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Use of a network of long-term experiments for analysis of soil carbon dynamics and global change: the North American model

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Summary. Soils contain a large proportion of the carbon (C) in the terrestrial biosphere, yet the role of soils as a sink or a source of net atmospheric C flux is uncertain. In agricultural systems, soil C is highly influenced by management practices and there is considerable interest in adapting management systems to promote soil C sequestration, thereby helping to mitigate atmospheric CO_2 increases. Long-term field experimental sites represent a unique source of information on soil C dynamics, and networks of such sites provide a key ingredient for making large-scale assessments of soil C change across ranges in climate and soil conditions and management regimes. Currently, there are collaborative efforts to develop such site networks in Australia, Europe, and North America.

A network of long-term experiments in North America was established to provide baseline information on the effects of management (i.e. tillage, crop rotations, fertilisation, organic amendments) on soil organic matter. Historical data on soils, primary productivity, climate, and management were synthesised by scientists from the individual field sites, representing a total of 35 long-term field experiments. An additional cross-site soil sampling campaign was carried out to provide uniform comparisons of soil C and nitrogen (N), both within and across sites.

Long-term field experiments are a principle component necessary for regional assessments of soil C dynamics. We describe a general methodology for combining long-term data with process-oriented simulation models and regional-level, spatially resolved databases. Such analyses are needed to assess past and present changes in soil C at regional to global scales and to make projections of the potential impacts of changes in climate, CO_2, and landuse patterns on soil C in agroecosystems.

Introduction

Soil organic matter (SOM) has long been recognised as an important aspect of soil fertility, and organic matter studies have been prominent in the fields of soil science and agronomy. Until recently most research was aimed at understanding SOM dynamics, to optimise its benefits for agricultural production. While these research objectives continue to be very important, recent concerns about human perturbations of the earth's atmosphere and the potential alteration of the earth's climatic systems have resulted in additional interest in the role of SOM dynamics in greenhouse gas emissions and the global carbon (C) cycle.

Aside from fossil fuel deposits, the world's soils contain the largest terrestrial store of C; cultivated soils alone are estimated to contain in the order of 170 Gt of C in the upper 1 m of soil (IPCC 1995). Thus, relatively small changes in soil C levels, when considered on a global scale, may significantly affect the terrestrial C balance. Current issues dealing with soils and the global C balance include the following: whether the world's soils are presently a source or sink for C (Bouwman 1990; Wisniewski and Lugo 1992; Wisniewski and Sampson 1993); how soil C levels will respond to global CO_2 enrichment and/or predicted global warming (Jenkinson *et al.* 1991; Schimel *et al.* 1994); and whether soils can be managed as a C sink to help mitigate increased atmospheric CO_2 (Barnwell *et al.* 1992; IPCC 1995). To answer these questions, scientists need the means to conduct regional and global level analyses of past and current trends in soil C and to integrate models of soil C dynamics with projections of future changes in climate, vegetation, and landuse.

Long-term field experiments have a number of characteristics lending them to addressing questions about C dynamics in soil. A primary attribute of such experiments is their longevity. Because annual changes in SOM are generally small relative to the amounts

Table 1. Description of long-term field experiments in the North America site network

MAT, mean annual temperature

Cropping systems: A, alfalfa; B, barley; brome, bromegrass; C, corn; Cl, clover; Fa, fallow; FB, faba bean; Fo, forage; H, hay; L, lentil; M, millet; NB, navy beans; O, oat; R, rye; S, soybean; SB, sugar beets; SF, sunflower; Sor, sorghum; W, wheat

Tillage: conv., conventional; min., minimum

Treatments: fert., fertility; rot., rotation; till., tillage

Site and location	Soil type	MAT (°C)	Precip. (mm)	Start	Cropping systems	Tillage	Treatments	No. of treatments	Source
1. Arlington, WI	Argiudoll	7.6	793	1958	C	Conv.	Fert.	3	Vanotti *et al.* (1996)
2. Lancaster, WI	Hapludalf	7.8	832	1967	C, A, C–S–C–O–A, C–C–C–A–A, C–C–O–A–A, C–A	Conv.	Rot., fert.	21	Vanotti *et al.* (1996)
3. Lamberton, MN	Haplustoll	6.2	632	1960	C	Conv.	Fert.	18	Huggins and Fuchs (1996)
4. Kellogg Biol. Stn, MI	Hapludalf	9.2	920	1986	C–S, never-tilled grassland	Conv., no-till.	Till., fert.	7	G. P. Robertson (pers. comm.)
5. E. Lansing, MI	Hapludalf	8.5	728	1963	C (grain), C (silage)	Conv.	Fert.	10	Vitosh *et al.* (1996)
6. E. Lansing, MI	Ochraqualf	8.5	728	1980	C, C–C, C–R	Conv., no-till.	Till., rot.	4	Pierce and Fortin (1996)
7. Saginaw, MI	Haplaquept	8.5	788	1972	C–SB, NB–SB, O–NB–SB, C–C–C–SB, C–C–NB–SB, O–A–NB–SB	Conv.	Rot.	6	Christenson (1996)
8. Champaign-Urbaba, IL	Argiudoll	11.0	940	1876	C, C–O, C–O–H	Conv.	Rot., fert.	15	Darmody and Peck (1996)
9. W. Lafayette, IN[A]	Haplaquol	10.8	952	1981	C, C–S, S, C–S–W, S–W	Conv., conservation, no-till.	Rot., till., weed control	45	M.V. Hickman (pers. comm.)
10. W. Lafayette, IN[A]	Haplaquol	10.8	952	1975	C–S	Conv., chisel, ridge-till, no-till.	Till.	4	Griffith *et al.* (1988)
11. Wooster, OH	Fragiudalf	9.5	733	1962	C, C–S, C–O–meadow	Conv., min., no–till.	Rot., till.	9	Dick *et al.* (1996)
12. Hoytville, OH	Ochraqualf	9.8	835	1963	C, C–S, C–O–meadow	Conv., min., no-till.	Till., rot.	9	Dick *et al.* (1996)
13. S. Charleston, OH	Ochraqualf	10.4	910	1963	C	Conv., min., no-till.	Till.	3	Dick *et al.* (1996)
14. Kutztown, PA	Fragiudalf	10.5	1180	1981	C–W–H–C–S, C–S–W, C–C–S–C–S	Conv.	Rot., fert.	3	Peters *et al.* (1996)
15. Mead, NE	Argiudoll	10.2	680	1975	C–S–C–O/Cl, C	Conv.	Rot., fert.	4	Lesoing and Doran (1996)
16. Columbia, MO	Ochraqualf	12.4	814	1888	W, A–brome, C, O, red Cl (3-, 4-, 5-, 6-year rot.)	Conv.	Rot., fert.	39	Buyanovsky *et al.* (1996)
17. Lexington, KY	Paleudalfs	13.1	1127	1970	C	Conv., no-till.	Till., fert.	8	Frye and Blevins (1996)
18. Horseshoe Bend, GA	Kanhapludult	16.5	1246	1978	Sor/S–R, Sor/S–Cl	Conv., no-till.	Till., rot.	4	Hendrix (1996)
19. Watkinsville, GA	Kanhapludult	16.0	1252	1982	Cl–Sor, Sor, S	No-till., conv.	Rot., irrigation, till.	18	Bruce and Langdale (1996)
20. Griffin, GA[A]	Kanhapludult	16.6	1267	1976	S–W–Sor	Conv., min., no-till.	Till.	6	D. V. McCracken (pers. comm.)

Table 1. *(continued)*

Site and location	Soil type	MAT (°C)	Precip. (mm)	Start	Cropping systems	Tillage	Treatments	No. of treatments	Source
21. Breton, Alberta	Cryoboralf	2.1	547	1930	W–O–B–Fo, W–Fa	Conv.	Rot. fert.	9	Juma *et al.* (1996)
22. Lethbridge, Alberta	Haploboroll	5.5	384	1911	W, Fa–W, Fa–W–W	Conv., min.	Rot. fert.	12	Janzen *et al.* (1996)
23. Lethbridge, Alberta	Haploboroll	5.5	384	1951	W, Fa–W, Fa–W–W, L–W, L–W–W, Fa–W–W–H–H–H	Conv.	Rot., fert.	12	Janzen *et al.* (1996)
24. Lethbridge, Alberta	Haploboroll	5.5	384	1911	10-year A–cereal–tuber A–A–A–W–B, C–W–C–W–B, FB–W–FB–W–B,	Conv.	Rot., fert.	15	Janzen *et al.* (1996)
25. Lethbridge, Alberta	Haploboroll	5.5	384	1955	W–Fa	Conv., min., no-till.	Till.	5	Janzen *et al.* (1996)
26. Melfort, Sakatchewan	Udic Boroll	0.8	396	1957	Fa–W, Fa–W–W, Cl–W–W, W, Fa–W–W–H–H–W	Conv.	Rot., fert.	8	Campbell *et al.* (1996)
27. Indian Head, Sakatchewan	Udic Boroll	2.5	435	1957	W, Fa–W, Fa–W–W, sweet Cl–W–W, Fa–W–W–H–H–H	Conv. no-till. (1990)	Rot., fert.	9	Campbell *et al.* (1996)
28. Swift Current, Sakatchewan	Haploboroll	3.7	328	1966	Fa–W–W, Fa–flax–W, Fa–R–W, W, Fa–W, W–L	Conv.	Rot., fert.	9	Campbell and Zentner (1996)
29. Mandan, ND	Argiborol	5.0	402	1984	Spring W–Fa, spring W–winter W–SF	Conv., min., no-till.	Rot., fert., till., cultivar	36	Black and Tanaka (1996)
30. Pendleton, OR	Haploxeroll	10.2	417	1931	Fa–W	Conv.	Fert., residue burn	9	Rasmussen and Smiley (1996)
31. Pendleton, OR	Haploxeroll	10.2	417	1940	Fa–W	Conv., reduced	Fert., till.	18	Rasmussen and Smiley (1996)
32. Sidney, NE	Haplustoll	8.2	381	1970	Fa–W, native sod	Conv., stubble mulch, no-till.	Till.	4	Lyon *et al.* (1996)
33. Akron, CO	Paleustoll	9.3	424	1967	Fa–W	Conv., reduced, no-till.	Till.	3	Halvorson *et al.* (1996)
34. Sterling, CO	Argiustoll	9.3	451	1985	Fa–W, W–C–Fa, W–C–M–Fa	No-till.	Rot., fert.	6	Peterson and Westfall (1996)
35. Stratton, CO	Argiustoll	10.7	410	1985	Fa–W, W–C–Fa, W–C–M–Fa	No-till.	Rot., fert.	6	Peterson and Westfall (1996)
36. Walsh, CO	Ustochrept	11.9	400	1985	Fa–W, W–Sor–Fa, W–Sor–Sor–Fa, Sor	No-till.	Rot., fert.	8	Peterson and Westfall (1996)
37. Manhattan, KS	Haplustoll	12.8	835	1974	Sor, W, Sor/S, W, W/S	Conv, reduced, no-till.	Rot., till.	15	Havlin and Kissel (1996)
38. Bushland, TX	Paleustoll	12.7	473	1982	W, Sor, W–Fa, W–Sor–Fa	Stubble mulch, no-till.	Till., rot., terrace	16	Jones *et al.* (1996)
39. Bushland, TX	Paleustoll	12.7	473	1981	W–Sor–Fa, W	Stubble mulch, no-till.	Till., rot.	3	Jones *et al.* (1996)

[A] These experiments were included in the cross-site sampling only.

present in soil, repeated measurements over several years to decades are necessary to detect changes in SOM. Another important attribute is the availability of ancillary data such as long-term climate records, production estimates, and documented management histories. Such information is invaluable in interpreting soil C changes (e.g. using crop production data to estimate C input rates to soil). Finally, most agronomic field experiments include treatments such as alternative tillage methods, different crop rotations, and varying fertility levels, which represent important controls on SOM formation, turnover, and stabilisation. Thus, the treatments often induce significant changes in SOM even where experiments were not specifically designed to study SOM dynamics.

The main alternative to long-term experiments for inferring changes in SOM is paired comparisons (i.e. chronosequences, toposequences, adjacent plots). However, data from such comparisons suffer several weaknesses including a lack of controlled experimental conditions, less statistical rigor, and uncertainties about histories of individual plots. Hence, long-term field experiment sites, the great majority of which are in agricultural systems, represent the highest quality source of data for analysing soil C dynamics in the context of global change.

Several collaborations around the world are aimed at organising networks of long-term experiment sites, including in Australia (see papers in this volume), Europe (D. Powlson pers. comm.), and North America (this paper). The key attribute of a network is that information from a variety of locations representing a range of climates, soil types, and management systems can be organised in a common format and applied in a broader, regional context. In this paper we describe a network of long-term field experiment sites in North America and outline a methodology for incorporating long-term site data into a framework for ecosystem analysis on a regional scale, with emphasis on applications dealing with global climate and landuse change. The objectives, structure, and general methodology of the work provide a potential case study for similar research in Australia.

Site network description

As part of a research effort originally sponsored by the U.S. Environmental Protection Agency, we solicited the collaboration of scientists at a number of long-term field experiments in Canada and the United States to collate data on climate, primary production, soil properties (including SOM measurements), and management histories for each site. Network collaborators were invited to a workshop and asked to present summary papers of the results from the field experiments, focusing on responses of SOM to different management treatments. The papers, together with standardised data appendices, are being published in a forthcoming book (Paul *et al.* 1996).

Summary papers and data from 35 experiments at 30 research sites were compiled (Table 1). Four additional sites were included in the cross-site sampling, but detailed historical data for these sites were not compiled for the network volume. We therefore have information on soils and management from 39 experiments at 33 locations. The longest experiments have continued for well over 100 years (Sanborn Plots, Columbia, Missouri; Morrow Plots, Champaign-Urbana, Illinois), and the newest experiments have been running for 9 years (crop rotation experiments at Sterling, Stratton and Walsh, Colorado). The average duration of the experiments is 35 years and all sites are ongoing experiments, with the exception of the corn grain–corn silage experiments at E. Lansing, Michigan, where the experimental treatments were discontinued in 1982. However, these plots have been maintained under uniform management since, and were resampled in 1991 to examine residual effects of manure applications.

The sites span a wide range of climates representing much of the agricultural land area of North America. Mean annual temperatures range from a low of 0.8°C (Melfort, Saskatchewan) to a high of 16.6°C (Griffin, Georgia). The driest site is Swift Current, Saskatchewan (328 mm) and the wettest is Griffin, Georgia (1267 mm). Locations of the sites are shown in Figure 1, and their distribution according to mean annual temperature and precipitation is given in Figure 2.

The dominant soil orders, using the USDA classification (Soil Survey Staff 1975), are Mollisols (16 sites) and Alfisols (12 sites), with 2 sites having Enceptisols (Walsh, Colorado; Saginaw, Michigan) and 3 with Ultisols (Griffin, Horseshoe Bend, and Watkinsville, Georgia). Soil textures represented at the sites span a full range from clays to loamy sands; however, most sites have medium-textured (loam and silt loam) soils (Fig. 3).

Collectively, the long-term experiments comprise a rich array of management practices (e.g. tillage, crop rotation, fertiliser application, organic matter amendments, irrigation), which can affect soil C both through influencing the amount of C returned to the soil and by affecting the rate of decomposition of SOM and the stabilisation of decomposition products. The primary management variables represented are tillage, crop rotation, and fertiliser rates. Nineteen experiments have tillage comparisons, 26 have crop rotation as a treatment variable, and 23 have treatments with different rates of fertiliser application. In addition, 19 sites have areas nearby of native vegetation with uncultivated soils, providing a baseline for assessing historical changes in SOM due to cultivation. A total of 439 treatment combinations are represented in the network.

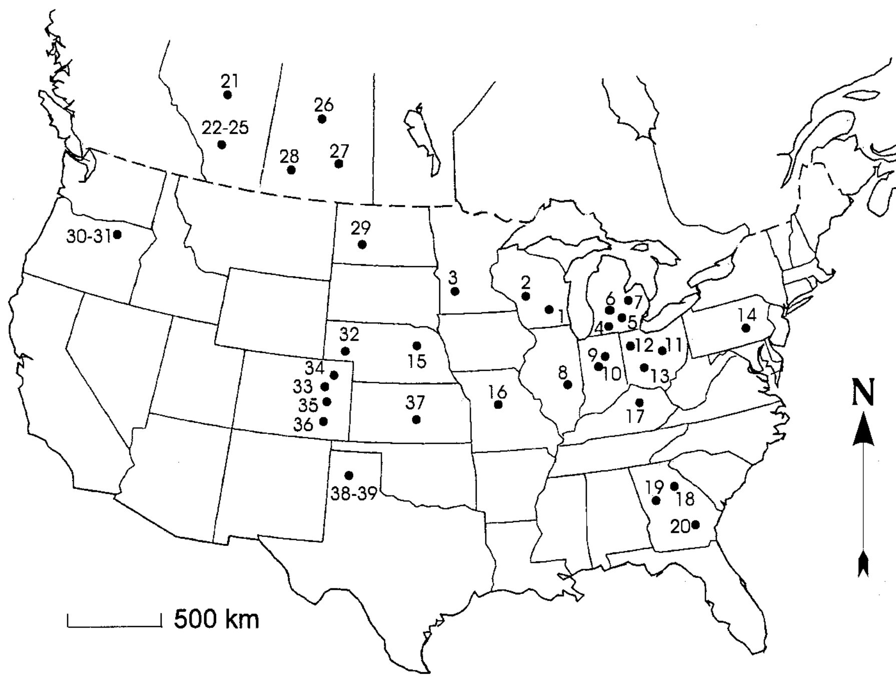

Figure 1. Location of field sites in the North American long-term experiment network. Numbers designate the experiments listed in Table 1.

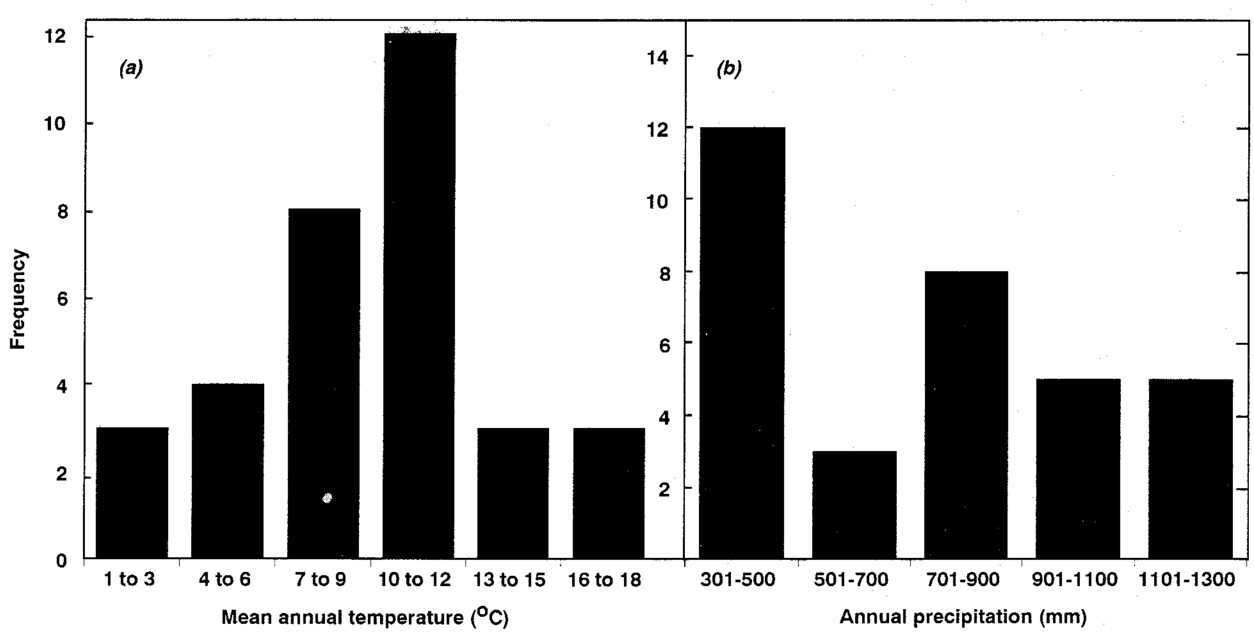

Figure 2. Distribution of sites (33 total) according to (*a*) mean annual temperature and (*b*) annual precipitation totals (30-year average). Locations with more than one experiment at the same site were only counted once.

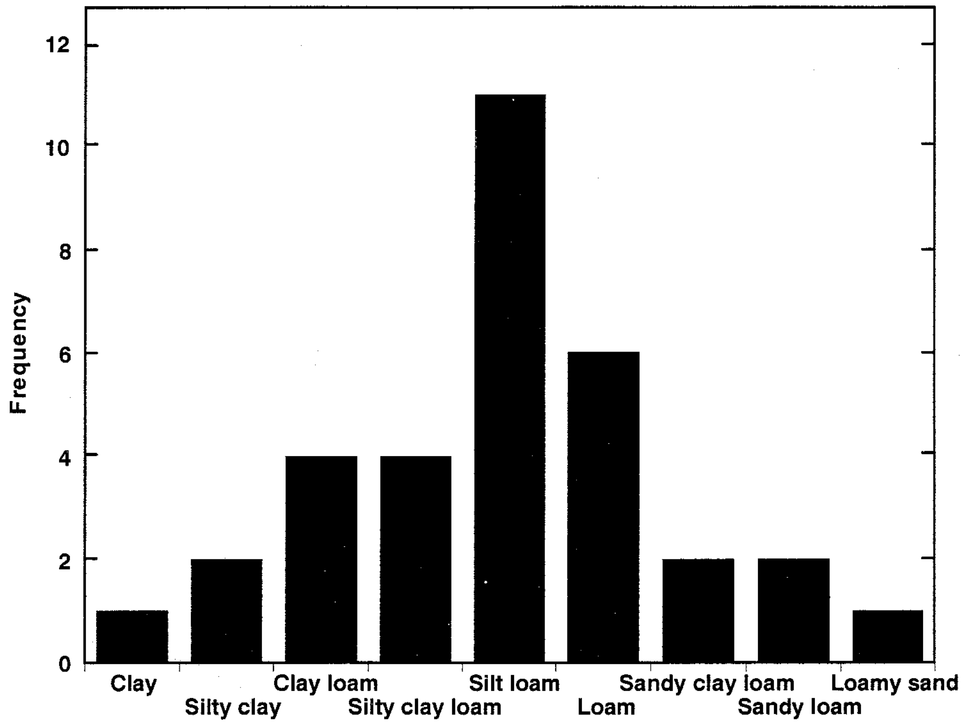

Figure 3. Distribution of sites according to surface soil texture.

Network data

Existing data from experimental sites were organised in a common format including site background information, management schedules, production and soils data, and long-term climate averages (Paul *et al.* 1996). Table 2 outlines the structure and contents of the site databases. Site background information includes the location and administration of the sites, and the scientists responsible for the experiments. Information on geology, vegetation, and landuse is relevant for reconstructing landuse history and for estimating precultivation levels of plant production and SOM. Descriptions of experimental design and management schedules document the agricultural treatments of the plots, including changes in management over time in many of the older experiments. Time series of production and soils measurements are tabulated, generally for each year sampled, except for production data for some of the older experiments, for which periodic (e.g. 10 years) averages are given. Because many of the experiments span long periods during which laboratory techniques have changed, dataholders were requested to provide information on analytical methods where possible.

To complement the existing data on soil organic matter, a cross-site sampling program was carried out at most of the sites listed in Table 1, with an aim of providing a consistent determination of organic matter amounts and properties across all sites, to minimise

Table 2. Organisation of North American experiment site databases

1. Site identification
   (*a*) Geographic location
   (*b*) Administrative authority
   (*c*) Contact personnel
2. Site description
   Soil taxonomy, soil texture, geomorphology, native vegetation, landuse before establishment as a field experiment
3. Experimental design
   (*a*) Date experiment started
   (*b*) Treatment description
   (*c*) Statistical design
4. Management schedule
   (*a*) Planting and harvest dates
   (*b*) Crop varieties, seeding rates
   (*c*) Fertiliser and pesticide applications
   (*d*) Tillage method, depth, frequency
5. Soils data
   (*a*) Bulk density
   (*b*) Soil C and N
   (*c*) Other soils information (according to availability)
6. Production data
   (*a*) Grain and/or forage yields (i.e. economic yields)
   (*b*) Straw (crop residues) production (if available)
   (*c*) N content of grain and/or forage (N content of residues if available)
7. Climate
   Long-term averages of monthly min. and max. temperature and precipitation

Table 3. Sampling and laboratory analyses used in cross-site comparison

Field sampling
1. Soil cores (6.4 cm diam.) taken to 1 m depth, 6 per plot (divided into 5 depth increments: 0–20, 20–25, 25–50, 50–100 cm, plus additional 0–2.5 cm samples in no-tillage treatments only)
2. Surface litter from 0.25 by 0.25 m subplots (excluding current year's residue)
Laboratory analyses
All soil samples
1. Total C and N (dry combustion in Carlo-Erba analyser)
2. Bulk density
3. pH (10 g soil : 20 mL H_2O)
Sampled from 0–20 cm increment only
1. $CHCl_3$-labile C and N (by direct extraction after 24 h fumigation; Brookes *et al.* 1985)
2. Particulate organic matter C and N (>53 μm fraction with wet sieving; Cambardella and Elliott 1992)
3. Aerobic incubations (>200 days) for C and N mineralisation (Boyle and Paul 1989)

biases associated with differences in sampling techniques, analytical methods and equipment, and personnel (Table 3). In addition, soils were sampled to 1 m depth, whereas previous SOM data for many of the sites were restricted to the upper soil horizons. Sites in the eastern portion of the network were sampled by researchers from Michigan State University (MSU), and western sites by researchers at Colorado State University (CSU). Individual laboratory assays of samples from all sites were then made at a single facility, at either MSU or CSU. In addition, subsamples from all treatments and depths sampled were air-dried and archived for possible later use.

Another aim of the cross-site sampling was obtaining new information on diagnostic SOM fractions. These included a series of biological and physical fractionation procedures to assay SOM fractions, which, we hypothesised, would be more sensitive to management than total soil C and N. Many methods have been developed to determine the amounts and kinds of SOM. Chemical extractions of whole soils have been able to distinguish various soil types but have not been valuable for identifying specific pools that are lost upon cultivation (Stevenson and Elliott 1989). Biological and physical methods have been better able to make these distinctions (Tisdall and Oades 1982; Elliott 1986; Cambardella and Elliott 1992, 1993, 1994). Due to the large number of samples, a suite of widely used but relatively simple fractionation methods was used (Table 3).

Together, the long-term databases and cross-site organic matter characterisations provide essential data for analysing the interactive effects of climate, soils, and management on SOM in a regional context. Below we outline a methodology combining field experimental data with simulation modelling and geographical information system (GIS) methods and data to make regional assessments of soil C.

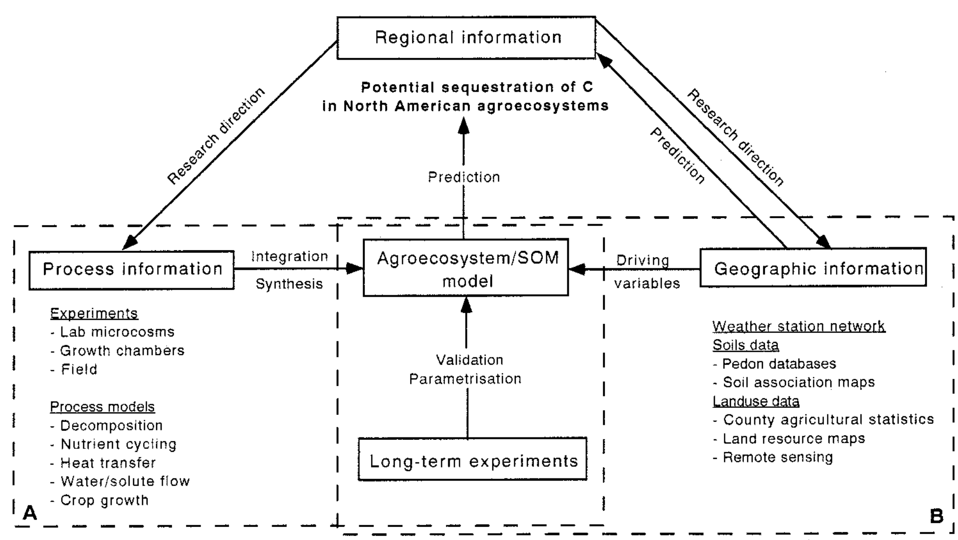

Figure 4. Conceptual diagram showing the integration of process information, long-term experiment data and site networks, simulation modelling and regional GIS databases. Box A denotes components which can be applied for local scale analyses (i.e. at a particular location) and box B denotes components which are necessary for regional scale analyses. Long-term experiments are a key element for both local- and regional-scale research.

A methodology for regional assessment of soil carbon dynamics

There are 2 main steps in making regional level assessments of soil C dynamics. The first is designing a methodology to integrate the various factors controlling soil C dynamics on a local scale (e.g. a field). The second is applying this methodology on a regional scale, encompassing the spatial and temporal variation in factors controlling soil C, including climate, soil properties, and management systems. Our approach (Fig. 4) combines process studies, long-term field experiments, simulation modelling, and spatially resolved regional databases and GIS (Elliott and Cole 1989).

The first step involves the use of process studies as a basis for formulating ecosystem simulation models to predict soil C dynamics as a function of the interaction of climate, soil, and management driving variables on the field scale (box A in Fig. 4). In this context, information from individual long-term studies has been instrumental in the development and testing of several simulation models (e.g. Parton *et al.* 1983; Jenkinson *et al.* 1987; Verberne *et al.* 1990; Paustian *et al.* 1992; Parton and Rasmussen 1994). The second step, application of models on a regional scale, depends on the use of spatially resolved databases of driving variables (e.g. temperature, precipitation, soil texture, landuse systems) organised using GIS technology. At the regional level, databases from networks of long-term experiments provide the means to validate the model results for various combinations of driving variables as they occur across the region (box B in Fig. 4). The rationale behind this approach and examples of how we are applying the methodology are given below.

To understand the dynamics of soil C and the potential for sequestration of C in this pool, we must understand the functioning of the whole ecosystem with its inherent interactions and feedbacks (Elliott *et al.* 1994). The best way we know to accomplish this is through the use of simulation models. Simulation modelling provides a means to integrate the numerous factors affecting soil organic matter and to predict changes in soil C as a consequence of altered management practices and/or changes in climate. Simulation models also enable an explicit representation of important feedbacks, for example, the feedbacks between organic matter turnover, nutrient availability, crop production, and crop residue inputs. While various SOM models have been developed and refined over the past 15 years, several key features are common to most models (Paustian 1994). These include temperature and soil moisture as the major abiotic controls on plant production and/or decomposition, effects of soil physical properties and soil disturbance on organic matter stabilisation, and the influence of the quantity and quality of crop residues on the formation of new soil organic matter. Hence, a limited set of driving variables, including temperature and precipitation, soil physical properties such as texture, mineralogy and cation exchange capacity (CEC), and management systems (e.g. crop type, tillage, fertiliser application) constitute the necessary inputs to execute ecosystem/SOM models.

Spatially resolved databases can be stored and manipulated using GIS techniques. For example, data from weather station records can be gridded and used to derive contours of temperature and precipitation from which areas of similar climate can be delineated within a region. Digital soil maps can be used to derive spatial data layers of the distributions of soil texture, CEC, or other variables of relevance for a particular model. Regional patterns in landuse, crop production, and/or agricultural management systems may be derived from a variety of sources including satellite imagery and conventional compilations of agricultural and landuse statistics within a region. By overlaying climate, soils, and landuse data layers, sets of model-driving variables can be associated with specific geographic units within the region. These driving variable sets are then input to the model to execute a series of simulations. Simulation results can then be exported to the GIS and displayed geographically.

While simulation models and spatial databases of driving variables are sufficient to derive regional projections of soil C distributions and changes over time, long-term site data organised in a regional context provide the most effective means for validation of the model results. By analysing model results at multiple sites representing a range of climate, soil, and management variables, the reliability of the model can be assessed and weaknesses and systematic biases in model predictions identified and quantified.

We are using this approach in several research projects including (i) assessing historical changes in soil organic matter in the Great Plains and Corn Belt regions of the USA; (ii) modelling climate change and CO_2 enrichment effects on soil C balance and the potential effects of management adaptations in response to climate and CO_2 changes; and (iii) assessing C sequestration potential under the Conservation Reserve Program (i.e. set-aside of agricultural land to perennial vegetation) in the central USA. Networks of field experiment data and the active collaboration and participation of scientists working at long-term research sites are vital components in each of these regional studies.

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