt}$). Decomposition data can be used to estimate active soil carbon accumulation rates.

- The size of the active pool < 25% of the soil carbon in temperate and warmer climates, but possibly > 25% in colder climates.

Slow Pool

- Amount of soil carbon is related to the amount of aggregation.

- There is no good way to measure the size of this pool, except by measuring the other pools and calculating the difference.

- There appears to be a strong positive relationship between soil organic carbon content and measures of soil aggregates and aggregate stability.

- Tilling the soil causes a shift from a system of large aggregates to a system of small aggregates. We can destroy aggregates a lot faster than we can reform them. It is not exactly clear what causes aggregate stability and what the role of soil flora and fauna is.

- This is probably the pool from which we lose most of the organic carbon from when land use shifts from natural systems to agriculture.

- This pool ranges from 25 - 50% (or even larger) of the soil carbon.

Very Slow and Passive Pools

- Evidence based upon $\delta\ ^{14}C$ (δ = the change in ^{14}C or ^{13}C) content of soils when C_3 plants are replaced with C_4 plants or visa versa. C_3 and C_4 plant type differentially discriminate in the uptake of ^{13}C from the atmosphere. This can be used to determine how much "new" carbon has been added to the soil. To use this technique, it's necessary to have long-term soil samples to monitor the changes in $\delta\ ^{13}C$ content.

- The point is that by using this $\delta\ ^{13}C$ technique, evidence for the change in the level of "stable" soil carbon is easily shown. Using this technique on a field that was shifted from C_3 plants (prairie) to C_4 plants (wheat) in 1888, found that is a decrease in the carbon content of the soil from 44 mg carbon/g soil to 7 mg carbon/g soil in about 70 years.

- In coarse textured soils this pool is < 25% of the soil carbon, but could be as large as 50% in fine textured soils--where there are a lot of micro-aggregates. This is particularly true in highly weathered soils that have lots of Fe and Al, and in volcanic soils high in allophane.

5. Soil organic matter stability is not absolute. Rather, it's a conditional parameter that's dependent upon the actual management practices.

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1. Soil carbon can accumulate relatively quickly in southern Piedmont soils. If the soils are mismanaged, it can also be quickly lost. The dispersible nature of these kaolinitic soils may help soil carbon accumulate.

2. The upper equilibrium limit for organic carbon in southern Piedmont soils is about 2.5%. The lower limit is about 0.6%.

3. Existing soil carbon models (e.g., Meentemeyer, Post) tend to over estimate the amount of carbon found in southern Piedmont soils. These results led to the development of conceptualization of management practices that affect the composition and activities of soil biota that in turn affect soil carbon contents. We hypothesized that reduced tillage agroecosystems would promote the biotic control of soil aggregate formation and stabilization leading to more protected soil carbon and soil carbon accumulation. With conventional tillage soil aggregates are dispersed and microbially mediated organic matter decomposition is optimized, leading to carbon losses from the soil. The extent of these effects will be influenced by climatic and edaphic factors.

4. Conceptually, soil carbon exists in three pools: the active unprotected pool, the active protected pool, and the passive pool. The active pool is operationally defined as that carbon associated with soil aggregation. The active carbon pools (protected and unprotected) regulate the turnover of carbon to the slow and passive pools.

5. Degraded soils that were studied had a lower amount of water stable aggregates than other soils. Higher clay contents also promote aggregation, particularly macro-aggregates. Aggregates in clayey soils appear to have less water stability than sandy soils.

6. The effect of fungal activity on aggregate stability was studied by inhibiting fungus with Captan. The percent of water stable aggregates was less for Captan treated soils for all by the very smallest aggregate category.

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1. This discussion deals with soil carbon content as affected by temperature and moisture. This analysis is based on data for more than 4,500 soil profiles which were corrected for bulk density and coarse fragment content. Plotting these data on the triangular Holdridge life-zone plot shows that soil carbon content increases as the climate is cold and wet, and decreases when the climate is hot and dry. The global average for soil carbon content is 10 kg/m^2. There is a lot of soil carbon in the moist tropics, but not much in dry tropical climates. The tundra and tropical forests have a large portion of the total world soil carbon.

2. This approach gives a picture of carbon storage under equilibrium conditions. We're interested in how it changes. Soil carbon content is a function of production and decomposition. The carbon turnover rate can be calculated by:

   C turnover rate = carbon in litter / turnover time.

   The average carbon turnover rate of soil carbon and litter is 26 years and the rate for soil carbon is 78 years. This is not really true because there are dates of less than 100 to 1000s of years. There are different forms of organic matter which have different turnover times.

3. To study soil carbon losses and cultivation, data for 700 paired sites were analyzed. The amount of carbon loss depended on the initial amount. If a site started with low carbon content, the losses were low. Conversely, if the initial carbon content was high, there was a large carbon loss. Soils lost up to 40% of their carbon when converted to cultivation.

4. The greatest potential for increasing soil carbon through management systems is for soils that have lost the most carbon. Species composition of forest succession is also a factor depending the amount of soil carbon. Aspen forest was determined to accumulate an additional 40 Mg/ha of soil carbon than pin cherry. Pastures have higher soil carbon content than row cropping systems.

5. Soil carbon content is the result of production, species composition, nutrient decomposition, and how climate influences all those variables. If climates change so that the temperature rises and there is adequate soil moisture, the soil carbon content would increase, but if there was a drought carbon content would decrease. Soil texture affects the moisture holding capacity so soil maps can be used to regionalize the effects of changes in moisture. The timing of precipitation is an important factor to consider when modeling response to climate change.

6. There is some concern about what is going to happen in the tundra with climate change. Boreal and tundra soils are a net sink of 0.2 to 0.4 Pg of CO_2 per year. General circulation models predict that temperature changes will be the greatest at high latitudes. If one assumes a temperature change of 7°C, the boreal and tundra would contribute 1.0 to 2.5 Pg of CO_2 per year compared to the 5.5 Pg of CO_2 released annually to the atmosphere from fossil fuel burning.

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1. Data from Buol and Sanchez, regarding areal distribution of soils; average organic carbon from the top 6 inches, assuming: weighted average of 1.45% organic carbon content for the tropics, 1% decline in existing mass per year, and existing stone-free bulk density of 1.4 (maybe high) for coarse Alfisols, the total emission was 128 billion tons of carbon per year. Conclusion: there can be a very large loss of carbon from those soils.

2. Question: Is soil degradation somehow related to loss of soil carbon via emissions and global climate change? Hypothesis: soil structure is related to soil carbon and if soil carbon is lost, then structure is changed/lost. Other controlling factors of soil structure: erosion, leaching, mineralization, and sedimentation.

3. In converting forests to arable lands, some loss of soil carbon can be attributed to surface runoff and soil erosion.

4. Results of long-term experiments: if started with 4% organic carbon in forest ecosystem, either 100 or 25 yrs old, the amount of carbon in the top 6 inches of soil declined, regardless of which management system was used. conventional tillage was most, no tillage a little better, and no tillage with agroforestry a little better still; yet all declined at the same rate: Similar decline results from savannahs where organic carbon was initially 2%.

5. Is there a relationship between decay rate and soil properties? We have found that true clay content and rainfall were the two important factors for savanna soils. Other factors: mean altitude above sea-level and latitude (both mean greater rainfall).

6. Soil erosion data collected in watersheds for 15-18 years shows a significant negative correlation of soil carbon loss with soil erosion: R^2 value of 0.71. Data from Ivory Coast, on how much soil carbon is lost: forests = almost nothing, if maize on 7% slope = 2 t carbon/ha/yr, i.e. displaced some 25 m, not lost to atmosphere. Erosional displacement selectively removes clay and organic matter only, leaving skeletal materials behind. There is about 3 - 5 times more carbon in eroded material than in non eroded material. Results from continually plowed plots on steep slopes: assuming erosional losses of 200-300 tons/ha/yr and bulk density of 1.4, this translates to 2 cm of soil.

7. When one wants to go from a deforested system back to agricultural practices, factors to consider when assessing greenhouse effects in term of burning are: In shifting cultivation, the farmer does not add fertilizer (resource based agriculture versus science based). If he needs 100 kg/ha/yr of nitrogen, it can come from the soil or from biomass additions.

8. For tropical deforestation, assuming 11 million ha of land cutover annually [range is from 4-20 million ha], initial organic carbon content at 2%, and 10% decline in first year after clearing, then this corresponds to 40-50 million tons of soil carbon lost per year to the atmosphere.

9. Why are there big losses of soil carbon from deforestation? The important factor is increase in soil temperature! Under forest the soil temperature is 22-23 °C. When the forest is cleared, the soil temperature climbs to 42-47 °C, in 1, 5, and 10 cm depths. In some instances, we have monitored soil temperatures as high as 56 or 57 °C, from 11 a.m. and 12 noon until about 4 p.m. For every 10 °C increase in temperature, the rate of chemical reactions doubles. Thus, the rate of organic matter oxidation increases drastically when forest cover is removed, as both above- and belowground temperatures increase.

10. What happens if one puts mulch back on the soil surface after a forest is cleared? Under the mulch, at application rate of 6 tons/ha, the soil temperature was lowered to 35-37 °C from 47 °C. This is still 10 °C higher than under forest cover. Deforestation significantly changes microclimates.

11. Other mulch experiments: if no mulch is added after clearing, the organic carbon dropped from 3.3 to 1.4% in 18 months; if 2 tons/ha of mulch added, the decrease was still from 3.3 to 1.4%; at rate of 12 tons/ha

[leaf litter addition rate in forest], the decrease was from 3.3 to 1.8%. Higher mulch addition rates were not used. The rate of soil carbon decomposition is much higher even with mulches as compared to the natural forest.

12. Soil profile levels of organic carbon up to 50 cm for different practices: no-till has almost 2 times the organic carbon compared to plowed practice in the surface layer; the average at 50 cm depth is about 15-20% greater in the no-till practice due to lower soil temperatures and greater soil moisture. One drawback: poorer seed germination on no-till plots, perhaps due to greater ethylene and methane production in anaerobic (wetter) soil conditions?

    Another scenario: After five years of having a degraded site from deforestation, with organic carbon decreasing from 3 to 1%, how does one build up the soil organic carbon? Use cover crops such as legumes and grasses. After two years, there was a 30% increase in organic carbon--results, however, were very species dependent.

13. Influence of termites on decomposition rates? In Africa, we monitored residue decomposition from corn, rice, and 28 other kinds of plant materials and a large proportion of them disappeared in 60 days primarily because of termite activity.

14. Live mulches: alternate rows of corn with Stylosanthes [live mulches can out compete corn and other ag crops for moisture in dry weather], Centrosema with corn [out competed corn also], cow peas and corn together [worked well on steep slopes in contoured rows to prevent erosion], planting tree seedlings under mulch in desert places of Sahel [only about 20% success rate if animal grazing can be controlled], Leucaena trees with coffee, fodder trees in windbreaks along fields [(Azadiracta indica) takes moisture from nearby crop rows], alley cropping, with legume trees (Leucaena) between crop rows on steep slopes [lowers erosion but raises organic carbon only slightly in the long-term].

15. Increased decomposition and emissions = lower soil carbon accumulation. Factors such as: mechanized deforestation, continuous cropping, residue removal, drought-prone soils, and low-input (shifting) agriculture that mines soil nutrients, can lead to depleted soil carbon stocks.

16. Decreased decomposition and emissions = higher soil carbon accumulation. Practices such as : maintaining natural vegetative cover, use of cover crops, managed pastures, no-till agriculture [no-till doesn't work everywhere], controlling soil erosion, judicious input agriculture, and agroforestry [the latter two are too often popularized by myths rather than facts], can lead to increased soil carbon stocks.

17. How does one minimize risks to soil for losing soil carbon?

    - Reduce the need for deforestation by a) intensifying agriculture on existing farm lands and b) transform traditional (shifting) agriculture into commercial agriculture--give people a reason not to move!

    - Minimize soil and water degradation by preventing erosion, regulating burning through effective legislation, decrease use of marginal lands, and promote judicious use of all-farm input agriculture.

    - Utilize improved (good) farming systems: manual vs. machine-cleared forests; frequent use of cover crops; conservation (perhaps no-till) tillage practices that minimize plowing; agroforestry; afforestation; improved grafts and cultivars.

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1. Using the GISS GCM to provide climate change scenarios for the Great Plains, we project that soil organic carbon to reach new, lower equilibrium levels due to higher soil temperatures associated with global warming. The losses are an order of magnitude less than carbon losses from cultivation, 200-300 g m^{-2} (over a 50 year period) compared to 2000 g m^{-2} (also over a 50 year period). Most of the carbon is lost from the top 20 cm of soil. Some of soil organic carbon losses were from erosion, but we don't know how much. In some instances, primary productivity is projected to increase because the increased temperatures promote soil organic matter decomposition that releases organic N, which stimulates productivity.

2. Soil texture (the texture phase of the series and texture of the mineral surface horizon) was selected as an important soil property by regressions of properties from the US Soil Conservation Service (SCS) national soil pedon database. Soils with fine texture had higher amounts of carbon to loose when cultivated.

3. Soil texture has a large impact on the amount of carbon stabilized in the soil; fine soils have higher amounts of soil organic carbon compared to sandy soils.

4. The CENTURY model is useful to for projecting soil fertility and organic matter. It is built around three soil carbon pools: 1) active, 2) slow, and 3) passive. The active and slow are affected by management. The active pool very quickly gets into equilibrium with new carbon inputs; it is manageable but is only about 3% of the total soil carbon pool. The slow pool has about a 20 year turnover period. The passive pool is about 50% of the total soil carbon pool.

5. Using the CENTURY model to simulate different management strategies in two areas of the Great Plains: Eastern Colorado (30 cm ppt annually) short grass prairie currently under a wheat/fallow cropping system, and eastern Kansas (100 cm ppt annually) tall grass prairie currently under annual corn cropping system. In the great plains, every time the soil is cultivated, soil carbon decomposition is increased by 50% for one month

Eastern Colorado - wheat/ fallow agricultural system

- First 100 years of cropping - decrease soil carbon by about 40% on a fine textured soil.

How do we build back the soil carbon?

- Conventional tillage plus fertilizer --> no increase in soil carbon
- No till plus fertilizer --> increase of 500 g m^{-2} in 100 years (5 g $m^{-2}yr^{-1}$)
- Grass without fertilizer --> increase of 700 g m^{-2} in 100 years (7 g $m^{-2}yr^{-1}$)
- Grass plus fertilizer:

  with grazing --> increase of 1000 g m^{-2} in 100 years (10 g $m^{-2}yr^{-1}$)

  without grazing --> increase of 1400 g m^{-2} in 100 years (14 g $m^{-2}yr^{-1}$)

  If you want to build up carbon quickly, you need to add fertilizer. Return of crop residue also important.

Kansas - corn agricultural system

Corn with no till plus N fertilizer and returning all residue to the soil will increase soil carbon in less than 100 years to levels greater than native grassland. Native grassland had about 6800 g carbon m^{-2}; potential for 7800 g carbon m^{-2}. It takes about 30 years to get from current level of 4000 g carbon m^{-2} to 6800 g carbon m^{-2}. No-till plus fertilizer out yields conventional till plus fertilizer. Residue return to the soil is important. The model assumes 100% return of residue with no-till and 50% return with conventional tillage.

Grazing plus fertilizer returns soil carbon levels to that of native grassland in about 50 years. Grazing requires burning every fourth year to maintain palatability and prevent forest encroachment.

6. Forest systems stabilize the least amount of carbon in soil because of allocation of carbon in the system. About 30% of the carbon is allocated the roots in forest system. In grassland systems about 60% of the plant carbon is allocated to the roots. Wood carbon production shows large amounts of carbon (17000 g carbon/m^2) in 100 years. However, wood carbon may go right back into the atmosphere when the tree is harvested. Carbon fixed in the soil will stay there for a much longer time. If you look at the short term vs the long-term, that has a great impact on your interpretation. Wood carbon is cycled back to the atmosphere on 15 to 30 year cycle. One needs to look at long-term carbon storage.

7. What would be the total carbon benefit possible on the Great Plains? All of the Great Plains agricultural systems could potentially be put into no-till systems. The benefit would be that much of the soil carbon would be recovered in a 50 to 100 year period. The dryer areas of the plains do not have the potential to get back all of the carbon in that time frame, but the wetter sites have the potential to exceed original amounts of soil carbon with best management options. The total amount is basically equal to the amount that was lost. The carbon loss map also is a map of potential gain, about 1000 to 3000 g carbon/m^2.

8. The amount of fertilizer used should to be determined by the amount that is needed to meet the deficiencies of the system at a specific location.

9. Roots may have to grow deeper to acquire more moisture to support the increased growth due to N fertilization.

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1. Soil erosion removes carbon. A 11.2 ton/ha erosion rate removes about 135 kg carbon/ha from a soil profile with 20 g of organic matter/kg soil.

2. The soil is a sink for carbon. Long-term data indicate that about 18% of organic carbon added to soil in subhumid regions is retained in the organic matter fraction (82% is respired as CO_2 through microbial activity). This percentage probably increases to about 26% in cool humid agricultural regions. The percentage is not known for forested soils or tropical soils.

3. Residue type does not have a large effect on carbon retention in soil carbon. Manure, mature legume material, cereal straw, corn stalk and cobs, and sawdust react similarly. The amount of lignin and complex cellulose material is a factor in retention, thus green manures may not be particularly effective.

4. Carbon input into soil is increasing in agricultural soils where erosion is minimal. The increase is promoted by increasing the intensity of cropping (reducing frequency of fallowing) and the use of fertilizers (inorganic or organic); both promote increased crop residue production. Grain crops (corn, wheat, sorghum) have a greater effect than legumes (soybeans, beans, alfalfa) because a much greater amount of crop residue is returned to the soil.

5. The amount of carbon being returned to soil is steadily increasing in grain crops concurrent with the yield increase from improved varieties and management practices. In wheat, for example, a grain yield increase of 85% over the past 50 years is accompanied by straw yield increase of 54%.

6. Minimum tillage practices promote carbon retention in soil. For cereal grains, retention is about 20% greater with stubble mulch tillage than with moldboard plowing.

7. Straw burning may produce no measurable reduction in organic carbon in soil, but burning releases CO_2 to the atmosphere (about 65% of cereal residue is volatilized during burning), decreases microbial activity and soil quality, and predisposes the soil surface to greater erosion.

8. Projected atmospheric CO_2 increases should be accompanied by increased water-use-efficiency in subhumid areas. This should promote more vegetative growth of cool-season grasses and cereal grains. Faster development will permit cereals to better escape summer drought-stress. Thus, unless precipitation is drastically reduced, cereals should have greater straw production, increasing carbon-retention in soil. It is uncertain whether the percentage retention (18-20%) would increase but it could if soil warming is not substantial.

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1. Natural perturbations of the landscape, such as fire, set forested ecosystems back and may alter the species composition. This has a considerable effect on the carbon content of ecosystems. Fire also affects succession.

2. Nitrogen fixers, such as red alder, enhance the potential of forested ecosystems to accrete carbon by increasing system productivity. Including N-fixers in silvacultural mixtures enhances the productivity of conifer species. From an economic point of view and from a carbon storage point of view it makes sense to use N-fixers to bolster system productivity.

3. Fire is not an unmixed blessing. Systems may take a long time to recover following an intense fire or series of fires. Fire is a useful forest management tool that can enhance system recovery following clear cutting. If misused, it can damage the system and slow recovery.

4. Coarse woody debris is an important carbon pool and nutrient reservoir. Microbes and pioneering tree species use coarse woody debris. Nitrogen fixation can occur in decaying coarse woody debris. Following fire, charcoal is an important carbon pool, with a very long residence time.

5. A large proportion of carbon is allocated belowground to support root production and maintenance, and to support synergistic rhizosphere biology. We have little data on the carbon dynamics of these belowground processes.

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1. Primary effects of forest management include harvesting, fertilization, and fire. Secondary effects may be just as important and should be considered. For instance, how does carbon management affect nitrogen dynamics? In particular, nitrogen availability, mobility, and losses through nitrate leaching?

2. Another important question is "What happens when a soil is warmed and stirred?" Carbon is lost, but what happens to nitrogen? Eventually nitrogen is lost too, either through nitrification followed by leaching or denitrification. If soil warming is a consequence of climatic change we may see nitrogen being lost from forested systems. Not only is this an important secondary effect, increased nitrate leaching may be an indicator of soil warming.

3. Forest fertilization studies by Swedish investigators found that several years after high levels of nitrogen (inorganic form) fertilization, none of the applied nitrogen could be found in the soil. The soil must have acidified and the nitrogen was nitrified to nitrate and leached. When you add nitrogen do you arrive at a new permanent carbon increase in the system, or after a brief system response do you return to a lower site controlled steady-state condition? The nitrogen and carbon cycles are closely related which may help explain why we see this kind of response.

4. Fertilization with other nutrients such as phosphorous, potassium, calcium, or magnesium has a much more longlasting effect on the site because these nutrients are less likely to be lost through leaching or volatilization. These nutrients enhance the inorganic nutrient pool and cycle in place for a long time. Nitrogen additions in sludge or by nitrogen-fixers may have a more permanent effect because they are usually in organic forms.

5. There is a difference between nitrogen and non-nitrogen nutrients and their ability to increase soil carbon. The non-nitrogen nutrients are more likely to cause more permanent increase in soil carbon, whereas, nitrogen additions are not likely to have long-term effects on soil carbon.

6. As a management tool, controlled burns do not necessarily decrease the amount of carbon in soils. Published data show that controlled burns results in the translocation of carbon as charcoal and particulates into the soil profile. Fire also affects species composition, which affects belowground carbon inputs and dynamics.

7. Early indications are that water and nitrogen limited plants will respond to elevated CO_2. This may indicate increased water and nutrient use efficiencies with elevated CO_2. This may have an effect on litter quality and decomposition. There may not be any mechanism for phosphorus deficient plants to improve their phosphorus use efficiencies.

8. As the amount of wood removal increases, the C/N ratio of the residue decreases. This leads to increased nitrogen availability and potential decomposition.

Possible Mechanisms for the Accumulation and Loss of Soil Organic Carbon in Agroecosystems on the Southern Piedmont

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It is well known that conventional cultivation of native prairie and forest ecosystems has contributed significantly to a depletion of soil organic carbon (SOC) and net releases to the atmosphere (Jenny 1980, Coleman et al. 1984, Mann 1986). The extent of these losses appears to depend on the intensity and nature of cultivation practices, the length of time under continuous cultivation and on soil type and climatic regimes. Although alternative agricultural management practices (minimum or no-tillage) have been shown to reduce SOC losses as compared to conventional cultivation practices, it is not generally known whether intensification of these alternative practices (increased fertilizer use, increased primary production, return of crop residues to soils) can result in significant accumulation of SOC on degraded soils.

The piedmont region of the southeastern U.S. extends from Virginia into Alabama, and consists of diverse landscapes of urban, forest, pasture and row crop land uses. Annual rainfall and temperature regimes fall between warm, moist-temperate and subtropical. The highly weathered Ultisols of this region contain highly dispersable kaolinitic clays that present unique problems for SOC (and N) management. Giddens (1957) reported rapid losses of SOC (30% in 3 years) following cultivation of virgin forest soils on the Georgia Piedmont (Fig. 1). Other studies suggest that after extended periods of cultivation, equilibrium carbon levels in these soils approach 0.6-0.7%C, a decline of approximately 70% from initial levels. Similiar amounts and rapid losses of SOC have been reported from tropical and subtropical ecosystems under cultivation (Dalal and Mayer 1986, Lugo et al. 1986). Accumulation of SOC also occurs rapidly in Piedmont soils when SOC-depleted agroecosystems are converted to sod (Fig. 1) or conservation management (Hargrove et al. 1982).

These results are in sharp contrast to observations from agroecosystems on the North American Great Plains. First, SOC content of undisturbed prairie soils in cool, temperate regions is typically higher than in undisturbed thermic, udic Ultisols. Second, equilibrium levels after extended cultivation of prairie soils reflect total SOC losses of approximately 30-50% (compared to 70% - Piedmont soils). Third and perhaps most interesting, SOC loss rates appear to be much slower for soils of north temperate ecosystems (Tiessen and Stewart 1983) than for those of south temperate to subtropical ecosystems. Presumably, rates of SOC accumulation in soils of north temperate ecosystems are also equally slow.

Compared to SOC dynamics in north temperate regions, the trends in Fig. 1 may result from basic differences in processes of SOC accumulation and loss in warm, humid regions. We suggest that these differences are not based solely on temperature (Q_{10}) and moisture effects, but also on more fundamental differences in ecosystem properties. The coarse texture (high sand and low silt content) of highly weathered Ultisols diminishes their capacity to store SOC. Further, the kaolinitic clays dominant in these soils are highly susceptible to slaking and dispersion (Buol 1983 etc.). Thus, low aggregate stability and high dispersability, coupled with high temperature and moisture regimes, promote rapid losses of SOC following disturbance (intensive cultivation) of these soils.

Under such conditions, biotic control over the abiotic soil environment may become more important for maintenance of ecosystem structure and function. Central to our current research is the idea that soil biota (esp. fungi, roots and earthworms) enhance soil aggregate formation and stabilization in minimally disturbed soils and that soil aggregates function in protecting SOC (and N) from rapid mineralization (loss)(Tisdall and Oades 1982). Our ideas revolve around the thesis that agricultural management practices influence the composition and activities of soil biological communities. Under reduced tillage practices, selected soil biota may enhance soil aggreagte formation and stabilization resulting in a larger pool of protected SOC (and N). Under intensive cultivation, we suggest that organisms with faster turnover rates will enhance SOC losses when protected SOC is exposed with physical disruption of aggregates.

We have proposed the conceptual model shown in Figure 3 to explore the dynamics of SOC in agroecosystems of the Piedmont. Although based on other models of SOC dynamics (Parton et al. 1987, van Veen et al. 1984) the model is intended to be operational for which all pools and flows (fluxes) are measureable. Central to the conceptual model are the dynamics of the active protected and active unprotected pools (after

Elliott 1986, Gupta and Germida 1988) of SOC which may be important to the formation of longer term and more stable SOC pools (slow/passive pools).

Although, we do not yet have sufficient data from piedmont soils to fit to this model, similiar relationships can be calculated for data from the Great Plains . Table 1 shows the effects of long term cultivation (69 yr) practices on carbon pools in soil aggregates as calculated from data of Gupta and Germida (1988). Macroaggregates declined in abundance in these cultivated soils and resulted in a net loss of nearly 2.2 kg C m-2 as compared to native soils. On a percentage basis, the slow/passive and active unprotected pools of carbon remained unchanged relative to the native soils in both macro- and microaggregates. However, the active protected pool of carbon in macroaggregates from the native soils was approximately 5 times greater than that of the cultivated soils.

Of the soils we are investigating from the Georgia Piedmont, aggraded fescue soils have greater quantities of macroaggregates and higher SOC content than those of degraded (cultivated) arable soils (Table 2). Soil texture also appears to effect soil aggregation. While finer textured soils (Griffin sandy loam and Watkinsville sandy clay loam) tended to maintain greater macroaggregates, these aggregates were more susceptible to dispersion resulting in lower estimates of aggregate stability. Soil aggregate formation and stabilization appear to be important processes regulating SOC accumulation in these soils, however, the specific mechanisms regulating these relationships needs further study.

A greater understanding of the susceptibilty of different soils under different management practices to soil carbon fluxes and of the mechanisms that influence SOC accumulation and loss would aid significantly in developing soil management strategies for sequestering soil organic carbon.

Literature Cited

Bruce, R.R., G.W. Langdale and P.F. Hendrix 1991. Soil-climate Dimensions for crop culture technology transfer. ASA special publication (In press).

Coleman, D.C., C.V. Cole, and E.T. Elliott 1984. Decomposition, organic matter turnover and nutrient dynamics in agroecosystems. In:

Agriculture Ecosystems: Unifying concepts. R. Lowrance, B.R. Stinner, and G.J. House (eds.). John Wiley and Sons, New York. pp. 83-104.

Jenny, H. 1980 The Soil Resource: Origin and Behavior. Springer-Verlag, New York.

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

Giddens, J. 1957. Rate of loss of carbon from Georgia soils. Soil Sci. Soc. Proc. 21: 513-515.

Dalal, R.C. and R.J. Mayer 1986. Long-term trends in fertility of soils under continuous cultivation and cereal cropping in southern Queensland. II. Total organic carbon and its rate of loss from the soil profile. Aust. J. Soil Res. 24: 281-292.

Lugo, A.E. and M.J. Sanchez 1986. Land use and organic carbon content of some subtropical soils. Plant and Soil 96: 185-196.

Hargrove, W.L., J.T. Reid, J.T. Touchton, and R.N. Gallaher. 1982. Influences of tillage practices on the fertiltiy status of an acid soil double-cropped to wheat on soybeans. Agron. J. 74: 684-687.

Tiessen, H. and J.W.B. Stewart. 1983. Particle-size fractions and their use in studies of soil organic matter: II. Cultivation effects on organic matter composition in size fractions. Soil Sci. Soc. Am. J. 48: 312-315.

Buol, S.W. 1983. Soils of the southern states and Puerto Rico. Southern Cooperative series Bulletin 174. Raleigh, North Carolina.

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

van Veen, J. A., J.N. Ladd, and M.J. Frissel. 1984. Modelling C and N turnover through the microbial biomass in soil. Plant and Soil 76: 257-274.

Elliott, E.T. 1986. Aggregate structure and carbon, nitrogen and phosphorus in native and cultivated soils. Soil Sci. Soc. Am. J. 50: 627-633.

Gupta, V.V.S.R., and J.J. Germida. 1988. Distribution of microbial biomass and its activity in different soil aggregate size classes as affected by cultivation. Soil Biology and Biochemistry

Specific Research Needs

1) Assimilation and synthesis of existing data sets from agricultural systems to explore relationships between agricultural management practices and SOC accumulation and loss in various agricultural regions and soils.
2) Establish longer term experiments to evaluate the effects of changing climatic regimes on soil carbon dynamics and carbon pools.
3) Investigate relationships between various soil C pools and management practices on regional and soil type basis.
4) Consider mechanisms of SOC accumulation and loss (biotic and abiotic) to advance possible management strategies for accumulating soil organic carbon.

Table 1. EFFECTS OF CULTIVATION ON CARBON POOLS IN SOIL AGGREGATES (calculated from Gupta and Germida, 1988)

Soil Type/ Size Class	% Water Stable Aggregates	Total C $g\ m^{-2}$	Estimated C Pools ($g\ m^{-2}$) Slow/ Passive	Active Unprotected	Active Protected
<u>Native</u>					
>250 µm	77.1	5412	5325	76.4	10.9
			(98.4%)	(1.41%)	(0.20%)
<250 µm	22.9	1614	1598	16.1	
			(99.0%)	(1.00%)	
<u>Cultivated</u>					
>250 µm	61.4	3006	2961	42.9	2.13
			(98.5%)	(1.42%)	(0.07%)
<250 µm	38.6	1853	1833	19.6	
			(99.0%)	(1.00%)	

Table 2. Soil organic carbon and soil aggregation in aggraded and degraded ecosystems on the Georgia Piedmont. (M.H. Beare et al. unpublished data)

Aggregate fraction (μm)	Aggraded Fescue Soils HSB Bottomland(LS)	Aggraded Fescue Soils Griffin Upland(SL)	Degraded Arable Soils Watkinsville (SL)	Degraded Arable Soils Watkinsville (SCL)
Soil C (%)	1.60	2.33	0.73	1.00
		% Water Stable Aggregates[1]		
> 2000	25.80 ± 7.24	55.80 ± 5.72	17.89 ± 2.44	22.30 ± 3.07
1000-2000	6.96 ± 0.84	6.09 ± 1.25	5.57 ± 0.26	8.54 ± 0.77
250-1000	6.56 ± 0.85	4.08 ± 0.66	6.30 ± 0.68	11.29 ± 1.39
105-250	2.21 ± 0.27	1.17 ± 0.22	2.14 ± 0.25	3.11 ± 0.36
53-105	0.95 ± 0.18	0.79 ± 0.11	1.16 ± 0.37	1.14 ± 0.14
		Aggregate Stability (T_{20}/T_2)[2]		
>2000	0.39 ± 0.03	0.29 ± 0.03	0.30 ± 0.04	0.13 ± 0.01
1000-2000	0.44 ± 0.03	0.38 ± 0.04	0.38 ± 0.01	0.13 ± 0.02
250-1000	0.68 ± 0.02	0.65 ± 0.03	0.47 ± 0.02	0.16 ± 0.02
105-250	0.77 ± 0.04	0.81 ± 0.01	0.65 ± 0.03	0.30 ± 0.04
53-105	0.78 ± 0.02	0.72 ± 0.02	0.74 ± 0.01	0.49 ± 0.03

1. Aggregates > 250μm were collected from nested sieves by wet-sieving and dried @ 90° C. Less than 250μm aggregates were collected by gently passing the remaining suspension over a nest of 105 and 53μm sieves. All values are corrected for primary particles by size class. Values = x ± 1 S.E., n=4.

2. Based on a turbidimetric analysis after Williams et. al. (1966). Aggregates were seperated by wet-sieving and air-dried on the sieves. Intact, pre-wetted aggregates (0.25g d.w.) were placed on an end-over-end shaker for 2 and 20 mins, let settle for 30 mins, and transmittance measured (@520nm) with a spectrophotometer (Spec 20). Values=T_{20}/T_2; x ±1 S.E., n=4.

LS = Loamy sand
SL = Sandy loam
SCL = Sandy clay loam

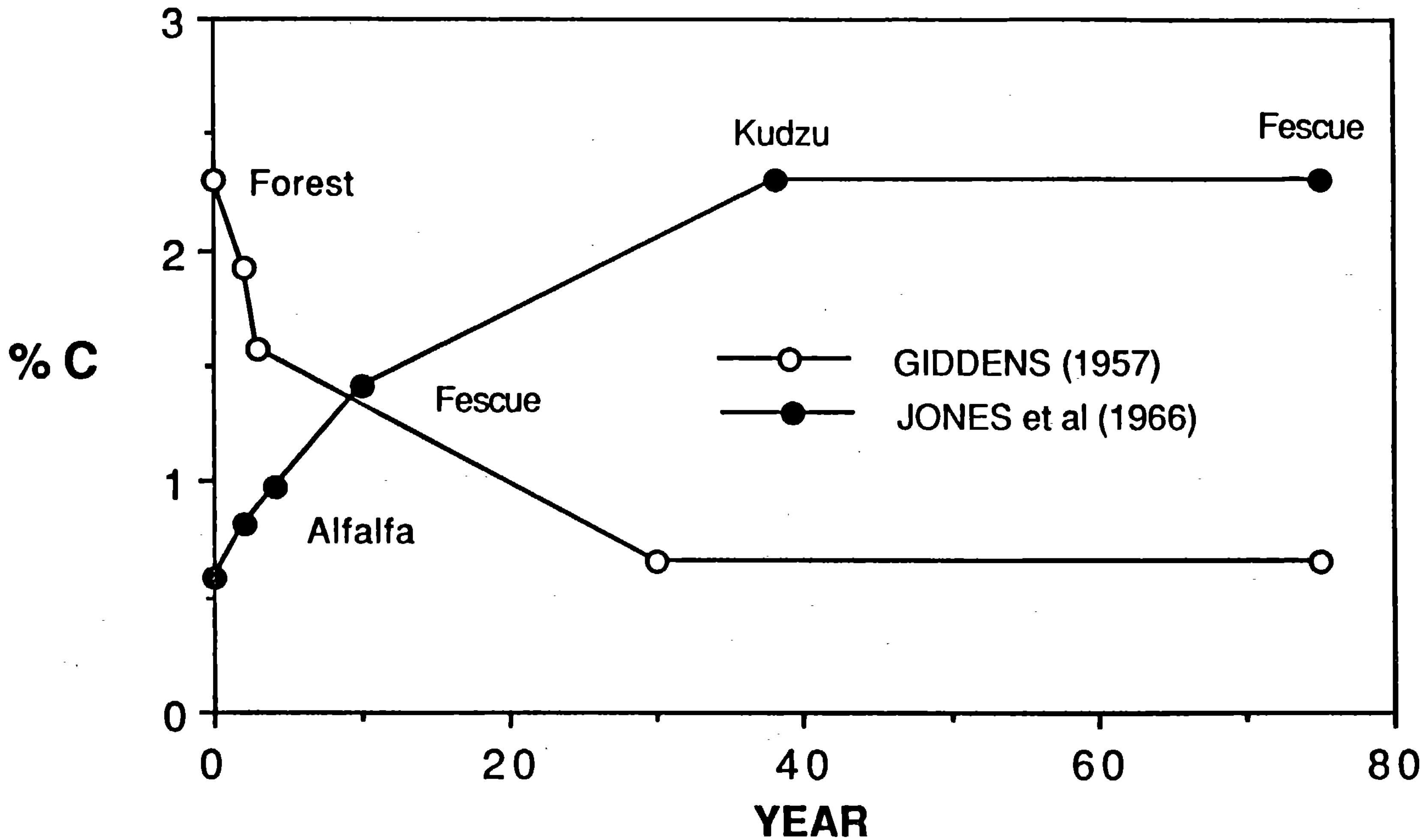


Figure 1. Chronosequences on the Georgia Piedmont show rapid losses of soil organic carbon when undisturbed ecosystems are plowed, and rapid accumulation when intensive cultivation of agroecosystems is ceased. Equilibrium levels appear to range between 0.6% C and 2.3% C. (R.R. Bruce et al. 1991)

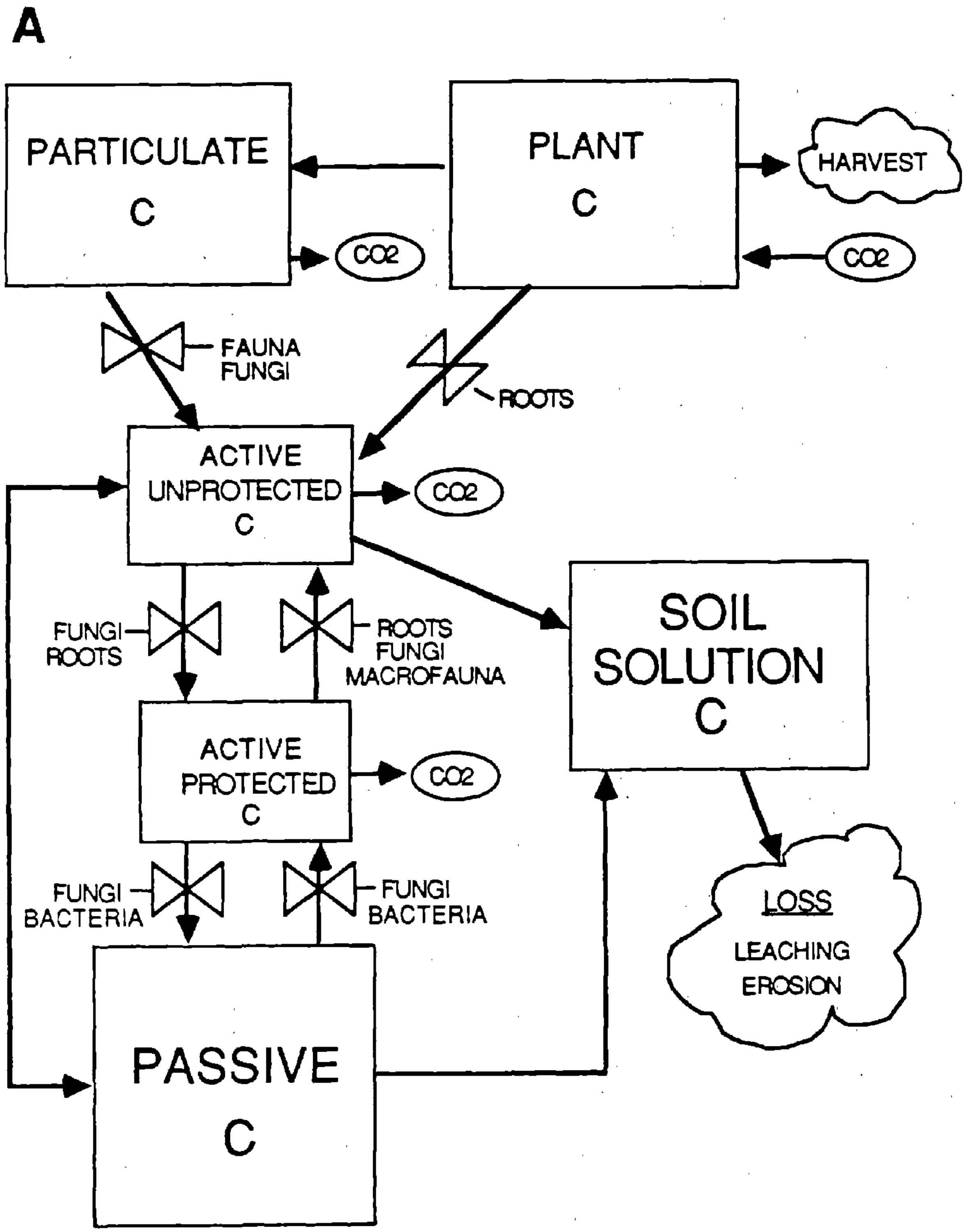


Figure 3. Conceptual model of carbon dynamics. Boxes represent measurable carbon pools. Valve symbols on arrows represent proposed biotic mechanisms that regulate C & N fluxes.

Pedogenesis of Carbon in Soils

S. W. Buol

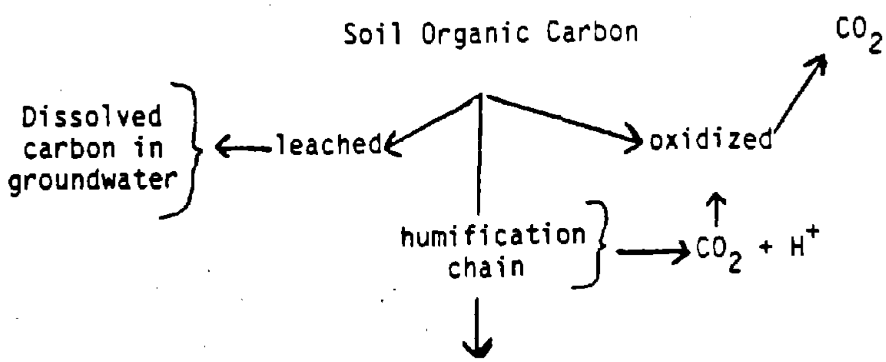
Two major forms of carbon are present in soils. Carbonates, especially $CaCO_3$, are abundant in arid parts of the world where the carbonate is inherited from geologic materials and often distributed via dust. Pedogenically CO_2 is released from carbonates if the soil becomes wetter or more acidic. It is usually translocated downward and precipitated in subsurface horizons of any soil receiving even slight precipitation.

$$CaCO_3 + H_2O + CO_2 \rightleftharpoons Ca(HCO_3)_2$$

$$\underline{\text{insoluble}} \qquad\qquad \underline{\text{soluble}}$$

Organic carbon results from the decomposition of plant, animal and microbial biomass both on the soil surface or near surface as in the case of soil microbes and plant roots.

The soil is but a brief repository of carbon in its cycle. The following schematic illustrates pedogenic pathways available for organic carbon:

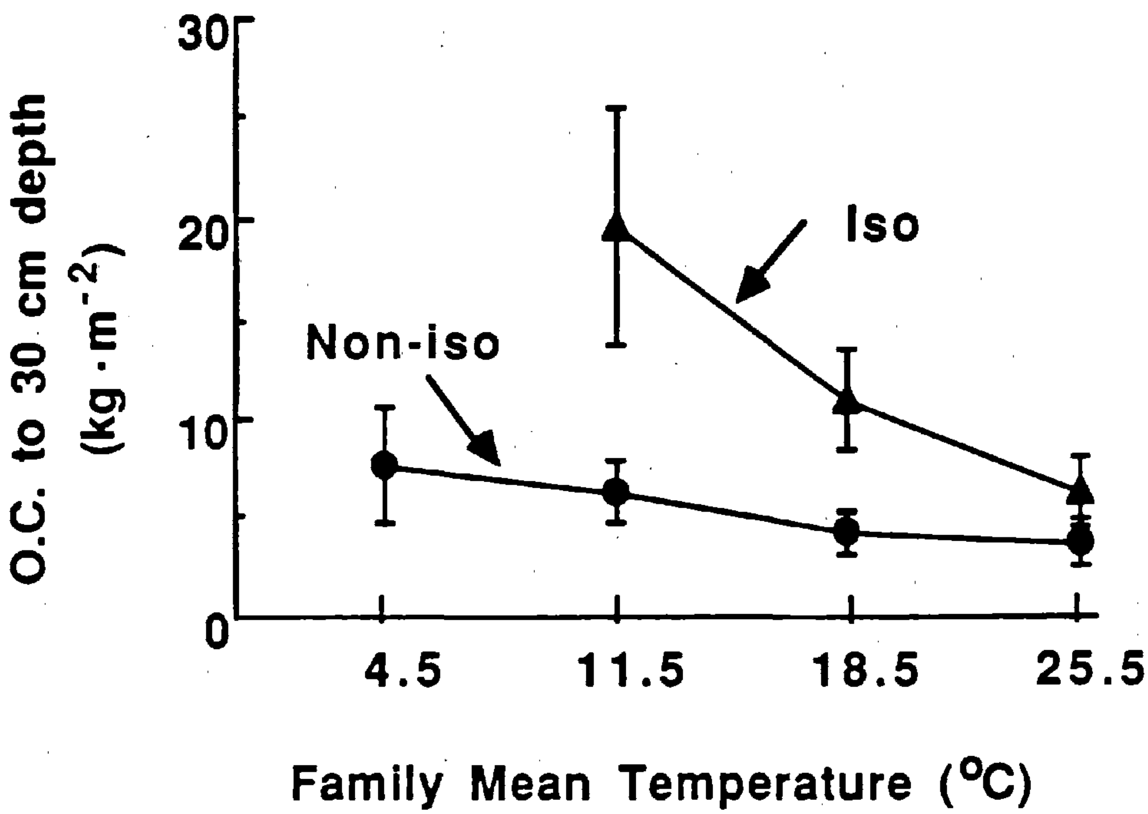


The amount of organic carbon in a soil represents a steady state between rate of organic carbon production, incorporation and oxidation. Production rates can be estimated from above and below ground biomass growth rates. Oxidation rates are subject to control by soil temperature, O_2 supply in the soil, and nature of the multitude of humus forms along the humification chain.

Soil organic carbon contents related to soil temperature are represented in this figure of data in the National Soil Survey Data base. The higher SOC contents in iso-soil temperature regimes probably reflect lack of summer extremes in the tropics versus the temperate zone.

Within any given climate, those parts of the landscape where the soil is saturated with water for long periods of time, excluding O_2 from the soil, have higher organic carbon contents than do better aerated soils. The extreme of this condition results in oxidation rates slower than biomass production and Histosols are formed. Subsequent burial of such soils has formed our coal deposits.

How long carbon is retained in the soil varies greatly. Age of soil organic matter determined by radio carbon dating indicates deeper samples are older than near surface samples. Within Alfisols and Mollisols, age values extend from 200 year B.P. at the surface to 7000 years B.P. for samples at 150 cm. Spodosols, notable for their release of organic carbon to surrounding groundwater, ultimately forming "black water rivers," have carbon ranging in age from a few years to only about 2000 years B.P.


30
20
10
0
O.C. to 30 cm depth
(kg·m-2)
Iso
Non-iso
4.5
11.5
18.5
25.5
Family Mean Temperature (°C)

At a United Nations Environmental Protection (UNEP) meeting in Nairobi two weeks ago a subcommittee formulated the following outline of conditions that can be expected to increase the content of carbon in soil, albeit a new steady state will be reached in response to the altered condition.

Soil Change	Practice	Applicable Soils
Cooler soil	Mulch, shade	All soils
Wetter soil	Irrigation	Dry areas
Increase fertility	Mineral fertilizer	Most soils
Increase subsoil pH	Deep liming	Acid subsoil
Fracture subsoil pans	Subsoiling	Hardpan soils
Deeper rooting	Al tolerant cultivars	Acid subsoils
Reduced aeration	Limited tillage	All soils

MANAGING SOIL CARBON IN TROPICAL AGRO-ECOSYSTEMS

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Summary

World soils have a potential to immobilize atmospheric carbon as soil organic matter and reverse the trend of increase in atmospheric concentration of carbon dioxide. Globally, world soils contain more carbon than atmosphere or worlds biota. Misused, soils can be a major source of carbon emission into the atmosphere. Agricultural operations that enhance emission of carbon into the atmosphere as CO_2, CH_4 or CO include deforestation, burning, intensive cultivation, and manuring. Soil degradation by accelerated erosion, compaction, leaching and acidification also cause depletion of soil organic matter and emission of carbon into the atmosphere. In contrast, soils can be a major sink for carbon through judicious land use and proper soil management. Restoration of degraded lands through afforestation and management of these man-made forests as carbon sinks would fix carbon back into the soil. Soil-enhancing agricultural practices include conservation tillage, mulch farming, agroforestry, judicious use of off-farm input, transformation of resource based subsistence farming into science-based and market-oriented agriculture. Sustainability of agricultural systems should be judged in terms of their effect on global carbon.

Introduction

The "greenhouse effect" is a popular term denoting the warming of atmosphere due to attenuation of radiation by elevated levels of radiatively active gases in the atmosphere. Technically, greenhouse effect is the difference between the planetary surface temperature (T_s) and a radiative temperature (T_r). In the absence of the atmosphere, T_r equals T_s. Other than water vapors, most important radiatively active gases in atmosphere include derivative of carbon such as CO_2, CO and CH_4. These and other trace gases permit the short-wave radiation reach the earth surface relatively unattenuated. However, the main effect comprises of absorption by these gases of the long-wave outgoing radiation and re-radiating some of it back to earth. Consequently, the mean global temperature is believed to have been increased by 0.5 - 0.7°C over the last 100 years. If the present trend continues, the global average temperature may increase by 2 to 6°C during the next century (Schneider, 1989).

World's soil contain more organic carbon as soil organic matter than world biota or the atmosphere. The size of soil carbon reservoir is about twice that of the atmosphere (Stevenson, 1982; Sedjo and Solomon, 1989). In fact, soil organic matter is a major active reservoir in the global carbon cycle. However, there are few reliable estimates of its size and rate of turnover (Moore et al., 1988). The lack of knowledge about this major reservoir of carbon is due to several factors. We have reliable estimates of different soil types and major soil groups, estimates of the amount and temporal variations in organic matter content for different soils are not known. Reliable estimates of the areas devoted to different land uses and cropping/farming systems are also not available. Furthermore, it is difficult to obtain an accurate record of rate of change of land use systems on a global scale. Perhaps the most important missing link in assessing contributions of soils to global carbon budget is the lack of information about response of carbon reservoir in soil to changes in land use.

There has been a steady increase in atmospheric concentration of CO_2 and other greenhouse gases into the atmosphere since about 1850. The increase in atmospheric concentration of CO_2 is attributed to several factors, e.g. deforestation and release of CO_2 from the biomass by decomposition or burning (Houghton, 1987), and combustion of fossil fuel (Batch 1986). Methane is produced in swamps and flooded rice fields (Mikkelsen, 1988). However, the soil as a potential source or sink for atmospheric concentration of CO_2, CO, or CH_4 has not been given the attention it deserves. Tans et al. (1990) observed that oceans alone do not account for the possible sink of carbon. The magnitude of the unknown sink is about 2 to 3.4 Gt of C per year. The mechanism of this C sink is unknown, and may be related to terrestrial ecosystems.

The objective of this report is to highlight the importance of soil as a source or sink for atmospheric carbon, and to discuss soil and crop management, and land use systems that may mitigate or enhance the warming trend. Preliminary calculations are presented to show that world soils can, in fact, be a major factor in global carbon balance. Specific examples are cited from some soils of the tropics.

Dynamics of Organic Matter in Soils

Carbon in soil organic matter, as a dynamic entity, is a function of numerous interacting factors that include steady addition by biota and agricultural operations, and depletion by biochemical changes, leaching and soil erosion (Figs. 1 and 2). A simple model to predict the rate of change of organic carbon in soil proposed by several researchers (Greenland and Nye, 1959; Greenland, 1971; Jenkinson and Raynor, 1977; Stevenson, 1982) is shown in Equation 1:

$$\frac{dc}{dt} = -KC + a \qquad \text{(Eq. 1)}$$

where K is the decomposition constant, C is the carbon content of a given mass of soil at time t, and a is the accretion constant giving the amount of carbon added to the given mass of soil in unit time through biomass, agricultural operations, etc. It is the difference between KC and a that determines whether soil serves as a source or sink for

C. Soil degradation by different processes would lead to a net emission of carbon from soil into the atmosphere (Fig. 2). Soil becomes a net contributor of carbon to the atmosphere when KC exceeds a, but serves as sink when KC is less than a. Depending upon soil and crop management and ecological environment, soil attains a mean value of organic carbon C_m. In that case, it is possible to consider the factor KC_m that determines whether soil is source or sink for atmospheric carbon. Agricultural practices that affect the magnitude of K are listed in Table 1.

There is a similarity between mineralization of N and C in soil. With that assumption, the following analysis for C is adopted from that proposed by Greenland (1971) for N. The amount of carbon in soil depends on management, e.g. duration of cultivation vs. fallowing. Lengths of cropping (t_c) and fallowing (t_f) can be adjusted to attain the desired level of carbon in soil. The emission of carbon during cropping phase is $\left(\frac{dc}{dt}\right)_c t_c$ and gain during the fallowing phase is $\left(\frac{dc}{dt}\right)_f t_f$. The mean amount of organic carbon during these periods is approximately C_m. When steady state is attained the amount of carbon emission from soil must equal the amount stored into the soil according to the law of conservation of mass (Equation 2).

$$(-K_c C_m + a_c)\, t_c + (-K_f C_m + a_f)\, t_f = 0 \qquad \text{(Eq. 2)}$$

re-arrangement of Equation 2 leads to Equation 3 that can be used as a guide to attain the desired ratio of cultivation to fallow phases for soil enhancement.

$$\frac{t_c}{t_f} = \frac{a_f - K_f C_m}{K_c C_m - a_c} \qquad \text{(Eq. 3)}$$

If K and a are known experimentally, C_m can be calculated for a given land use system. Equation 3 can be used to develop a national or a regional soil policy regarding the land use intensity or land use factor.

If soil is subjected to continuous cultivation, carbon content of soil declines exponentially until an equilibrium (C_e) value is attained. The magnitude of C_e depends on cropping system, soil type, and the climatic regime (Fig. 3). The difference (ΔC) in initial (C_o) and the equilibrium level of carbon (C_e) is approximately that emitted into the atmosphere or carried in water as dissolved carbon. The amount of carbon in soil at time t is given by Equation 4:

$$C = C_e + (C_o - C_e) e^{-rt} \qquad \text{(Eq. 4)}$$

where C is soil organic carbon at a time t, r is fraction of C decomposed per year and t is time in years. The magnitude of C is a function of management and environmental characteristics.

Soil as Source of C

The magnitude of decomposition constant K is generally more for tropical than temperate environment. The Van't Hoff's law states that the rate of any chemical reaction approximately doubles for every 10°C rise in temperature. All other factors remaining the same, the rate of decomposition is expectedly more in the tropics because mean soil temperature is higher than in temperate regions. The amount of carbon in soil is, therefore, related to temperature (Equation 5).

$$C = a e^{-KT} \qquad \text{(Eq. 5)}$$

where T is mean annual temperature.

The amount of carbon that can be emitted from soils of the tropics can be computed from the data in Table 2. The weighted mean carbon content of the soil computed from the data in Table 1 is 1.45%. Assuming the bulk density of top 15-cm layer to be 1.4 Mg m^{-3} and the rate of decrease of carbon due to cropping to be 1% per year, the amount of emission from soils of the tropics equals 30 - 45 Mg C/ha/yr or 127.9 x 10^9 Mg C/yr. This is a large amount, indeed. In addition, new land is annually being brought under cultivation. The rate of new land development is approximately 11 million hectares annually (Lal, 1987). The initial soil organic carbon in the top 15-cm layer is about 2%. The rate of loss of carbon due to cultivation in the first year may be as much as 10% (Lal, 1981). Assuming the bulk density value of 1.4 Mg m^{-3}, carbon emission from newly cleared land is 46 x 10^6 Mg/yr.

There are several soil-related processes that accelerate the rate of carbon emission from soil. These include respiration and exposure of organic matter to microorganisms, dissolved carbon in drainage water and overland flow, and entrainment of carbon with eroded sediment. Because of a preferential removal of organic matter, accelerated soil erosion rapidly depletes carbon content of the soil. Soil carbon content is, therefore, negatively correlated with the amount or severity of past erosion (Lal, 1980)(Equation 6).

$$\text{Carbon content of soil (\%)} = 1.79 - 0.002E,\ r = -0.71 \qquad \text{(Eq. 6)}$$

where E is soil erosion in t/ha/yr. Humus is an important component of stable aggregates. Organo-mineral complexes are blocked within micro-aggregates as binding agents. In stable aggregates, resistant to detachment by raindrop impact, these organo-mineral complexes are even inaccessible to micro-organisms. Soil erosion also removes the clay fraction from soil. Clays stabilize organic matter content in the soil. There exists a positive correlation between carbon and clay contents of a soil (Stevenson, 1982).

Agricultural Operations and Carbon Emission

There are several agricultural practices that enhance carbon emission from soil (Table 3). Conversion of tropical rainforest and burning directly impact carbon release from the biomass. In this regard, shifting cultivation and related bush fallow systems plan an important role. When shifting cultivation is practiced with a long fallow phase and a high Land Use Factor[1] (L >10), carbon balance is favorably maintained with relatively high storage in soil and the biota. However, increase in the duration of cultivation phase and drastic reduction in that of the fallow phase leads to soil degradation and emission of carbon into the atmosphere. In contrast to deforestation and intensive cropping, agriculture practices that would increase carbon storage in soil include afforestation, pasture establishment and cover crops with controlled grazing and low stocking rate. Resource-based agricultural practices that mine soil fertility would enhance carbon emission from soil. For example, to harvest an

[1] Land Use Factor $L = t_c + t_f/t_c$

equivalent of 100 Kg N/ha in a crop would require mineralization of 1000 Kg of carbon from humus considering a C:N ratio of 10:1. If used as low-input resource-based agriculture, the total cultivated area of 5×10^9 ha in the tropics would emit 5×10^9 Mg C/yr. On the other hand, a large proportion of this carbon can be retained in the soil if fertilizers or other amendments were used as is the case in science-based agriculture. In addition to socio-economic and political considerations, there is a strong environmental justification for transforming resource-based subsistence farming into science-based and market-oriented commercial agriculture.

In addition to agro-economic considerations, sustainability of agricultural practices must be evaluated in terms of their effectiveness in minimizing risks of carbon emission from soil. Some of those practices that have potential to reduce carbon emission from soil-related processes are listed in Table 4. There are three principal considerations. Firstly, it is important that the need for bringing new land under cultivation is reduced by intensively farming existing land and by transforming subsistence and extensive farming into intensive agriculture. Secondly, resource management policy must be adopted to minimize soil and environmental degradation. Degradative trends can be reversed by preventing or decreasing soil erosion, regulating burning and grazing, decreasing use of steep/marginal lands for agriculture, and through a judicious use of off-farm input. Judicious use of organic soils is an important consideration. Globally there are 240 million ha of peat soils (Table 5). Once cleared and drained, these soils are highly susceptible to degradation. The rate of decomposition of carbon from organic soils is far greater than those of mineral soils. It is not uncommon to lose 2 m of organic soils in less than a decade. Thirdly, adoption of improved best-management-technologies must be vigorously pursued. These technologies are often site-specific and have to be locally validated and adapted. Use of improved crops and cultivars, conservation tillage, agroforestry and planted fallow can drastically reduce carbon emission from soil.

Soil As a Carbon Sink

Soil, the uppermost layer of earth that is agriculturally productive, is a major component of potential terrestrial sink that can be used for carbon sequestering. A viable alternative to exploit this vast sink for reversing the trend in global carbon emission is to restore degraded soils. It is estimated that for 1.5 billion ha of currently cropped land, an additional 2.0 billion ha of once biologically productive land has been rendered unproductive through irreversible degradation (UNEP, 1986). Some surveys have estimated that soil degradation, of one type or another, affects about one-third of earth's land surface. The current rate of soil degradation is estimated to be 5-7 million ha per year with a potential to increase to 10 million ha per year by the year 2000 (FAO, 1983). From a global perspective, the first priority should be to restore biological productivity of these soils and use them as a terrestrial carbon sink. Afforestation for using these lands to produce biomass, and intentionally maintain them as a sink of carbon, would immobilize atmospheric carbon into biota, and drastically increase carbon flux into the soil. Such carbon-sinks should be financed by international agencies.

In addition, soil-enhancing agricultural practices must be adopted for arable land uses. Use of crop residue mulches (Table 6), conservation tillage (Table 7), agroforestry system (Fig. 4), cover crops and planted fallows (Table 8) are proven technologies that minimize risks of soil degradation and maintain favorable level of carbon in the soil. There is a need to develop regional, national and international soil policy to adopt these soil-enhancing practices. Farmers should be given incentives and encouragement to adopt those cultural practices that encourage influx of carbon into the soil.

Conclusions

World soils have a potential to mitigate the global warming risk through their capacity to immobilize carbon as soil organic matter or humus in the root zone.

Improperly used, soils are also a major source of carbon emission into the atmosphere. Carbon emission from soil-related processes is enhanced by bio-degradation of soil organic matter. The latter depends on temperature, moisture regime, cultivation systems and managerial input. Depletion of soil organic matter and its release into the atmosphere is enhanced by deforestation and biomass burning, plowing, intensive use of marginal lands and reduction in the length of fallow phase. In contrast, carbon influx into the soil can be increased by restoring productivity of degraded lands through afforestation and maintaining these man-made forests as carbon sinks. Soil-enhancing agricultural practices, e.g. agroforestry, conservation tillage, mulch farming, etc. should be encouraged through proper incentives. There is a need to develop regional, national and international soil policy toward using world soils as sink for atmospheric carbon.

References

Batch, W. 1986. The gases and their influence on climate. Natural Resources and Development 24:90-124.

Beek, K. J., W. A. Blokhuis, P. M. Driessen, N. Van Breeman, R. Brinkman and L. J. Pons. 1980. Problem soils: their reclamation and management. International Soil Reference and Information Centre, Wageningen, The Netherlands.

FAO/UNEP. 1983. Guidelines for control of soil degradation. Land & Water Div., FAO, Rome, Italy.

Greenland, D. J. and P. H. Nye. 1959. J. Soil Sci. 10:284-299.

Greenland, D. J. 1971. Changes in the nitrogen status and physical condition of soils under pastures, with special reference to the maintenance of the fertility of Australian soils used for growing wheat. Soils & Fertilizer Abstract 34(3):237-251.

Houghton, R. A. 1987. Terrestrial metabolism and atmospheric CO_2 concentrations: independent geophysical and ecological estimates of seasonal carbon flux address global change. Bio Science 37:672-678.

Jenkinson, D. S. and J. H. Raynor. 1977. The turnover of soil organic matter in some of the Rothamsted classical experiments. Soil Science 123:298-305.

Juo, A. S. R. and R. Lal. 1977. The effect of fallow and continuous cultivation on the chemical and physical properties of an Alfisol in the tropics. Plant Soil 47:567-584.

Juo, A. S. R. and R. Lal. 1979. Nutrient profile in a tropical Alfisol under conventional and no-till system. Soil Sci. 127:168-173.

Lal, R. 1987. Conversion of tropical rainforest: agronomic potential and ecological consequences. Adv. Agron. 39:173-264.

Lal, R., G. F. Wilson and B. N. Okigbo. 1979. Changes in properties of an Alfisol by various cover crops. Soil Sci. 127:377-382.

Lal, R., D. De Vleeschauwer and R. M. Nganje. 1980. Changes in properties of a newly cleared tropical Alfisol as affected by mulching. Soil Sci. Soc. Am. J. 44:827-837.

Lal, R. 1981. Clearing a tropical forest. II. Effects on crop performance. Field Crops Res. 4:345-354.

Lal, R. 1989. Conservation tillage for sustainable agriculture. Adv. Agron. 42:85-197.

Lal, R. 1989. Agroforestry systems and soil surface management of a tropical Alfisol. III. Soil chemical properties. Agroforestry Systems 8:113-132.

Mikkelsen, D. S. 1988. Technological options for reducing emissions. U.S. - EPA Workshop on agriculture and climate change, March 1988, Washington, DC.

Moore, B., M. Gildea, C. Verosmarty, D. Skole, J. Medillo, B. Peterson, E. Rasteller and P. Steudder. 1988. Biochemical cycles in global ecology: Towards a science of the biosphere. M. B. Ramble et al. (eds.) Academic Press, New York:113-141.

Sedjo, R. A. and A. M. Solomon. 1989. Climate and Forests. In: Rosenberg, N. J. et al. (eds.) "Greenhouse Warming: Abatement and Adaptation". Resources for the Future, Inc., Washington, DC.

Stevenson, F. J. 1982. Humus chemistry: genesis, composition reactions. J. Wiley & Sons, New York, 443 pp.

Tans, P., I. Y. Fung and T. Takahashi. 1990. Observational constraints on the global atmosphere CO_2 budget. Science 247:1431-1438.

UNEP. 1986. Farming systems principles for improved food production and the control of soil degradation in arid and semi-arid tropics. ICRISAT, Hyderabad, India.

Table 1. Effects of agricultural operations on relative magnitude of the decomposition constant.

High K	Low K
Mechanized Deforestation	Natural Vegetation Cover
Plowing	Planted Fallows
Continuous Cropping	Afforestation
Accelerated Erosion	Cover Crops
Drought-Prone Soils	Managed Pasture
Residue Removal	No-Till
Low Input Agriculture	Erosion Control
Soil Fertility Depletion	Judicious Input
	Agroforestry

Table 2. Average organic carbon contents and hectarage of some tropical soils (0-15 cm).

Soil	Area (10^6 ha)	Organic Carbon (%)
Oxisols	1,100	2.07
Ultisols	550	1.39
Alfisols	800	1.30
Aridisols	900	0.75
Entisols	400	1.50
Inceptisols	400	1.50
Mollisols	50	2.44

Lal (1986), Sanchez (1976), Greenland et al. (1989)

Table 3. Agricultural practices in the tropics that enhance the greenhouse effect.

- Burning
- Deforestation
- Intensive and Continuous Upland Farming
- Rice Paddies
- Pasture
- Chemical Fertilizers

Table 4. Agricultural practices that minimize carbon emission from soil.

I. Reducing Need for Deforestation

a. Intensive Farming on Existing Land

b. Transforming Traditional Into Commercial Agriculture

II. Minimizing Soil and Environmental Degradation

a. Prevent Erosion

b. Regulate Burning

c. Decrease Use of Marginal Lands

d. Judicious Use of Off-Farm Input

e. Judicious Management of Peat, Muck and Other Organic Soils

III. Adopt Improved Farming Systems

a. Manual/Shear Blade Clearing

b. Frequent Use of Cover Crops and Planted Fallow

c. Conservation Tillage

d. Agroforestry

e. Afforestation

f. Improved Crops and Cultivars

Table 5. Global distribution of peat soils (Beek et al., 1980).

Region	Area (10^6 ha)
Africa	12.2
Near and Middle East	-0-
Asia and Far East	23.5
Latin America	7.4
Australia	4.1
North America	117.8
Europe	75.0
World Total	240.0

Table 6. Mulching effects on soil organic C (Lal et al., 1980).

Mulch Rate	C (%) at Different Times (Months) After Clearing		
T/Ha/Yr	0	12	18
0	3.3	1.7 (52%)	1.4 (42%)
2	3.2	2.0	1.4
4	3.2	2.0	1.5
6	3.2	2.3	1.7
12	3.2	2.5	1.8

Table 7. Organic carbon profile in a no-till system (Juo and Lal, 1979).

Depth (cm)	Organic Carbon (%) No-Till	Plowed
0-5	2.87	1.17
5-10	1.77	1.19
15-15	1.23	1.10
15-20	1.11	1.09
20-25	0.71	0.91
25-30	0.96	0.82
30-35	0.57	0.82
35-40	0.47	0.62
40-45	0.42	0.47
45-50	0.34	0.37
$\bar{x}$	1.05	0.86

Table 8. An example of carbon sequestering in a tropical soil by planted fallows and cover cropping (Lal et al. 1979).

Cover crop	Soil organic carbon content (%) Initial in 1974	Final in 1976	% Increase
Brachiaria	1.21	1.57	29.8
Paspalum	1.23	1.45	17.9
Cynodon	1.30	1.70	15.4
Pueraria	1.27	1.50	18.1
Stylosanthes	1.30	1.63	25.4
Stizolobium	1.30	1.57	20.8
Prophocarpus	1.20	1.57	30.8
Centrosema	1.30	1.53	15.4
Weed fallow	1.33	1.37	3.1
LSD (.05)	0.50	0.23	

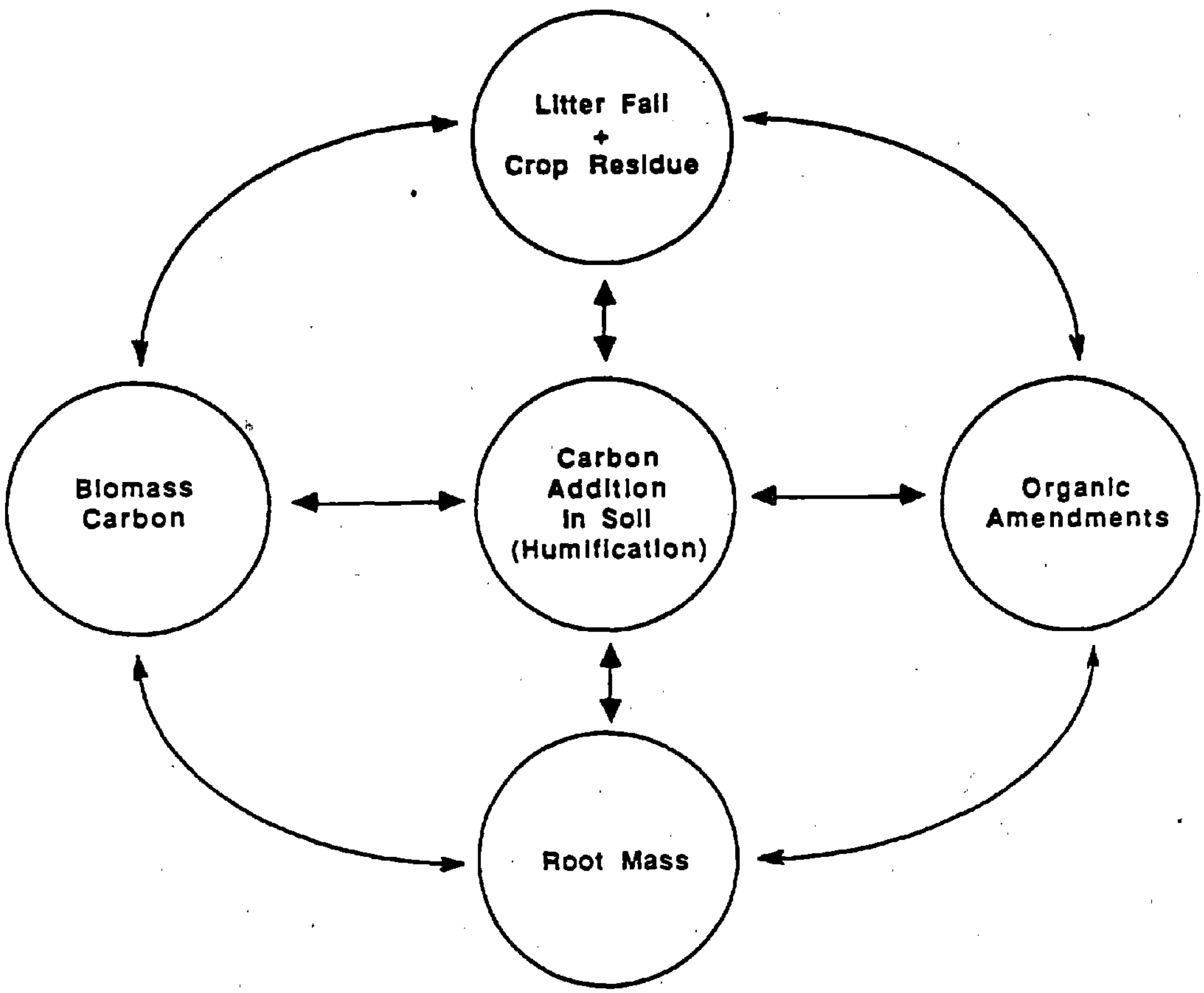

Fig. 1. Carbon addition to the reservoir of soil organic matter.

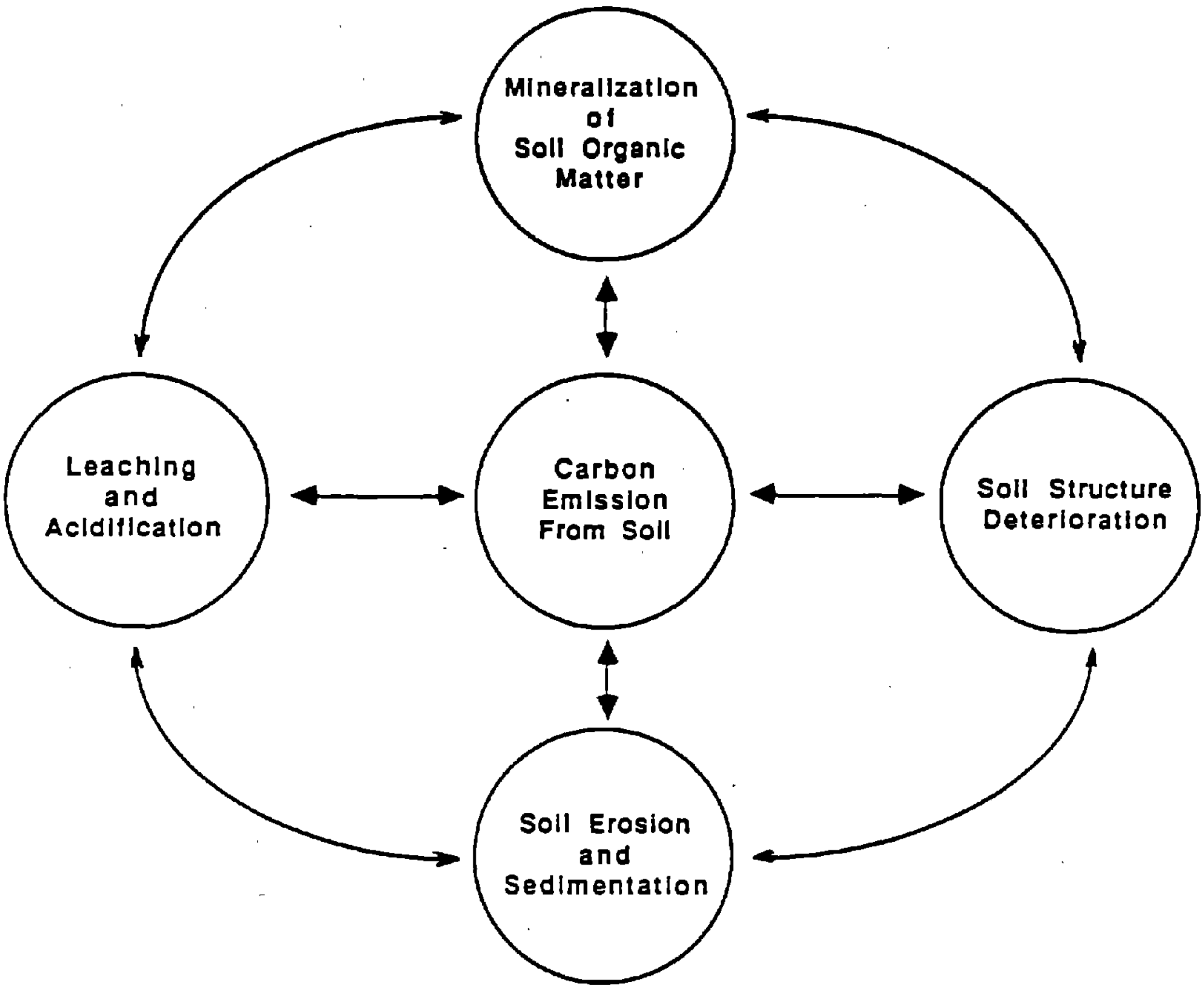

Fig. 2. Processes of soil degradation leading to carbon emission from soil.

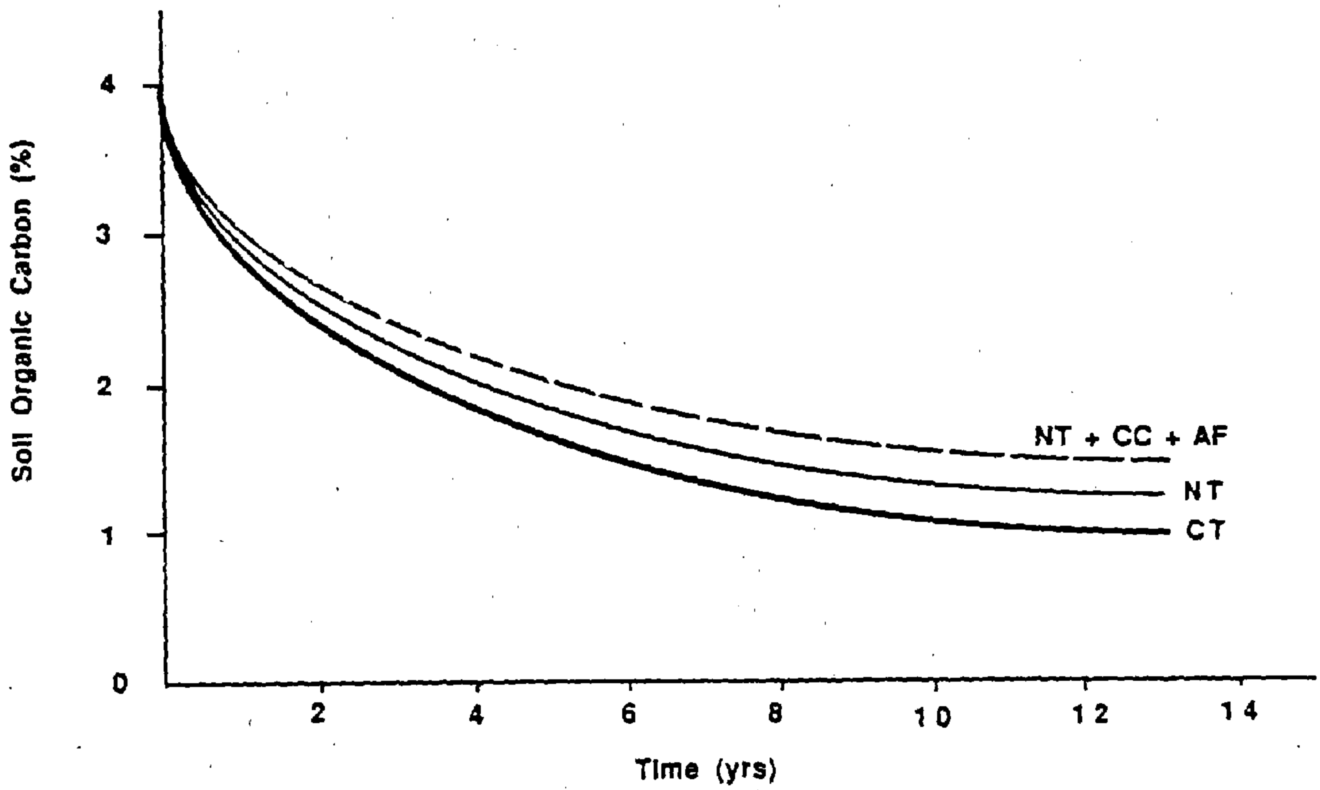

Fig. 3. A generalized curve showing changes in soil organic carbon with time after deforestation of tropical rainforest and conversion to arable landuse. CT: plow-based farming, NT: no-till farming, CC: cover crop, and AF: agroforestry.

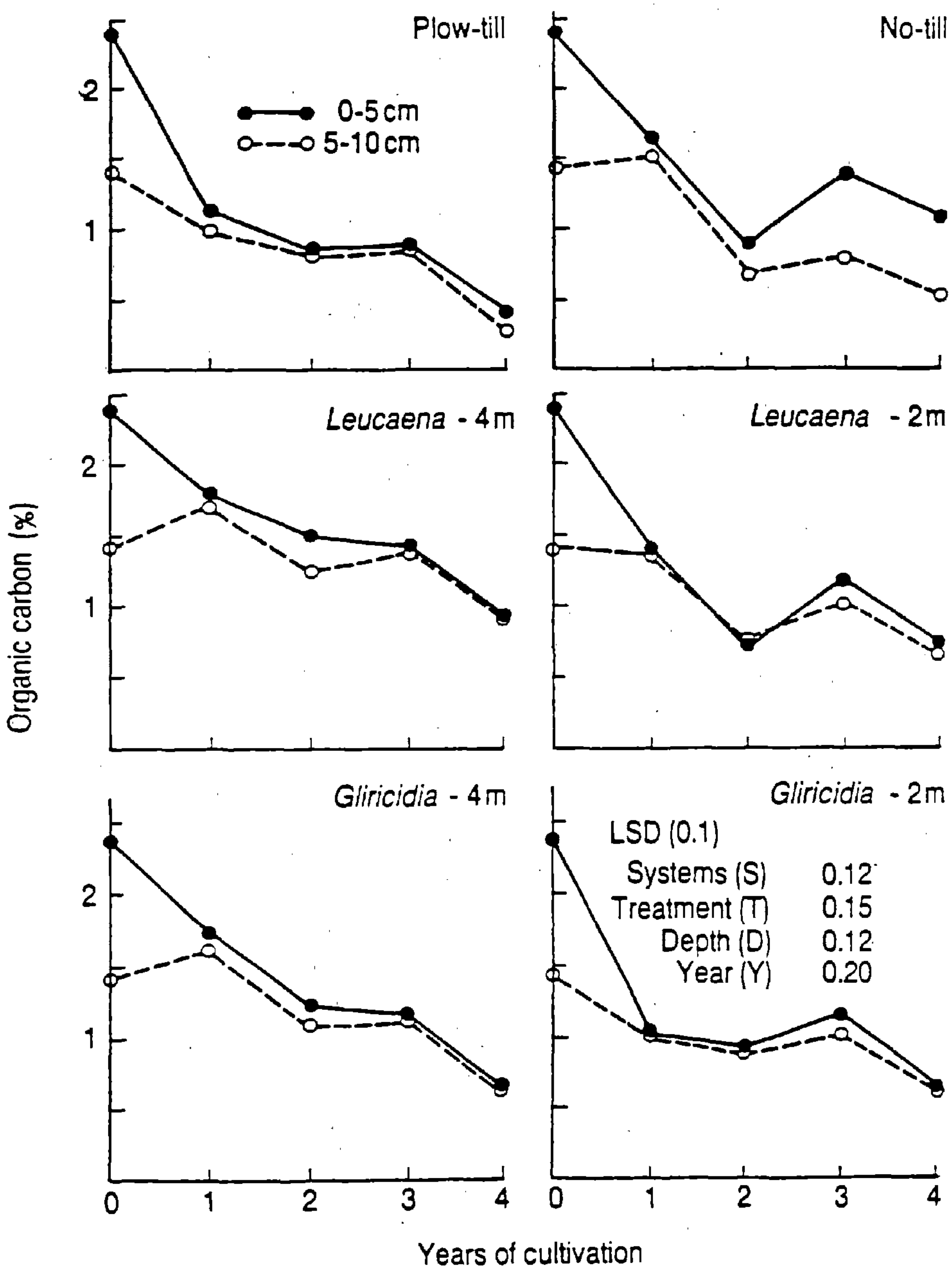

Fig. 4 Changes in soil organic carbon content in agroforestry versus crop-based systems (Lal, 1989)

Lugo, A.E., and S. Brown, Management of Tropical Forest Lands for Maximum Soil Carbon Storage

INTRODUCTION

Our research has focused on the accumulation of soil organic carbon (SOC) in tropical forests under various types of land uses. Results of our studies are summarized below according to major land use. We then discuss some general aspects of our work and suggest management strategies for maximizing SOC in tropical forest lands. Finally, we discuss research needs.

RESULTS

Mature Forests

The Holdridge life zone system provides an objective framework for studying large scale patterns of SOC content and distribution. Life zones embody the effects of climatic factors on ecosystem structure and function. We found that, in mature tropical forests, SOC increases with available moisture.

However, to fully understand the dynamics of SOC, it is necessary to study smaller spatial scales. Within plant associations (the next lower level of the life zone system of Holdridge), SOC may be different. The factors that regulate SOC accumulation at this scale are biotic, edaphic, and topographic factors. At the third level of the hierarchical life zone system, i.e., the successional stage, time and land-use factors come into play. The age of a stand, its land-use history, and current use status, all have a measurable effect on SOC.

After Forest Conversion

Soil carbon decreases immediately after conversion of mature forests to other uses. However, the degree of the reduction varies according to the type of conversion, the intensity of use, and the length of time a soil is under a given use status.

Agricultural Systems

Agricultural systems are usually characterized by low amounts of SOC. In comparison to adjacent mature forests, agricultural systems have lower amounts of SOC. Intensive agricultural use with low regard to fertilization or organic matter management reduces SOC. However, there appears to be a minimum SOC below which no further loss occurs. Addition of straw or organic debris to agricultural soils helps improve their SOC content and their nitrogen fertility.

Pastures

Pastures accumulate high amounts of SOC. We have measured as much or more SOC in pastures as in adjacent mature forests. Improved pastures have higher SOC than non-improved ones. High root production by grasses may explain why pastures accumulate so much SOC.

Tree Plantations

Tree plantations accumulate SOC as they mature. The rate of SOC accumulation in tree plantations is species-dependent. Intensively-managed plantations can accumulate more litter and do so faster than unmanaged plantations or natural successions. The accumulation of litter in plantations is species dependent. The plantations that we have studied exhibit nutrient and organic matter dynamics that result in high magnitude of accumulation in various ecosystem compartments (e.g., vegetation, litter, and soils). In contrast, we have observed that natural successions have dynamics that result in lower accumulations of nutrients and organic matter, but faster turnovers.

Secondary Forests

In spite of the fast turnover of nutrients and organic matter, tropical secondary forests accumulate SOC as they mature. The rate of accumulation of SOC is dependent on available moisture and previous land use. Comparisons of organic matter budgets of plantations and natural forests suggest that different compartments in these ecosystems have different behaviors. The accumulation of SOC is through different pathways. For example, root productivity appears to be higher in natural forests as opposed to plantations. But plantations tend to accumulate more litter.

General Aspects

The life zone condition (climate) is a good predictor for SOC accumulation and behavior for large scale analyses. Soil texture helps explain the magnitude of SOC, particularly the sand fraction. Sandy soils tend to accumulate less SOC than clay soils. However, our results from Costa Rica and Venezuela do not support the sand-SOC relationship. Root biomass and turnover may be more important determinants of the accumulation of SOC in tropical forests than litter input, at least in the short term.

Management Implications

Soil organic carbon is a long-term carbon sink with a slow turnover. As such it is a more secure carbon sequestering mechanism than plant biomass. However, the accumulation of SOC need not be slow. Our results show fast rates of accumulation in successional forests, tree plantations, and pastures. An obvious management recommendation is that by allowing the growth of successional systems, SOC accumulation is also promoted. Because of the apparent relative importance of root production and turnover to SOC accumulation, the establishment of systems with high rates of these processes should be considered.

A critical question is the recovery of SOC in degraded or damaged lands. Land rehabilitation efforts can begin with the establishment of grasses and pastures. These plants modify site conditions, favor future tree establishment, and immediately favor SOC accumulation.

Tree plantations using exotic species offer another mechanism for the rehabilitation of damaged lands and for increasing SOC accumulation. Species selection is a critical factor for consideration when artificial systems are used to maximize SOC accumulation. Some species have high litter productivity but low root production. Others have the opposite pattern. And, each species produces organic litter (roots, wood, and leaves) of different qualities and suitability for becoming SOC. We have documented that at least for two plantation species, pine and mahogany, the rate of root production is lower, and the rate of litter production higher, than comparable secondary forests.

Acceleration of SOC production can also be accomplished by accelerating succession or ecosystem productivity. This can be accomplished by fertilization and watering. However, both of these actions are expensive. Yet, where a supply of domestic sewage is available, it is possible to couple land rehabilitation with the application of treated sewage. A side benefit of this strategy is sequestering SOC.

The most fundamental approach for the management of SOC on a large-scale basis, is to implement a system of landscape management. Such a system management takes advantage of the natural patterns of SOC accumulation and ecosystem productivity. An objective of such management should be to maximize organic matter productivity and ecosystem values, while optimizing SOC conservation and accumulation.

Research Needs

More attention on total carbon budgets is needed. Studies must be constrained by: life zone, edaphic and topographical factors, age of stands, and land use (past and present). More attention on SOC turnover and quality (they are related) is also a priority. For a general understanding of this problem we will need standardized methodology. The Tropical Soil Biology and Fertility Program of IUBS and MAB programs is a good example to follow. We also need to develop and test landscape-level management schemes that focus on the productivity and biodiversity of the land and seek long-term sustainable solutions to the question of natural values.

Literature Consulted

Brown, S. and A.E. Lugo. 1982. The storage and production of organic matter in tropical forests and their role in the global carbon cycle. Biotropica 14:161-167.

Brown, S. and A.E. Lugo. 1990. Effects of forest clearing and succession on the carbon and nitrogen content of soils in Puerto Rico and US Virgin Islands. Plant and Soil (in press).

Brown, S. and A.E. Lugo. 1990. Tropical secondary forests. Journal of Ecology 6:(in press).

Holdridge, L.R. 1967. Life Zone Ecology. Tropical Science Center, San Jose, Costa Rica.

Lugo, A.E. 1988. The future of the forest. Environment 30(7):16-20, 41-45.

Lugo, A.E. Comparison of four small tropical tree plantations (Pinus caribaea and Swietenia macrophylla) with secondary forests of similar age. In review, Ecological Monographs.

Lugo, A.E., D. Wang, and F.H. Bormann. 1990. A comparative analysis of biomass production in five tropical tree species. Forest Ecology and Management 31:(in press).

Lugo, A.E., E. Cuevas, and M.J. Sanchez. 1990. Nutrient and mass in litter and top soil of ten tropical tree plantations. Plant and Soil (in press).

Lugo, A.E. and F.N. Scatena. 1991. Ecosystem-level properties of the Luqillo Experimental Forest with emphasis on the tabonuco forest. In A.E. Lugo and C. Lowe, eds., One Hundred Years of Tropical Forestry Research. Springer-Verlag (in review).

Lugo, A.E., M.J. Sanchez, and S. Brown. 1986. Land-use and organic carbon content of some subtropical soils. Plant and Soil 96:185-196.

Wang, D., F.H. Bormann, A.E. Lugo, and R.D. Bowden. The implications of nutrient-use efficiency on fiber harvest for five tropical tree taxa. Manuscript.

Weaver, P.L., R.A. Birdsey, and A.E. Lugo. 1987. Soil organic matter in secondary forests of Puerto Rico. Biotropica 19:17-23.

APPENDIX D: LETTER FROM DAVID JENKINSON

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8 February 1990

Dear Dr Johnson,

I am very sorry I will not be able to attend the workshop you are arranging on 'Sequestering Carbon in Soils', particularly as I am sure it will prove to be a most interesting and useful meeting. When we spoke on the 'phone, I promised you details of Rothamsted work that might be relevant to some of the workshop topics. Herewith a list.

1. Retention of organic manure carbon by soil
Two of the Rothamsted Classical Experiments provide data on this - see enclosed Intecol paper. figures 5 and 6. A very large input of farmyard manure (35 tonnes ha^{-1} $year^{-1}$) has been applied every year for more than 100 years in both experiments. Thirty-five tonnes of wet FYM contains about 3 tonnes of C, which comes from about 4 tonnes of fresh plant C, or about 10 tonnes of fresh plant dry matter. In the Hoosfield experiment (Fig. 6), 186 tonnes of FYM C had been added between 1851 and 1913. In 1913 the FYM plot contained 49 tonnes more C than the unmanured control, so that an average of 26% of the FYM C had been retained in the soil over the 62 year period. The corresponding retention of FYM C in the Broadbalk experiment (Fig. 5) over the 1843-1914 period was a little less, 21%. These figures are of course only averages - retention will be a little higher in the early years and a little lower in the later years of the period. As time goes on, the retention of C will decrease as the soil comes to a new equilibrium, with the annual input of carbon the soil, *including that from FYM*, balanced by the annual output of CO_2-C.

2. Gain of C by soils reverting to woodland
I enclose two graphs showing the gains of organic C in the topsoil (0-23 cm) in two small areas of old arable land on Rothamsted Experimental Farm that were fenced off in the early 1880s and allowed to revert naturally to woodland. I also enclose a reprint of an earlier paper describing these two areas in detail. When sampled in 1964-65, some 80 years after reversion had started, the Geescroft site had gained 21 tonnes C ha^{-1} in the 0-23 cm layer (corrected for changes in bulk density) and 72 tonnes C in the trees: the corresponding figures for the Broadbalk site were 43 tonnes and 110 tonnes.

LAWES AGRICULTURAL TRUST

3. Crop yields and soil organic matter levels
I enclose a reprint that may be of interest if you wish to consider this particular aspect of the sequestration of organic C in soils.

I hope these comments will be of use and wish you well in your task of organising the workshop.

With all good wishes

Yours sincerely

David Jenkinson

D.S. Jenkinson

Encs

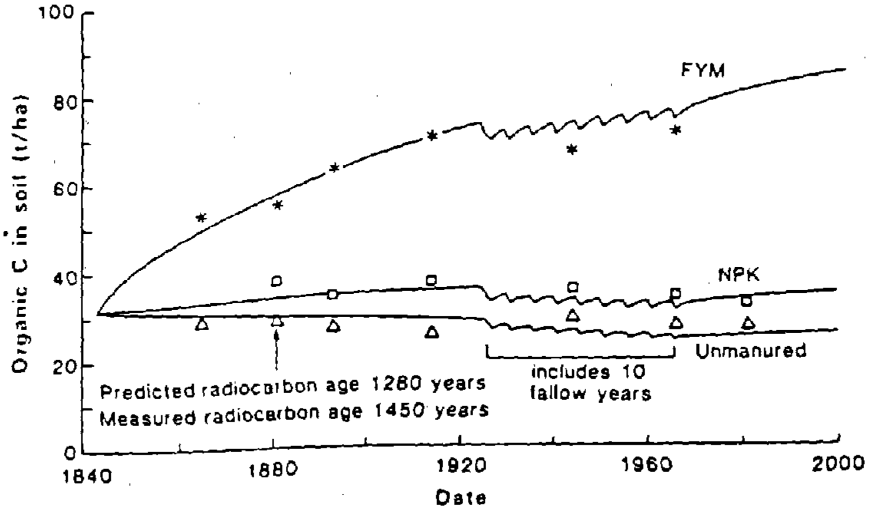


Figure 5. Organic C in the top 23 cm of a Rothamsted soil under continuous winter wheat (Broadbalk). Data calculated from %N in soil (as given by Jenkinson 1977b, using a soil weight of 2.91 M kg/ha, apart from the 1981 results which are from Powlson et al. 1986), using C/N ratios of 9.41, 9.91, and 10.28 for plots 03, 08, and 22, respectively, and allowing for changes in bulk density in plot 22. Inorganic CEC is 10.8 me/100 g soil in this and in all other Rothamsted field experiments (Figs. 6 and 7). Plot 03 is unmanured; the NPK plot (08) receives 144 kg N, 35 kg P, and 90 kg K/ha per year, apart from fallow years; the FYM plot (22) receives 35 t FYM annually. The FYM, applied in early autumn, was assumed to be equivalent to 75% of the original plant material from which it came and to contain DPM, RPM, and HUM (but no biomass) in the proportions 0.65, 0.30, and 0.05, respectively. In fallow years, decomposition was assumed to proceed as usual with no fresh FYM or plant debris entering the soil. The C inputs used, all in t C/ha per year, were: unmanured plot, 1.2; NPK plot, 1.9; FYM plot, 1.9 (plant debris) + 3.0 (FYM).

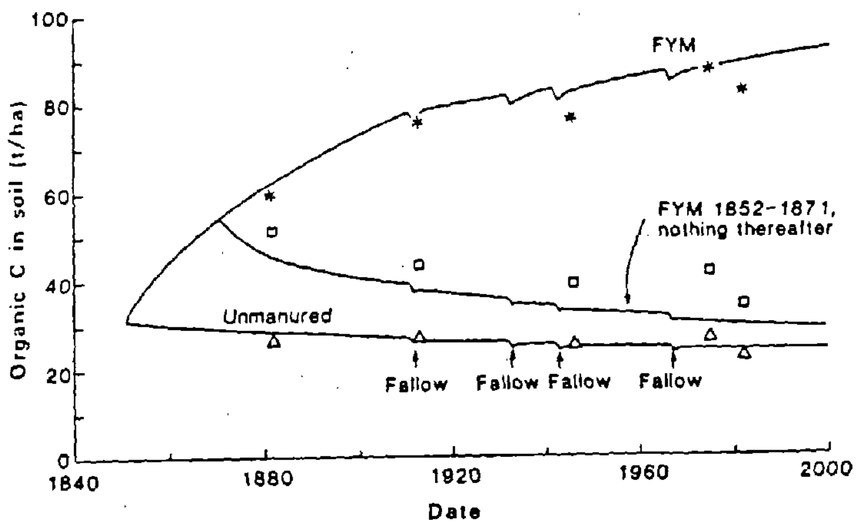
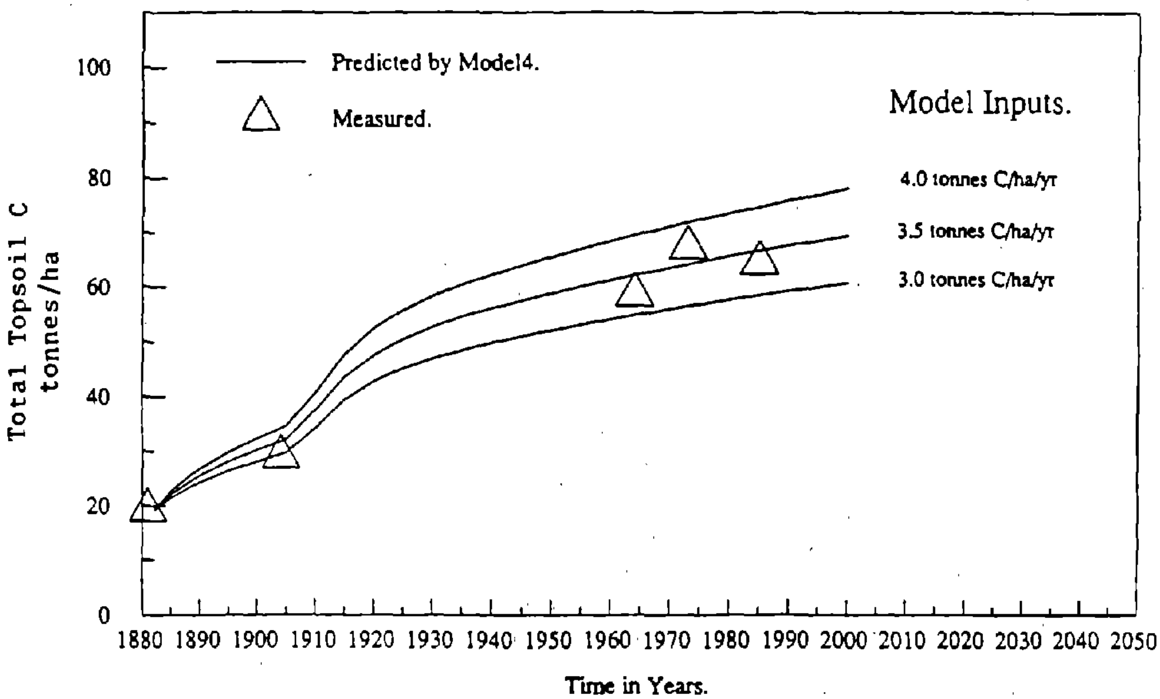
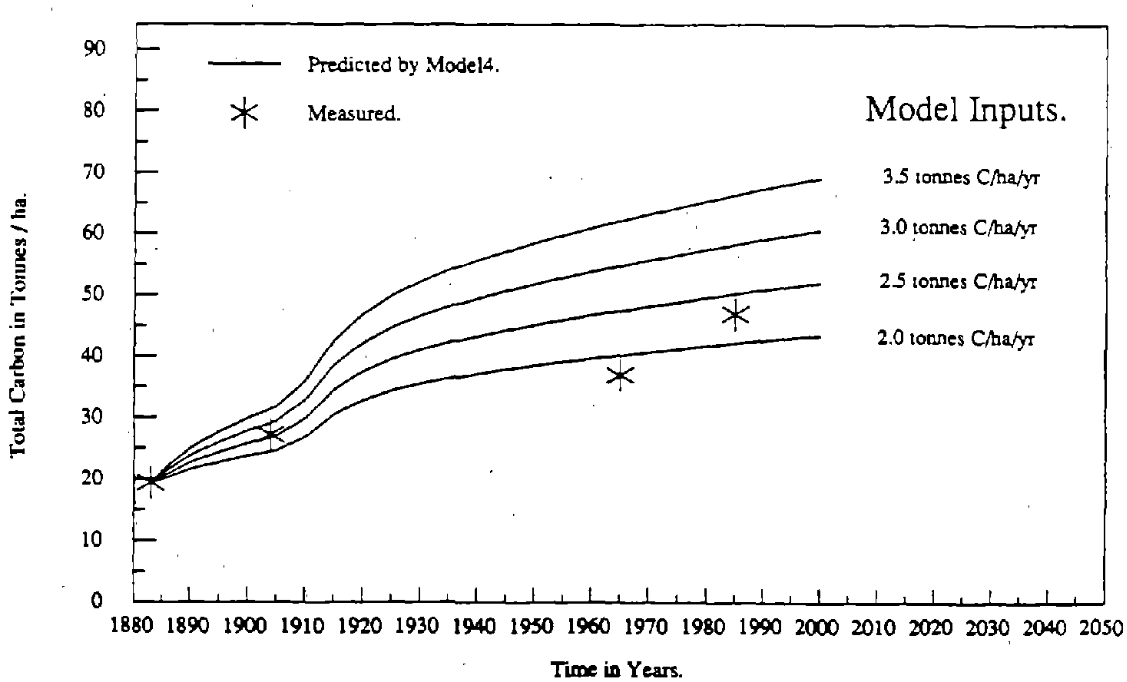


Figure 6. Organic C in the top 23 cm of a soil under continuous spring barley (Hoosfield). Data, corrected for changes in bulk density, are from Jenkinson and Johnston (1977), except for results for 1982 (unpublished). Plot 1-0 is unmanured; the FYM plot (7-2) receives 35 t FYM annually; the FYM residues plot (7-1) received 35 t FYM annually between 1852 and 1871 and nothing since. The FYM, applied in late autumn (after 1916), was assumed to be equivalent to 60% of the plant material from which it came and to contain DPM, RPM, and HUM (but no biomass) in the proportions 0.53, 0.38, and 0.09, respectively. Before 1916, FYM was applied in spring and was assumed to be equivalent to 45% of the original plant material, the corresponding proportions being 0.34, 0.49, and 0.17. The C inputs used, all in t C/ha per year, were: unmanured plot, 1.1; FYM plot, 1.5 (plant debris) + 3.0 (FYM); FYM residues plot, as FYM plot during 1852-1871, 1.5 during 1872-1876, thereafter, 1.1.

Broadbalk Wilderness, Rothamsted Experimental Station.



Geescroft Wilderness, Rothamsted Experimental Station.



APPENDIX E: LETTER FROM HANS JENNY

<u>Memorandum on sequestering carbon in soils</u>

Hans Jenny, February 1990

1. Soil is a good preserver of organic carbon. In lower horizons "apparent mean residence times" of 10,000 - 20,000 years have been measured.

2. A world-wide estimate of soil carbon content (exclusive of forest floor) was published by Jerry Olson and Paul Zinke. Dr. W.M. Post may be familiar with it. The survey may tell where on the globe soils acquired high carbon contents. I had concluded that well-drained soils at high elevation in the tropics tend to be high in carbon (H.J. The Soil Resource, p.320, 1980), and a Safari to Mt. Kilimanjaro in Africa confirmed it.

3. To estimate past oxidation of soil carbon caused by farming, assume the conservative loss of 50% C for the soil depth of 0-20 cm, and 10% for the rest of the profile.

4. Assumedly, incorporation of carbon into subsoils occurs mainly by root-growth and decay. Roots to depths of over 50 feet have been observed.

5. With this in view, forests and grasslands and crop rotations should be encouraged to include deep-rooting species.

6. This approach would require a reversal of the trend of plant breeders who now direct the flow of photosynthate to stems, leaves, flowers and seeds. Scientists would have to start breeding root systems.

7. To fill up a soil with carbon to its carbon-carrying capacity (near steady state) will require many generations of trees, shrubs, and other green species.

8. As a curiosity, if finely grounded basalt rock high in calcium (CaO) were spread in forests it would fix CO_2 and make a $CaCO_3$ -enriched soil.

Hans Jenny

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TECHNICAL REPORT DATA
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1. REPORT NO. EPA/600/3-91/031	2.	3. R PB91-216390
4. TITLE AND SUBTITLE Sequestering Carbon in Soil: A Workshop to Explore the Potential for Mitigating Global Climate Change		5. REPORT DATE April 1991
		6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Mark G. Johnson and Jeffrey S. Kern		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS METI, Inc., ERL-Corvallis, OR		10. PROGRAM ELEMENT NO.
		11. CONTRACT/GRANT NO.
12. SPONSORING AGENCY NAME AND ADDRESS US Environmental Protection Agency Environmental Research Laboratory 200 SW 35th Street Corvallis, OR 97333		13. TYPE OF REPORT AND PERIOD COVERED Published Report
		14. SPONSORING AGENCY CODE EPA/600/02

15. SUPPLEMENTARY NOTES

1991. U.S. Environmental Protection Agency, Environmental Research Laboratory, Corvallis, OR.

16. ABSTRACT

This workshop was an excellent forum for a scientific debate on the potential of soils to sequester additional carbon from the atmosphere. Two primary conclusions can be drawn from the workshop. First, that steps should be taken to protect and preserve the size and integrity of the global reservoir of soil carbon because continued losses of soil carbon to the atmosphere could exacerbate global warming and climatic change. Second, that steps should be taken to manage soils and ecosystems to store additional carbon. The latter being accomplished predominately by increasing net primary production. The major uncertainties related to carbon sequestration in soils and specific strategies for addressing these uncertainties and for managing soils to store carbon were also identified at this workshop.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
carbon, climate change, soils, global carbon cycle		

18. DISTRIBUTION STATEMENT Release to Public	19. SECURITY CLASS *(This Report)* Unclassified	21. NO. OF PAGES 100 pgs
	20. SECURITY CLASS *(This page)* Unclassified	22. PRICE

EPA Form 2220-1 (9-73)