AN APPROACH TO ASSESSMENT OF MANAGEMENT IMPACTS ON AGRICULTURAL SOIL CARBON

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ABSTRACT. Agroecosystems contain about 12% of the terrestrial soil C and play an important role in the global C cycle. We describe a project to evaluate the degree to which management practices can affect soil C in agroecosystems. The objectives of the project are to determine if agricultural systems can be managed to conserve and sequester C and thereby reduce the accumulation of CO_2 in the atmosphere, and to provide reference datasets and methodologies for agricultural assessments.

1. Introduction

Carbon movement between the atmosphere, oceans, and terrestrial systems is in a dynamic equilibrium. One recent generally accepted estimate of the sizes of these pools, and the fluxes among them, is shown in Figure 1, redrawn from the Intergovernmental Panel on Climate Change's (IPCC) report Climate Change (Houghton et al. 1990).

The atmospheric pool, at 750 Gt C (1Gt = 10^{12}kg) is the smallest of the major C pools and is reliably measured to be increasing at a rate of 3 Gt C yr^{-1}. Many recent studies, summarized in the IPCC report, have projected that this increase will cause worldwide climate change. This increase is attributed to deforestation ($\sim$2 Gt C yr^{-1}) and fossil fuel combustion ($\sim$5 Gt C yr^{-1}). A mass balance argument estimates that about 4 Gt C

Water, Air, and Soil Pollution **64**: 423–435, 1992.

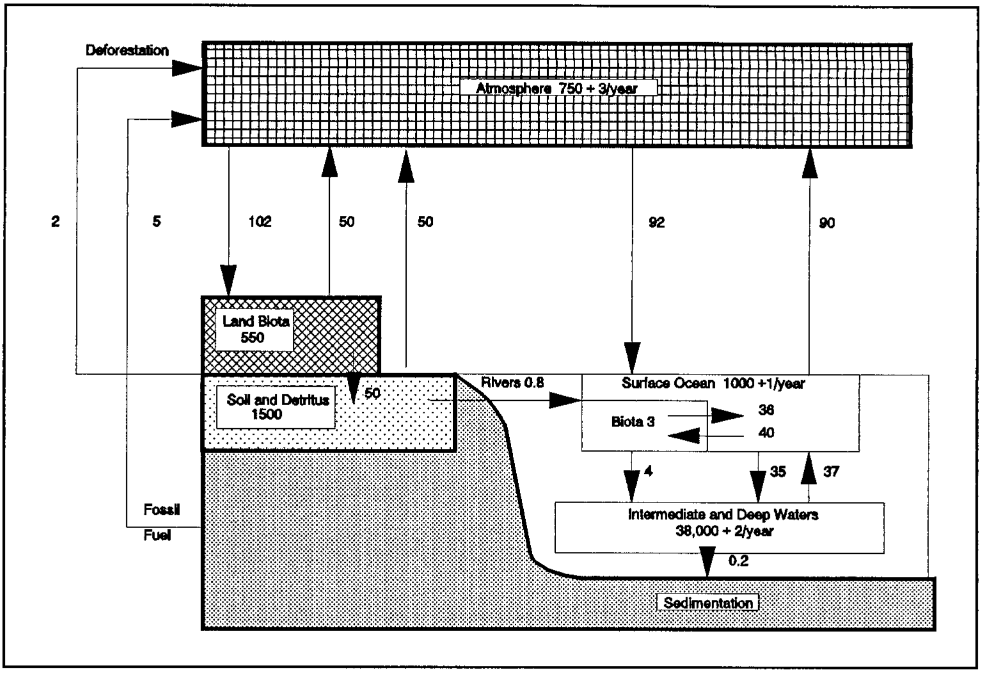


Figure 1 - Global Carbon Pools and Fluxes

yr^{-1} of these anthropogenic emissions are recycled back into the oceanic and terrestrial pools. The IPCC report allocates this recycled C equally between terrestrial and oceanic systems, but a recent paper (Tans et al. 1990) argues that the terrestrial sink is larger than the oceanic sink, and is between 2.0 and 3.4 Gt C yr^{-1}.

The surface ocean pool, at 1000 Gt C, is a large C reservoir, and some proposals for active management have been made. These proposals involve stimulation of biological activity in the southern oceans through addition of Fe, one of the limiting nutrients in these systems. There is, however, considerable scientific discussion with respect to the validity of this proposal. The deep ocean, at 38,000 Gt C, is the largest C reservoir, but is relatively inaccessible and generally not believed to be subject to active management.

Just over 2000 Gt C are contained in terrestrial pools, about 550 Gt C in living vegetation and 1500 Gt C in soil organic matter (SOM). Because this C pool is three times the size of the atmospheric pool, changes in terrestrial systems are important in affecting the sensitive atmospheric pool. It is interesting to examine the time history of net terrestrial C emissions (Figure 2, Houghton et al. 1983). For much of the last 100 yr, C emissions from land use change (degradation of biota and soils) have exceeded emissions from fossil fuel combustion. Fossil fuel emissions of C surpassed those from biota and soils in the 1950s and have increased dramatically since, although there has been a short-term trend in the 60s and 70s indicating that the biota/soils emissions have been constant, or at least decreasing less rapidly.

The U. S. Environmental Protection Agency is evaluating the potential for active management of terrestrial C, both through reforestation and good stewardship of agricultural resources. This paper deals with the approach being developed for agricultural systems. Clearly, some agricultural management practices can induce dramatic changes in soil organic C. The classic experiments at Rothamsted, England (Figure 3, Jenkinson 1991) demonstrate a three-fold increase in soil C storage through application of farm yard manure. It is probably not possible to achieve these results on a large scale, but the data do demonstrate potential. An interesting note concerning these data is that soil C still has an upward trend after 140 yr of active management. While reforestation can probably sequester great quantities of C in the short-term, steady-state will likely be reached in 15 to 30 yr. Soils, on the other hand, have the potential for much longer accumulation.

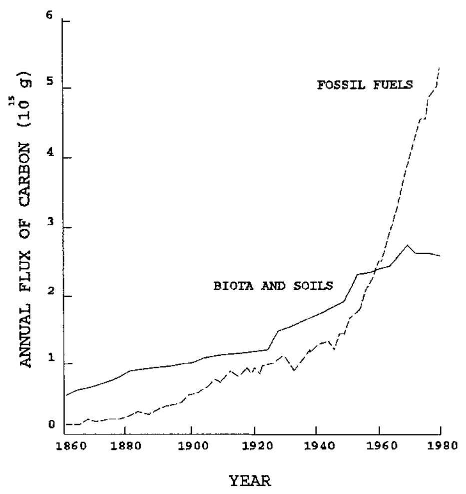


Figure 2 - Time history of terrestrial carbon emissions.

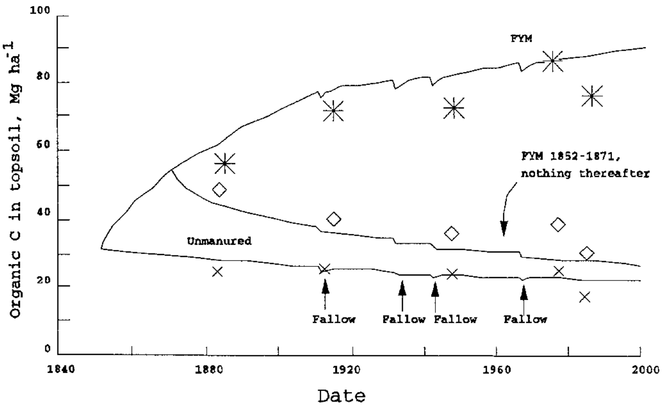


Figure 3 - Organic carbon in the topsoil of a plot at Rothamsted, England. The symbols show experimental observations; the solid line is a model fit. FYM is farm yard manure.

2. Assessment of soil C sequestration potential for U. S. agroecosystems

The objectives of the project are to determine if agricultural systems can be managed to conserve C and thereby reduce the accumulation of CO_2 in the atmosphere, and to provide reference datasets and methodologies for agricultural assessments. Application of agroecosystem management practices can increase the terrestrial C pool, thereby reducing the build-up of atmospheric C. In particular, many environmentally beneficial agricultural practices increase soil C content. The program will assess the potential agroecosystem contribution to global C conservation and sequestration.

The impact of alternative management practices on agricultural soil C is being estimated by a soil C mass balance model and analysis of agricultural production cycles, development of data bases for agroecosystem C pools and dynamics, development of spatial data bases for assessment of agricultural C sequestration poten-tial, and development of cost factors. A brief review of the Agroecosystems Carbon Pools and Dynamics project is included in this paper, as well as a review of soil C models. A strategy for incorporating policy considerations in the analysis is also described.

3. Agroecosystem Carbon Pools and Dynamics

The objective of this project element is to conduct field and laboratory investigations to develop defensible data to evaluate C pools and dynamics for agroecosystems, to identify critical soil and climatic parameters that might affect those dynamics, and to validate the models developed to assess the impact of alternative agricultural management practices on C storage and fluxes in agroecosystems.

The conversion of native ecosystems to agricultural lands in the Great Plains and Corn Belt regions of the Central United States was perhaps the most extensive ecological disturbance known in North America during the past 150 yr (Wilson 1978). A major consequence of this land conversion has been the substantial loss of organic matter from soils across the regions (Haas et al. 1957, Campbell 1978). These soil C losses have been a primary anthropogenic source of CO_2, second only to fossil fuel combustion in contributing to historical increases of global CO_2 concentrations (Houghton et al. 1983, Post et al. 1990).

Since soil C levels in most Great Plains and Corn Belt agricultural areas have been reduced to levels well below those existing prior to the establishment of agriculture, the potential should exist to increase present soil C levels, thereby providing a sink for atmospheric CO_2. At present there is considerable debate whether increases in atmospheric CO_2 concentrations and global warming will result, independently, in significant changes in soil C storage (e.g., Prentice and Fung 1990, Schlesinger 1990). While not discounting the importance of these factors, increasing agricultural soil C levels may be more dependent on agricultural management practices and land use changes.

Many of the agricultural practices that have been traditionally applied in the Great Plains and Corn Belt (e.g., moldboard plowing, fallow with no plant cover, removal or burning of crop residues and monoculture cropping (Cole et al. 1989)) represent a "worst-case" for soil C maintenance by minimizing organic matter inputs and promoting a high degree of soil organic matter decomposition. Currently, agricultural management in the United States is undergoing rapid change in response to a variety of pressures, including high costs of energy and chemical inputs, environmental concerns about nutrient and pesticide pollution and soil erosion, and product quality demands by consumers. It is encouraging to note that many of the techniques designed to address these issues have also demonstrated a potential for increasing soil C levels above those maintained under conventional management. Such practices include reduced or no-till management (Blevins et al. 1983, Dick 1983, Lamb et al. 1985); reduction in the proportion of fallow land relative to crop in semiarid regions (Wood et al. 1991); and use of cover crops, green manure, and animal manure (Paustian et al. 1992, Jenkinson 1991, Vitosh et al. 1973). However, the extent to which soil C levels can be regulated through the application of various combinations of these practices for different cropping systems, soil types, and climatic regions is not yet clear.

In addition to changing management trends on production land, land use changes may have a considerable impact on region-wide C storage potential. Over the past 50 yr, significant acreage in cropland has been abandoned or converted back into perennial grassland and forest. For example, more than 100,000 ha of farmland in northeast Colorado alone were abandoned during the 1930s. In more recent years, large areas of Great Plains cropland have been converted to grassland under the Conservation Reserve Program (Joyce and Skold 1988). Similar changes have occurred in regions of the Corn Belt, in particular in the Great Lakes region and in eastern areas bordering on the Appalachians. For example, from 1950 to 1990, the agricultural land base of Michigan declined by $3x10^6$ ha, much of which was previously in corn, soybean and wheat production (Michigan Dept. Agric. 1990). To date, there has been little systematic evaluation of how these shifts in land use have affected regional soil C balances or what effect future changes may have.

While data from long-term field studies has provided much information about the possible rates and directions of change in soil C under various management regimes, our current knowledge base is very fragmented. Most of what we know concerning soil organic matter (SOM) dynamics has been obtained by studying SOM losses. We understand less about controls on SOM accumulation and how they vary across soil types, climatic regions and management regimes. Such information is crucial for estimating the potential for C sequestration in agricultural soils of the Great Plains and Corn Belt regions.

Studies are focusing on corn, soybeans, wheat and rangelands. Priority is being given to sites with historical data of the effects of management practices on SOM and supporting data pertaining to climatic conditions. Data will be used to parameterize and evaluate C budget models developed in other tasks of the project. A network of field sites (Figure 4) has been organized through a cooperative agreement with Colorado State University and Michigan State University. Emphasis is on collection, preparation, and evaluation of C budget data. Sites where comparisons of management practices are possible will be given highest priority. Because of their spatial and temporal variability, CO_2 and other greenhouse gas fluxes will be inferred from soil storages rather than measured. Outputs of the studies will be useful in the quantification of soil and plant organic C pools and dynamics for the dominant agricultural crops, including rangelands, in the two regions.

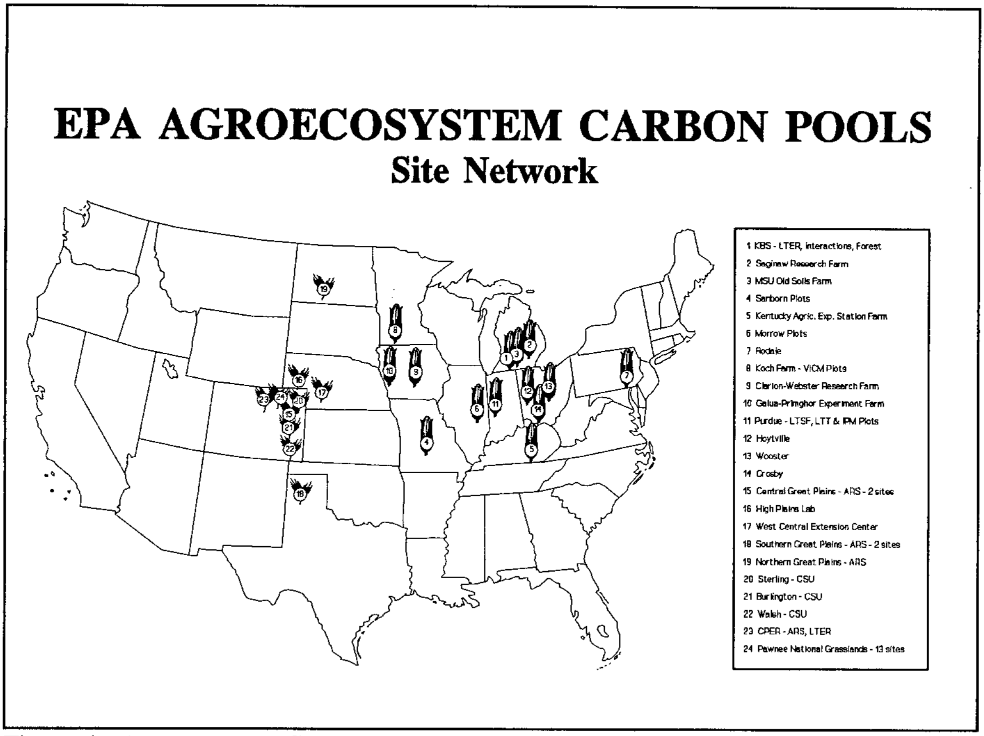


Figure 4 - Agroecosystem Carbon Pools Site Network

4. Soil Carbon Models

A literature review of soil C modeling, CO_2 emissions and climate change, and soil C budgets and impacts of soil and agricultural practices has been completed (Barnwell et al. 1991). In addition, a summary of major C computer models identified in the literature survey are included. Based on the preliminary review, a list of evaluation criteria and capabilities for comparison of soil C models has been compiled, and these criteria have been used to select models for evaluation of agricultural soil sequestration capabilities. These models will be incorporated into a comprehensive evaluation framework as described in section 5.

The focus of the literature search has been on the identification and documentation of available soil C models; investigation of soil C budgets, transformation, and pathways in agroecosystems; and determination of the impacts of tillage and cropping practices on the soil C cycle. The preliminary evaluation of available soil C models listed in Figure 5 reduced the number of 'candidate models' to four or five primary models that were evaluated further. The existing models are primarily 'research models' in that few have undergone more than limited independent field testing and validation. One of the key issues is to provide a level of model complexity (and associated data requirements) that is consistent with the project needs **and** is also compatible with the national level

Model Name	Reference
CENTURY Model	Parton et al., 1988
DNDC Model	Li et al., 1991a; Li et al., 1991b; Li et al., 1991c
Jenkinson and Rayner Model	Jenkinson and Rayner, 1977; Jenkinson 1990, Jenkinson et al., 1991
Frissel and van Veen	Frissel and van Veen, 1981; van Veen and Paul, 1981; van Veen et al., 1984
OBM Model	Esser, 1990
NCSWAP Model	Clay et al., 1985
TEM Model	Raich et al., 1991
Box Model	Box, 1988
Gildea et al. Model	Gildea et al., 1986
Moore et al. Model	Moore et al., 1981
Smith Model	Smith, 1979
PHOENIX Model	McGill et al., 1981

Figure 5 - List of soil C models reviewed

databases available for providing the model input.

The models selected for use and/or modification to meet the needs of representing soil C cycles in agroecosystems and impacts of management practices are CENTURY and DNDC. These models share a common ability to examine the impacts of alternative management practices on soil organic C, and are readily accessible for these studies. A brief review of the capabilities and application experience with these models follow.

4.1 CENTURY Model

Parton et al. (1988) developed the CENTURY model to simulate the dynamics of C, N, P, and S in cultivated and uncultivated grassland soils. The model uses monthly time steps for simulation, and runs can be performed for time periods ranging from 100 to 10,000 yr. The model simulates three soil organic matter fractions: 1) active fraction (turnover time of 1 to 5 yr); 2) a protected fraction that is resistant to decomposition (turnover time 20 to 40 yr); and 3) a physically protected and chemically resistant fraction (turnover time of 200 to 1500 yr). Model simulations yielded satisfactory results in terms of long-term soil formation, weathering of P and S from soil parent material and the formation of organic P and S in different SOM fractions.

Schimel et al. (1990) studied grassland biogeochemistry and its link to atmospheric processes. Model simulations obtained using the CENTURY model adequately represented the observed geography of C and N. Cole et al. (1989) modeled the effects of land use on SOM dynamics in the North American Great Plains using the CENTURY model. The model results were compared with a 30- to 40-year observed data set. The study found that "the effects of a range of soil textures on the original amounts and forms of C, N and P in the soils and changes upon cultivation correspond well with observations of detailed field studies". Parton et al. (1989) studied the regional pattern dynamics of C, N, and P in the U.S. central grassland region using the CENTURY model. A comparison of simulated P and C results with observed data showed good correlation. Paustian et al. (1991) performed model analyses using the CENTURY model for studying the influence of organic amendments and N-fertilization on SOM in long-term plots. Changes in soil C and N after 30 yr were predicted within $\pm$ 30% of observed values.

A geographic information system (GIS) was used with the CENTURY model for regional modeling of grassland geochemistry (Burke et al. 1990). The driving variables for the model consisted of soil texture, monthly precipitation, and monthly minimum and maximum temperatures, which were included in the GIS. Net primary production was affected primarily by climatic factors, and it closely followed spatial variation in precipitation. However, it was reported that SOM is controlled by soil texture.

4.2 DNDC Model

Li et al. (1991a) developed the physically based model DNDC (Denitrification Decomposition Model) for estimating N_2O and N_2 evolution from soils. The submodels included in the model are thermal-hydraulic flow, decomposition and denitrification. The model calculates dynamic soil temperature and moisture profiles, and estimates the shift of aerobic-anaerobic conditions in soils using climatic data of rainfall events and air temperature. The dominant processes between rainfall events are the decomposition of organic matter and the oxidation reactions. These processes affect levels of total organic C, soluble C and nitrate in soils between rainfall events. However, during rainfall the dominant process is that of denitrification resulting in production of N_2O and N_2. The major input data requirements for the DNDC model consist of the climatic scenario, soil texture and its properties, and initial organic matter and nitrate in soil. Li et al. (1991b) have also conducted sensitivity and simulation analysis for the DNDC model. Li et al. (1991c) applied the DNDC model for estimating N_2O emissions from fallow, grass and sugarcane fields at Belle Glade, FL. Good agreement was reported between simulated and observed results of N_2O emissions, N mineralization rates, and changes in nitrate and ammonium at the soil surface.

5. Assessment Framework

An important aspect of this effort is the development of the modeling framework and methodology that will define the agricultural production systems and scenarios (i.e., crop-soil-climate combinations) to be assessed in terms of national and international policy, the integration of the model needs with available databases, and the operational mechanics of evaluating C sequestration potential with the integrated model/database system. Figure 6 represents our operational strategy at this time.

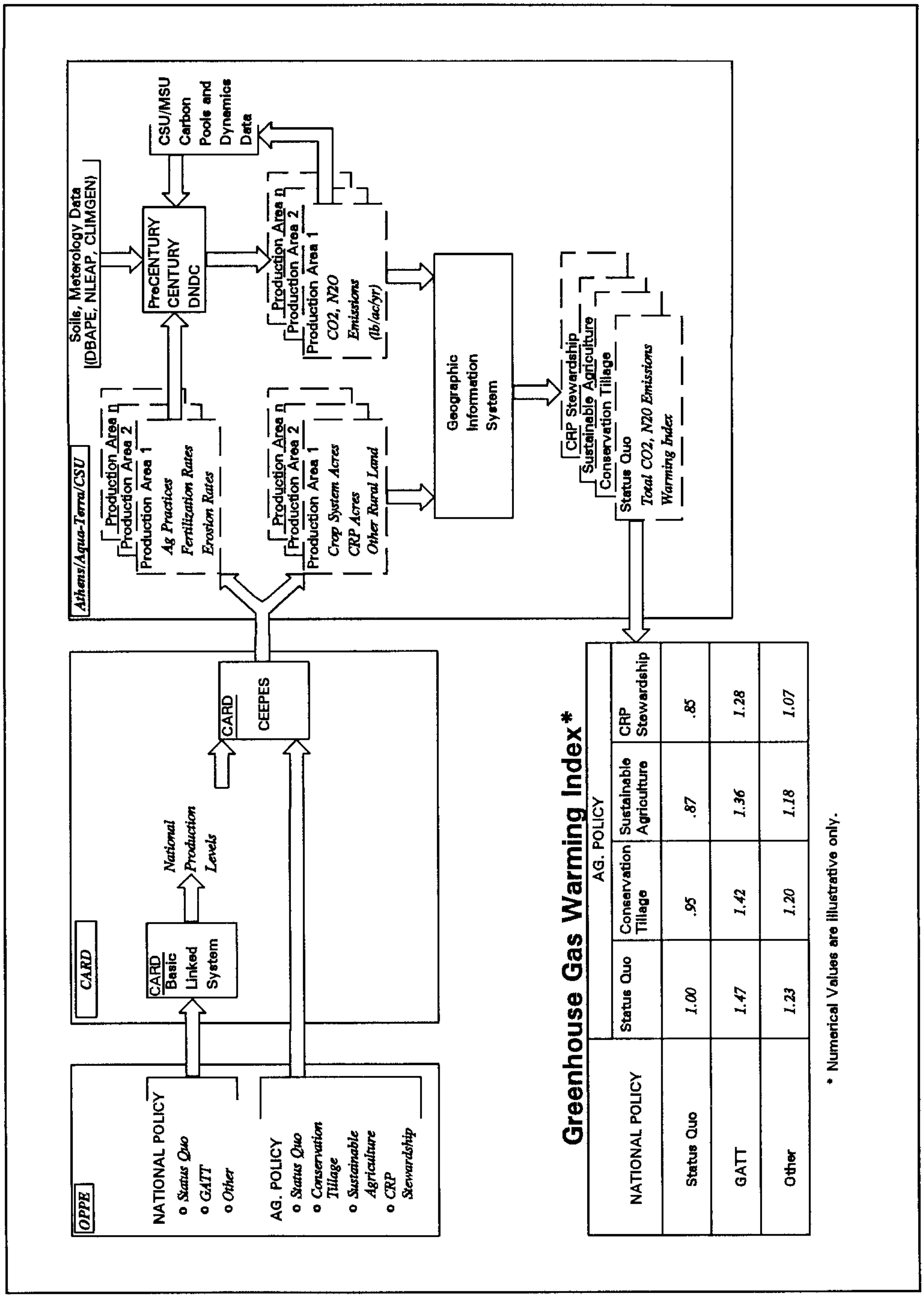
The objective of the assessment is to estimate the greenhouse gas emissions from agriculture and to estimate the relative impact of various policy alternatives on these emissions. We are working closely with the U. S. EPA's Office of Policy and Program Evaluation (OPPE) and Iowa State University's Center for Agricultural and Rural Development (CARD) to define a reasonable set of policy alternatives for this assessment. An example set of policy alternatives is shown in the box labeled "OPPE" in Figure 6. Included are national policy alternatives such as the impact of a Global Agreement on Trade and Tariffs (GATT) and their possible effect on national agricultural production levels, as well as agriculture policy alternatives that might be affected through a revised Farm Bill, such as incentives to selectively promote conservation tillage, sustainable agriculture, or good stewardship of the conservation reserve.

As shown in the box labeled "CARD", these policies will be used to drive economic models that predict national production levels using models such as the Basic Linked System (BLS), a set of national and regional models linked by policy and a world price determination process. CARD's Comprehensive Environmental Economic Policy Evaluation System (CEEPES) will be used to translate policy alternatives into basic data for use in soil C models. These data, including such elements as agricultural practices, fertilization rates, and erosion rates will be used in the soil C models to produce net greenhouse gas emissions on a per unit area basis.

Data will be produced for a range of "Production Areas," which are hydrologic areas defined by the Water Resources Council that are used for aggregated economic reporting. The economic models also will provide statistics on crop acres, acreage in the conservation reserve, and other rural land usage. The unit-area emissions will be combined with areal-extent data in a GIS to produce an estimate of total greenhouse gas emissions and to calculate an aggregate greenhouse gas warming index. The greenhouse gas warming index will represent the combined impact of CO_2 and N_2O emissions. We plan to produce a table (Figure 6) that, we hope, will communicate the aggregate impact of alternative policies in a simple, effective manner.

6. Conclusions

It is clear that agricultural soil C has been depleted over the last century. This study will assess the current size of this C pool and examine the potential for alternative agricultural management practices to alter its size. Many of the agricultural management techniques that favor accumulation of soil organic C also have other positive environmental benefits, so their use is being encouraged for other reasons. While it is not clear at present the extent to which soil C levels can be managed using these techniques, we hope through this study to provide a better estimate than currently available.



NATIONAL POLICY	AG. POLICY: Status Quo	Conservation Tillage	Sustainable Agriculture	CRP Stewardship
Status Quo	1.00	.95	.87	.85
GATT	1.47	1.42	1.36	1.28
Other	1.23	1.20	1.18	1.07

Figure 6 - Strategy for Assessment of Agricultural Carbon Sequestration Potential

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