Global Change Biology (1998) **4**, 131–141

Carbon cycling in cultivated land and its global significance

GREGORY A. BUYANOVSKY and GEORGE H. WAGNER
University of Missouri-Columbia, Soil and Atmospheric Science Department, 144 Mumford Hall, Columbia, MO 65211, USA

Abstract

Long-term data from Sanborn Field, one of the oldest experimental fields in the USA, were used to determine the direction of soil organic carbon (SOC) dynamics in cultivated land. Changes in agriculture in the last 50 years including introduction of more productive varieties, wide scale use of mineral fertilizers and reduced tillage caused increases in total net annual production (TNAP), yields and SOC content. TNAP of winter wheat more than doubled during the last century, rising from 2.0–2.5 to 5–6 Mg ha^{-1} of carbon, TNAP of corn rose from 3–4 to 9.5–11.0 Mg ha^{-1} of carbon. Amounts of carbon returned annually with crop residues increased even more drastically, from less than 1 Mg ha^{-1} in the beginning of the century to 3–3.5 Mg ha^{-1} for wheat and 5–6 Mg ha^{-1} for corn in the 90s. These amounts increased in a higher proportion because in the early 50s removal of postharvest residues from the field was discontinued. SOC during the first half of the century, when carbon input was low, was mineralized at a high rate: 89 and 114 g m^{-2} y^{-1} under untreated wheat and corn, respectively. Application of manure decreased losses by half, but still the SOC balance remained negative. Since 1950, the direction of the carbon dynamics has reversed: soil under wheat monocrop (with mineral fertilizer) accumulated carbon at a rate about 50 g m^{-2} y^{-1}, three year rotation (corn/wheat/clover) with manure and nitrogen applications sequestered 150 g m^{2} y^{-1} of carbon. Applying conservative estimates of carbon sequestration documented on Sanborn Field to the wheat and corn production area in the USA, suggests that carbon losses to the atmosphere from these soils were decreased by at least 32 Tg annually during the last 40–50 years. Our computations prove that cultivated soils under proper management exercise a positive influence in the current imbalance in the global carbon budget.

Keywords: carbon sequestration, crop residue, cultivated land, global carbon balance, net annual production

Received 24 October 1996; revised version accepted 11 March 1997

Introduction

Carbon flow through cultivated lands has never been studied to the same extent and detail as that in the native ecosystems. It is widely accepted that conversion of native land, be it prairie or forest, into a cultivated system causes precipitous degradation of the soil organic matter (SOM). Typically 20–40% of the native SOM is lost when virgin lands are converted to agriculture (Schlesinger 1986; Mann 1986; Detwiler 1986; Cole *et al.* 1989). It is generally assumed that over time cultivated soils reach a new equilibrium at a lower level of organic carbon (Haas *et al.* 1957; Hobbs & Brown 1965; Unger 1968; Mann 1985).

Correspondence: Dr Gregory Buyanovsky, fax + 1/573-884-4960, e-mail snrgregb@muccmail.missouri.edu

Post-harvest residues are the sole source of carbon to replenish soil organic matter decomposing as a result of cultivation. Linear relationships between carbon inputs with residues and soil organic matter levels have been established in several field experiments (Rassmussen *et al.* 1980; Cole *et al.* 1993; Rasmussen & Parton 1994). However, long-term observations of organic carbon dynamics in cultivated soils combined with data on total productivity of crops are extremely rare. Because of the 'non-nutrient' status of carbon, its flow rate and storage characteristics are almost never included in agronomic studies. Uncertainties in the carbon balance of agricultural lands prevent proper assessment of their role in global carbon balance, thus precluding accurate global carbon balance sheets, and, hence, approximations of the potential for sequestration of carbon in cultivated soils are imprecise.

There are concerns about a current imbalance in the global carbon budget. The difference between a 0 net flux and a release from tropical deforestation is 1.5–2.0 Pg y^{-1} (Houghton 1995). Assumptions have been made that the carbon which cannot be accounted for is accumulating in temperate ecosystems of the Northern Hemisphere (Tans *et al.* 1990), mainly in forests. Houghton (1995) argues, however, that an accumulation of this magnitude in forests is unlikely. As for croplands and grasslands, an increase in carbon content of such magnitude, in his opinion, would be too obvious to go unnoticed. Taking into account total amount of carbon in agricultural ecosystems (111–142 Pg) (Schlesinger 1984; Buringh 1984), a yearly accumulation of 1–2 Pg C would correspond to an increase of about 1%. For a soil with 2.5% of organic carbon such an increase would be unnoticeable for at least 40–50 years. Soil survey or occasional observations could not reveal changes of this magnitude due to differences in understanding of what constitutes SOM, the high variability in its content, and shortcomings of analytical techniques. Only long-term observations with permanent sampling sites, tightly controlled management and documented inputs and outputs can register small increase occurring during a span of decades.

Sanborn Field, one of the oldest experimental fields in the United States, uniquely meets the requirements for studies of this kind. The Field has been maintained throughout the last 110 years. Despite shortcomings of the initial layout and irregular sampling of soil and crops, the field presents an invaluable asset for studies of carbon flux. Records on management, fertilization, yields of grain and forage (above-ground biomass), as well as the results of some analyses of historic soil samples are available. Particularly applicable are Sanborn Field records related to numerous fertility experiments conducted during the last century, which allow an assessment of carbon dynamics during a 100 + year period since cultivation was commenced on the field (Upchurch *et al.* 1985). In addition, important complementary studies using this field have focused, in recent years, on carbon cycling. This has opened the possibility of using old records in combination with data from sophisticated recent measurements (Buyanovsky & Wagner 1986, 1987; Buyanovsky *et al.* 1987; Balesdent *et al.* 1988).

We evaluated experimental material collected during this long period and transposed this into carbon balance characteristics for cultivated fields representative of Midwest agriculture. Combined with national crop statistics these evaluations were used to assess possible carbon sequestration in U.S. croplands during postwar agricultural practices.

Sanborn Field Data Set

Sanborn Field, on the campus of the University of Missouri-Columbia, was established in 1888 with rotation and manure treatments on 39 plots, each 30 × 10 m in size, separated by grass borders 1.5 m wide. The soil is a Mexico silt loam (fine montmorillonitic, mesic, Udollic Ochraqualf) developed in thin loess deposits overlying glacial till. The surface layer contains 2.5–2.9% organic matter. Mean annual air temperature of the region is 13 °C, with maximum monthly average in July (26 °C) and minimum in January (– 1.5 °C). Mean annual precipitation is 973 mm, with potential evapotranspiration of 790 mm. The soil has an argillic horizon (Bt), which causes perching and lateral flow of water above. The soil is typical for the American Midwest claypan area, and there are about 20 million ha of agricultural land in central part of the USA with similar edaphic characteristics used for intensive grain production. Annual carbon circulation for this region can approach hundreds of millions of tons.

Sanborn Field plots have been cropped and managed under specified guidelines simulating regular farming practices since the inception of the field (Upchurch *et al.* 1985; Buyanovsky *et al.* 1990; Brown 1994). Initially, nine cropping practices, using corn, oats, winter wheat, red clover and timothy were used in the experiment. Some plots were under continuous single crops and other involved rotations. The continuum of management practiced on numerous plots of Sanborn Field reflects the history of agriculture in the central region of the USA.

For the analyses reported herein we have used data from treatment plots most of which have maintained their integrity throughout the whole period (Table 1). Periodically, some revisions were made in the experimental plan of the field, but for the work reported here only one change in management was of real importance, that of discontinuation from 1950 onward of the practice of collecting above-ground residues from plots cultivated to corn and wheat. Forages (timothy, alfalfa, bromegrass) have always been managed with forage harvested and removed from the plot.

Since 1981, we have conducted on Sanborn Field several small-scale field experiments with major regional crops, among them winter wheat (*Triticum aestivum* L.) and corn (*Zea mays*) (Buyanovsky & Wagner 1986, 1987, 1997a, 1997b; Buyanovsky *et al.* 1986, 1987, 1994). The experiments which employed ^{14}C labelling technique have been designed to assess total net annual production of the crops which includes grain, above-ground biomass at the time of harvest, and roots (measured several times during

Table 1 Cropping systems of Sanborn Field used for analysis of soil organic carbon dynamics

System	Treatment	Years under the treatment
Continuous wheat	Manure (13.4 Mg ha^{-1})	100
	Full mineral fertilizer	100
	None	100
Continuous corn	Manure (13.4 Mg ha^{-1})	100
	Full treatment	50
	None	100
Continuous timothy	Manure (13.4 Mg ha^{-1})	100
	None	100
Corn/Wheat/Clover	Manure (13.4 Mg ha^{-1})	60
	Manure (13.4 Mg ha^{-1}) + N (37 kg ha^{-1} under wheat, 112 kg ha^{-1} under corn)	40

a growing season). This information has been used to estimate the relationship between different parts of a crop (grain/TNAP, shoot/root ratio, etc.), and, subsequently, to calculate the total carbon input under different crops during the 100+ year period of the large-scale experiments.

Measurements of soil organic carbon have been taken with intervals of 10–30 years, by dry combustion in a purified stream of oxygen (Nelson & Sommers 1982). To recalculate organic carbon on soil mass we used detailed bulk density measurements from the 60s and 80s.

Data analysis

Total net annual production (TNAP) TNAP of crops cultivated on Sanborn Field have been heavily impacted by many factors, among which the major ones are management, weather and variety. With factors other than weather progressively improving, TNAP increased (Table 2). The only notable exceptions are plots without amendments.

Application of mineral fertilizers or manure to winter wheat provided a very slow increase in TNAP during the first 60 years. During that period, net production increased from ∓ 2 to 3 Mg C ha^{-1} y^{-1}. During the following 40 years, with modernization of cultivation practices, introduction of genetically improved varieties and with residues added back, each hectare of wheat accumulated 4–5 Mg C ha^{-1} y^{-1}. Rotation with manure applied annually supported high productivity during the whole 100-year period. However, when manure was used with mineral fertilizers its effect on TNAP was negligible.

Manured corn during the first 50 years produced an average of about 3.2 Mg C ha^{-1} y^{-1}, as compared with 2.2 Mg C ha^{-1} y^{-1} for the untreated plot. Corn response to manure was lower than that for wheat, which doubled TNAP under the effect of manure. In a 3-year rotation (corn, wheat, clover) with manure, annual carbon accumulation increased but not very significantly (from about 3.3 to 4.2 Mg C ha^{-1} y^{-1}) during first 60 years. Application of nitrogen was necessary to increase TNAP of corn to 9–10 Mg C ha^{-1} y^{-1}.

TNAP of unfertilized plots practically did not change during 100 years. Slightly higher TNAPs of untreated wheat and corn were observed after 1950, when the practice of collecting residues was abandoned. On average, nonfertilized wheat accumulated about 1–1.5 Mg C ha^{-1} y^{-1} during the growing season and corn accumulated 1.7–2.2 Mg C ha^{-1} y^{-1}.

Naturally, TNAP indirectly mirrored the increase in grain yields. A general progressive yield increase was observed from the inception of the experiment, but during the first 50 years, grain productivity of fertilized wheat increased from 0.9–1 to 1.5–1.6 Mg ha^{-1} y^{-1} and in the following 50 years it more than doubled to 4.2 Mg ha^{-1} y^{-1}. Productivity of corn in a 3-year rotation with 13.4 Mg ha^{-1} manure and 112 kg ha^{-1} of fertilizer nitrogen increased by ∓ 25% during the first 50 years and doubled during the later period.

The early period increases are probably attributable to improved varieties. During the latter period further progress in plant breeding would have accelerated the positive effect on yield by linking this breeding effort to selection toward fertilizer response and due to better weed control and improved cultivation practices. In the early years, plant breeders of wheat improved harvest ability of grain by selection of stronger stems and some years ago they successfully decreased straw length. The ratios of grain yield to vegetative biomass have narrowed only slightly, however (Buyanovsky & Wagner 1997a).

Carbon input to soils Sanborn Field was established on an area of tallgrass prairie with a plant cover characterized by several dominant warm season grasses including big bluestem (*Andropogon gerardi* Vitman), little bluestem (*Schizacharium scoparium* Nash), prairie drop seed (*Sporobolus heterolepis* [A. Gray] A. Gray), and Indian grass (*Sorghastrum nutans* [L.] Nash). Kucera (1987) estimated

Table 2 Average total net annual production (Mg ha^{-1} of C, grain included) of the major agricultural crops of the Central U.S. for each decade during 100 years (as represented by Sanborn Field data)

Crop	Treatment	1891–1900	1901–10	1911–20	1921–30	1931–40	1941–50	1951–60	1961–70	1971–80	1981–90
Wheat contin.	Full miner. fertil.	2.01 ± 1.29	2.53 ± 1.58	1.97 ± 1.07	3.14 ± 0.89	3.62 ± 0.70	3.11 ± 1.47	4.16 ± 1.66	5.18 ± 0.78	5.11 ± 1.06	4.71 ± 0.77
	Manure 13.4 Mg ha^{-1}	2.31 ± 1.55	2.21 ± 1.27	2.72 ± 0.94	3.14 ± 1.17	3.64 ± 1.13	3.13 ± 1.79	3.76 ± 0.89	5.78 ± 1.22	4.85 ± 2.24	6.74 ± 2.37
	None	0.48 ± 0.86	1.27 ± 1.30	0.97 ± 0.74	1.20 ± 1.07	1.76 ± 1.27	0.43 ± 0.32	0.89 ± 0.73	1.83 ± 1.01	1.42 ± 0.78	1.39 ± 0.70
in 3-year rotation	Manure 13.4 Mg ha^{-1}	2.61 ± 0.65	3.1 ± 0.85	3.66 ± 0.51	3.12 ± 0.93	3.29 ± 0.23	2.44 ± 1.32	2.18 ± 1.44*	4.49 ± 0.69	5.74 ± 2.16	5.09 ± 1.49
Corn contin.	Manure 13.4 Mg ha^{-1}	3.03 ± 0.86	2.86 ± 1.19	3.44 ± 0.73	3.28 ± 0.92	3.24 ± 0.75	3.74 ± 1.42	4.53 ± 3.16	4.11 ± 1.70	5.64 ± 3.36	4.78 ± 1.71
	Full miner. fert., reg. till	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	5.66 ± 2.70	9.16 ± 2.53	10.52 ± 2.38	9.55 ± 4.18
	Full miner. fert., no-till	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	6.34 ± 1.95	8.82 ± 2.0	7.79 ± 5.23	8.43 ± 3.72
	None	2.26 ± 0.84	1.66 ± 0.74	2.29 ± 0.49	2.00 ± 0.50	1.89 ± 0.46	1.71 ± 0.43	2.40 ± 0.99	2.17 ± 0.65	2.29 ± 0.81	1.53 ± 0.32
in 3-year. rotation	Manure 13.4 Mg ha^{-1}	3.82 ± 1.90	1.96 ± 0.81	4.92 ± 1.94	4.75 ± 0.59	3.79 ± 1.16	3.30 ± 0.17	5.91 ± 1.45*	9.68 ± 1.07	10.25 ± 4.67	11.09 ± 5.26

*Starting in 1950, 37 kg ha^{-1} of N was applied under wheat, 112 kg ha^{-1} under corn.

annual productivity of this plant community in carbon equivalents as 4.5 Mg C ha^{-1} y^{-1} (2.15 Mg C ha^{-1} y^{-1} of above-ground biomass, 2.35 Mg C ha^{-1} y^{-1} below-ground). The vegetation supported a high level of SOM, that amounted to 10.5–11.0 kg C m^{-2} y^{-1} in the upper 50 cm layer, and 13–14 kg C m^{-2} y^{-1} in 1 m (Buyanovsky *et al.* 1987).

Total net annual production of the crops during the first half of this century was much lower than that of native prairie (Table 2). Wheat (fertilized or manured) accumulated about 2–3 Mg C ha^{-1} y^{-1}, manured corn – 3–3.7 Mg C ha^{-1} y^{-1}. Calculations show that less than half of the accumulated carbon was returned to the soil with wheat residues and only about $^1/_3$ with corn residues (Table 3). For unfertilized crops usually no more than 0.5–0.7 Mg C ha^{-1} y^{-1} was returned to soil annually (corn was affected by the lack of nutrients to much higher degree than wheat).

From the beginning of 50s, amounts of carbon returned to the soil increased sharply for two reasons. First of all, TNAP of new varieties more than doubled during 50s and 60s, and, secondly, old practice of removing above-ground residues from the field was gradually abandoned. Only grain carbon was excluded from recycling through the soil (16–20% TNAP for wheat, 25–30% for corn). As a result, amounts of carbon returned to soil increased to 3–4 Mg C ha^{-1} y^{-1} under wheat, and to 6–7 Mg C ha^{-1} y^{-1} under corn.

Effect of management on carbon dynamics A direct dependence was observed, as one would expect, between amounts of carbon returned to the soil during 100 years and soil organic carbon content (Fig. 1). The annual new carbon entering the soil came from the crop residues and, in some plots, additionally from manure. From our current understanding of carbon dynamics, there is no reason to think that manure is more effective for SOM enhancement than plant residues. The graph suggests, however, that management is very important for carbon sequestration. Results from the different plots fell into two groups: those with regular tillage and those under no-till or conservation tillage. With the same application rate of carbonaceous materials, no-till plots contain 1.5–2 kg m^2 of SOM carbon more than plots under regular tillage.

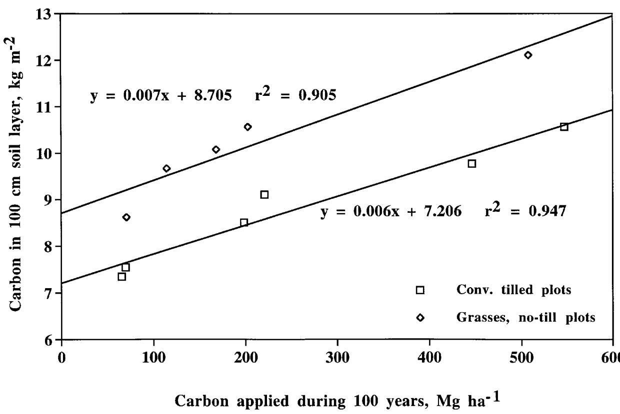

Fig. 1 Relationship between amounts of carbon applied during one hundred years and SOC level for various plots of Sanborn Field.

Slopes of the relationships are indicative of the small portion of residue carbon that passes into the 'stable' SOM pool, and this is less than 1% of inputs for both no-till and regular tillage plots (0.7 and 0.6%, respectively). No-tillage management data yielded a curve with a slightly steeper slope than that for regular tillage, indicating that the former provides conditions more conducive to humus formation. The values are particularly low because most of the residue has been under humification for a very long period extending to 100 years. For a shorter observation (10–20 years) the humification factor has been estimated to be 10–20% (Buyanovsky & Wagner 1997a). The intercepts of these curves presumably define the stable pool of organic carbon (7.2 kg m^{-2} under tillage, 8.7 kg m^{-2} without disturbance) that dates back beyond 100 years and is subject to little or no turnover. Of the 7 kg m^{-2} of stable carbon in the cultivated plots, about 2 kg m^{-2} in the upper 20 cm of the soil profile constitutes nearly one-half of the total carbon in the upper profile of cultivated soil (Balesdent *et al.* 1988). Below that depth nearly all of the carbon has been characterized as being very stable with probable mean residence time greater than 1000 years. Thus, the quantity of soil carbon in excess of 7 kg m^{-2} (up to about 10 kg m^{-2} for the cultivated soil) represents carbon that is relatively dynamic in character, originating from the crop residues added to the soil each year and occurs primarily in the plow layer of the profile.

All systems used on Sanborn Field show some loss of carbon relative to that present 100 years ago in the virgin soil. The greatest losses were observed in plots under nonfertilized monocrops. Soils under both wheat and corn lost almost half of the initial organic carbon (Fig. 2). The loss was caused by very low carbon return to the soil from residues (especially before 1950). The annual rate of loss of carbon for the first 25 years of cultivation was found to be very high: 89 g m^{-2} y^{-1} for wheat and 114 g m^{-2} y^{-1} for corn. The rate of loss of SOM carbon in soils receiving manure was about one-half that for untreated soil (56 and 61 g m^{-2} y^{-1} for wheat and corn, respectively). Wheat receiving mineral fertilizer lost 95 g m^{-2} y^{-1} during the first 25 years of cultivation.

Since 1950, the above-ground residues were returned to the soil, and this change in management reversed the direction of the carbon dynamics. Except nonfertilized monocrops, all other plots started to sequester a greater

Table 3 Amounts of carbon returned annually with crop residue to Sanborn Field plots during period 1891–1990 (Mg ha^{-1} of C)

Crop	Treatment	1891–1900	1901–10	1911–20	1921–30	1931–40	1941–50	1951–60	1961–70	1971–80	1981–90
Wheat contin.	Manure 13.4 Mg ha^{-1}	1.00 ± 0.53	0.97 ± 0.44	1.07 ± 0.39	1.22 ± 0.49	1.48 ± 0.48	1.32 ± 0.79	2.12 ± 0.94	4.61 ± 0.94	3.89 ± 1.72	3.21±1.73
	Full miner. fertil	0.86 ± 0.39	1.11 ± 0.43	0.86 ± 0.31	1.18 ± 0.37	1.46 ± 0.33	1.41 ± 0.50	2.80 ± 0.38	3.98 ± 0.54	3.94 ± 0.74	3.65±0.53
	None	0.48 ± 0.41	0.52 ± 0.54	0.38 ± 0.27	0.56 ± 0.39	0.71 ± 0.52	0.18 ± 0.14	0.82 ± 0.66	1.62 ± 0.63	1.14 ± 0.60	1.12±0.54
in 3-year. rotation	Manure 13.4 Mg ha^{-1}	0.75 ± 0.21	0.95 ± 0.26	1.12 ± 0.18	0.97 ± 0.33	1.10 ± 0.02	0.88 ± 0.34	2.02 ± 0.42	3.18 ± 0.48	4.06 ± 1.53	3.6±1.05
Corn contin.	Manure 13.4 Mg ha^{-1}	0.84 ± 0.26	0.84 ± 0.30	1.09 ± 0.30	1.05 ± 0.31	0.88 ± 0.20	1.09 ± 0.47	1.35 ± 1.08	1.22 ± 0.55	1.69 ± 1.01	1.98±0.97
	Full miner. fert., reg. till	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	3.92 ± 1.87	6.33 ± 1.75	6.49 ± 2.80	6.60±2.89
	Full miner. fert., no-till	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	3.94 ± 1.88	6.09 ± 1.39	5.38 ± 3.62	5.82±2.57
	None	0.67 ± 0.29	0.55 ± 0.26	0.72 ± 0.17	0.69 ± 0.18	0.55 ± 0.13	0.52 ± 0.14	0.87 ± 0.38	0.76 ± 0.29	0.81 ± 0.28	0.54±0.15
in 3-year. rotation	Manure 13.4 Mg ha^{-1}	0.8 ± 10.50	0.39 ± 0.11	1.35 ± 0.52	1.02 ± 0.20	0.75 ± 0.18	0.70 ± 0.08	4.11 ± 1.00	6.73 ± 0.74	7.13 ± 3.24	6.68±4.45

Table 4 Changes in carbon content in upper 20-cm layer of Sanborn Field soils under different managements from 1963 to 1988

Crop, treatment	Carbon, Mg ha^{-1}		
	1963	1988	Change
Continuous wheat			
manure	32.6	42.7	+10.1
miner. fert.	27.2	36.0	+8.8
none	25.4	24.4	−1.0
Continuous corn			
manure	32.3	37.7	+5.4
miner. fert., no till	26.7	37.9	+11.1
miner. fert., convent. till	24.9	32.5	+7.6
none	21.9	18.2	−3.7
Corn/Wheat/Clover			
miner. fert.	27.8	35.9	+8.1
manure + N	30.6	47.0	+16.4

part of the residue carbon after 1950 (Table 4). Wheat receiving mineral fertilizers accumulated carbon at a rate about 50 g m^{-2} y^{-1} during the most recent 15 years (1975–90). A similar rate of carbon sequestration was observed under manured wheat. Manured corn accumulated carbon during the same period at a much lower rate (about 20 g m^{-2} y^{-1}).

The virgin soil of Tucker Prairie has more SOM than so called no-till plots receiving the same amounts of residue. This is due to the fact that the latter plots experience some kind of disturbance from time to time such as reseeding (timothy has been reseeded every 5 years) or disking to chop corn stalks. Nevertheless, data also show that it is possible to maintain a carbon level of cultivated soil close to that of its native counterpart. The three year rotation (corn/wheat/clover) with manure and nitrogen lost more than 30% of organic carbon in its upper 20 cm during the first 60 years, and after 1950 it started to accumulate organic carbon. By 1988 the carbon content in this soil to the depth of 1 m was 13.47 kg m^2, a value approaching that of the native prairie. During the period from 1962 to 1988 this plot accumulated carbon at the rate of 150 g m^2 y^{-1}.

It is important to emphasize that the upper part of the soil profile experienced the most serious changes in carbon content. Nevertheless, certain amounts of organic matter have been lost from or gained in the lower part of the soil profile, beyond the plow layer (Fig. 3).

Regional and global implication

The annual carbon flux through the terrestrial biosphere is estimated at 45 Pg (Esser 1990). With a global cropland of 1.5 × 10^9 ha and grassland of 3 × 10^9 ha (⊤ 30% of the earth's land surface), agricultural activity makes a very significant input in atmosphere–biosphere flux, especially during the early stages of development (Schlesinger 1984; Buringh 1984).

Agricultural practices tend, generally, to cause a release of soil carbon to the atmosphere. Schlesinger (1984) suggested that ⊤ 36 Pg C have been released from soils from 1860 to the present. There is, however, a growing recognition that practices of modern agriculture may diminish carbon losses. The quiet revolution in agriculture which occurred after World War II was brought about by the introduction of new and more productive varieties of grain crops along with the wide scale use of high rates of mineral fertilizers. Amounts of crop residues dramatically increased and, even more importantly, the practice of removing residues as part of the harvest operation for small grains was abandoned. Increased

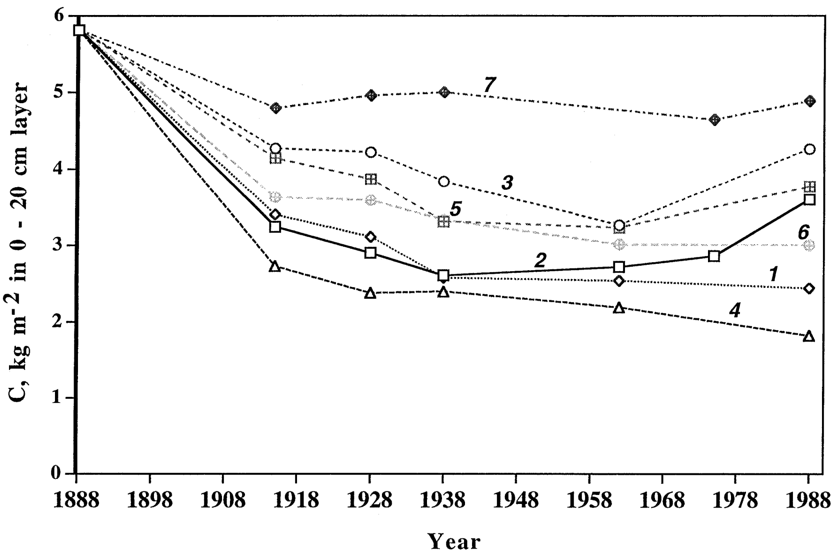

Fig. 2 Soil organic matter carbon dynamics in some Sanborn Field plots with common monocrops: 1, wheat, no treatment; 2, wheat, full mineral fertilizer; 3, wheat, 13.4 Mg ha^{-1} manure; 4, corn, no treatment; 5, corn 13.4 Mg ha^{-1} manure; 6, timothy, no treatment; 7, timothy, 13.4 Mg ha^{-1} manure.

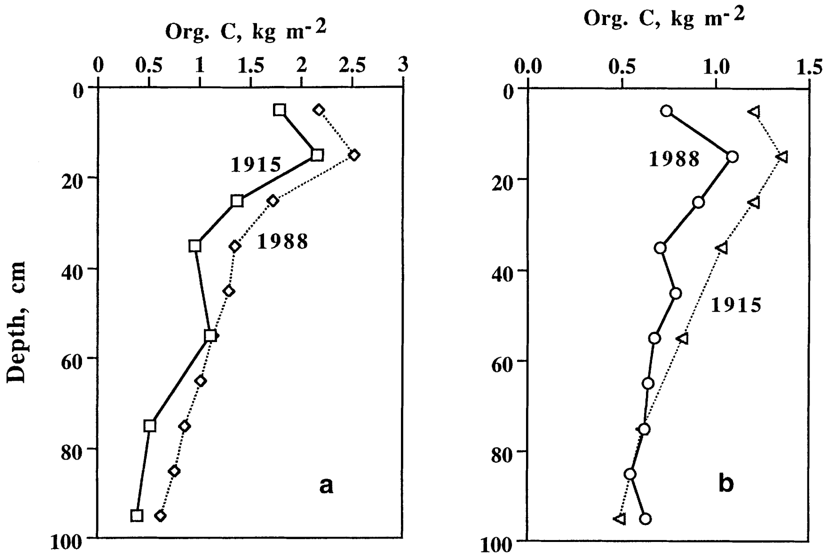

Fig. 3 SOC distribution within the soil profile for 1915 and 1988: (a) 3-year rotation. (corn/wheat/clover) with 13.4 mg ha^{-1} of manure and nitrogen; (b) corn, no treatment (in 10-cm increments).

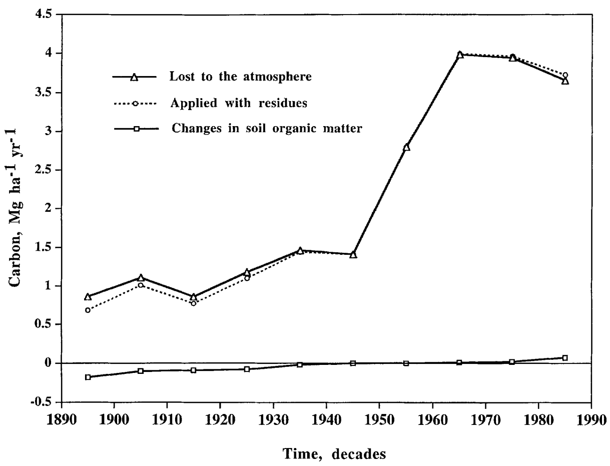

Fig. 4 Linkage between amounts of carbon applied to the soil with wheat residues and losses to the atmosphere, showing a net negative flux from the soil before 1950, 0 flux between the early 50s and late 60s, and a net positive flux to the soil thereafter. Return of carbon to the atmosphere after 1970 was less than amount accumulated by the crop due to the sequestration in soil.

input of carbon should lessen the negative effect of intensive cultivation on SOM level and perhaps allow sequestration of additional amounts of carbon into the soil. Sauerbeck (1993) postulates a feasible increase in C level for existing arable soils in the temperate zones as + 1 kg m^{-2} (10 Mg ha^{-1}) He estimates that it would take 50–100 years to reach this new level of SOC. Sanborn Field experiments show that this goal can be achieved even in a shorter period with a monocrop (winter wheat) receiving full mineral fertilizer. Corn under conservation tillage can provide even greater carbon sequestration. A rotation plot (corn/wheat/clover) with manure and nitrogen sequestered 16.4 Mg ha^{-1} of carbon during 25 years (Table 4). Sauerbeck's assumption that existing pool of agricultural land in the temperate zone can sequester about 6.2 Pg of carbon during 50 years looks very modest on this background and probably can be doubled.

Positive changes in carbon dynamics decreased amounts of CO_2 released to the atmosphere. Figure 4 illustrates the dynamics of carbon flow in soils under wheat receiving full mineral fertilizers. During the first 60 years, soil was loosing organic carbon, first at the rate 180 g m^{-2} y^{-1}, later at the much slower rate. Small increase in TNAP in the 20s and 30s did not change the direction of the process, soil continued to loose about 2% of SOM per year. In the late 50s and early 60s, when annual input of carbon to the soil increased, balance between input and output was reached and then surpassed, so that the soil started to sequester carbon.

For the whole area under wheat in the USA amounts of carbon involved in the process of wheat production almost tripled (currently at 104 Tg C) with acreage practically unchanged (Table 5). If the rate of accumulation of SOM carbon calculated for Sanborn Field is accepted for the national wheat production area, about 12–15 Tg of carbon was sequestered annually during the last 3 decades.

Changes in carbon flux through the soils cultivated under corn are more significant. Despite the fact that the total acreage under corn decreased significantly after 1950, TNAP and amounts of postharvest residues more than tripled between 1950 and 1990. From the early 20s through the 50s annual input of carbon varied in the limits of 1.0–1.5 Mg C ha^{-1} y^{-1}, by 1990 it increased to 7 Mg C ha^{-1} y^{-1}.

Assessments of soil organic carbon changes under corn in Central US are complicated by a high rate of erosion under corn during spring months when the soil is not

Table 5 Mean total net annual production (TNAP) and estimated residue carbon for corn and wheat in the USA in representative five year periods (US Department of Commerce 1975; US Department of Agriculture 1971–94)

Period	Harvested area, 10^3 ha	TNAP, Tg	Postharvest residue C, Tg
Corn			
1901–05	38 566	246.1	61.1
1931–35	41 052	221.3	55.2
1960–64	24 250	362.2	90.3
1975–79	28 761	658.3	164.2
1990–94	27 838	804.2	200.6
Wheat			
1901–05	19 035	100.2	27.0
1931–35	20 916	100.7	27.2
1960–64	19 635	181.4	49.0
1975–79	26 411	303.9	82.0
1990–94	25 446	353.2	95.3

Prior to 1960 about one-half of postharvest residues were removed from the small grain fields where they were grown in accord with current farm management practices. Some of these were later returned with manure spread on the field.

protected by live vegetation. It should be remembered, however, that carbon lost due to the erosion process is tied with clay particles and therefore is taken out of circulation for a long time.

Comparison of organic carbon in no-till and conventionally cultivated corn plots allowed to approximate this exclusion of carbon from the regular cycle. After 25 years under conventionally cultivated corn (monocrop) soil on Sanborn Field has 3.25 kg m^{-2} of carbon in the upper 20 cm layer. A parallel plot with no-till corn has 3.79 kg m^2 of carbon. It can be assumed that during 25 years at least 0.54 kg m^{-2} (or 0.22 Mg C ha^{-1} y^{-1}) of organic carbon was lost from the tilled plot as a result of erosion, which corroborates Gantzer *et al*'s (1989) calculations. Based on this assumption, the total carbon eroded from soils cultivated under corn (and therefore taken out from circulation) in the USA can be as high as 6 Tg y^{-1}. Above this loss, conventionally cultivated soil sequestered 0.3 Mg C ha^{-1} y^{-1}. Together with carbon lost through erosion, $\mp$ 0.52 Mg C ha^{-1} y^{-1} of carbon was incorporated into the soil organic matter each year during the period 1963–88, or about 16–17 Tg y^{-1} for the total US corn belt.

Combining the potential of corn and wheat, the annual carbon sequestered by those crops may be 32 Tg. Although this quantity amounts to 3–5% of the currently assumed imbalance, one has to remember that the area under wheat and corn in the USA in 1990–94 was 53 × 10^6 ha which is less than 10% of the arable soil in temperate region. Observations in other countries confirm the probability of carbon sequestration in cultivated soils and relate them to an increase in quantity of residues. In Canada, Campbell *et al.* (1995) documented an increase in carbon content of 0.15 Mg C ha^{-1} y^{-1} in sandy loam soil and 0.3–0.4 Mg C ha^{-1} y^{-1} on a medium-textured soil, which is much higher than Sauerbeck's (1993) assumption.

Simulation and analytical models have been used in many studies to predict potential soil carbon storage. Cole *et al.* (1993) emphasize steadily increasing rate of net primary production of agricultural ecosystems. Assuming annual crop increase of 1.5% per year, Donigan *et al.* (1995) concluded that extrapolation of current agricultural practices and trends will lead to a sequestration of about 1 Pg of carbon within Central US by the year 2030, what is very close to our assessment (32 Tg y^{-1}). They presume that nationwide the increase could be 50% greater.

Increasing role of reduced cultivation also have to be taken into account. In the late 80s – early 90s about 30% of crop land in the USA was under conservation tillage (Kern & Johnson 1993). This practice could increase carbon sequestration by another 15–20%, as our data in Table 4 show. Hunt *et al.* (1996) found that after 14 years of conservation tillage on light soils of Coastal Plain (Eastern USA) carbon content of the plow layer nearly doubled. Johnson *et al.* (1995) calculated that increase of conservation tillage practices to 76% of major crop land area may result in accumulation of 358 Tg of soil carbon in the USA.

One more aspect of cropland influence on carbon flux is variability of yields under the effect of climate variations. It is accepted that agroecosystems have carbon absorbed in the growing cycle offset by the heterotrophic respiration during the year. The presumption that these components of the carbon cycle are equal probably is legitimate for soils in a steady state over a long time period, but when considered year-by-year such a compensatory mechanism is less likely. In reality, annual yields of crops vary over wide limits, as does their TNAP and, correspondingly, the amount of carbon absorbed and then released.

If we consider consumption and release of carbon for a certain period, let us say 1980–88, we see tremendous variations in TNAP. Because of this, amounts of carbon absorbed in one year can be several times greater (or smaller) than in previous or following year. For instance, extremely low accumulation of carbon by corn on Sanborn Field in 1980, caused by unfavourable weather conditions, was followed by very high production in 1981. Carbon for this production could not be offset by mineralization of small amounts of residues accumulated in 1980. Each hectare of corn hit by crop failure in the previous year, in 1981 had 'to borrow' about 12 Mg C ha^{-1} of carbon from atmosphere. In contrast, in 1983 release of carbon to the atmosphere was much greater than limited consumption next year (4.2 vs. 2.5 Mg ha^{-1}). The corn belt of the USA experienced significant crop failures during the last decade (1983, 1988). In 1983, for example, harvested area and total yield were 30% less than in 1982 and 1984. Carbon absorption by corn in 1982 and 1984 was at least 250 Tg more than in 1983.

Concluding remarks

There are good reasons to reconsider the role of cultivated lands, especially in developed countries with moderate climate, in evaluating the global carbon balance during the second half of the 20th century. Lower productivity of crops than that of natural vegetation has long been assumed as a postulate. In reality, however, productivity of a modern man-made ecosystem and its native counterpart is very close. In Germany the ratio between agricultural and natural productivity is close to 1; in some countries (Belgium, Luxembourg) the ratio is above 1 (Esser 1990). The same was shown for the USA (Buyanovsky *et al.* 1987). Improvements in cultivation methods, better management and increased quantities of postharvest residues returned to the soil have caused very slow, however, detectable sequestration of carbon in SOM of properly cultivated agricultural land. It is quite probable that at least part of unknown terrestrial sink detected by analyses of the atmospheric gradients of CO_2 and $^{13}CO_2$ concentrations in Northern hemisphere (Schimel 1996) is none other than the vast pool of agricultural land in developed countries.

References

Balesdent J, Wagner GH, Mariotti A (1988) Soil organic matter turnover in long-term field experiments as revealed by carbon-13 natural abundance. *Soil Science Society of America Journal*, **52,** 118–124.

Brown JR (1994) The Sanborn Field Experiment. In: *Long-Term Experiments in Agricultural and Ecological Sciences* (eds Leigh RA and Johnston AE), pp. 39–52. CAB International, Wallingford.

Buringh P (1984) Organic carbon in soils of the world. In: *The Role of Terrestrial Vegetation in the Global Carbon Cycle: Measurement by Remote Sensing* (ed. Woodwell GM), pp. 91–110. Wiley, Chichester.

Buyanovsky GA, Aslam M, Wagner GH (1994) Carbon turnover in soil physical fractions. *Soil Science Society of America Journal*, **58,** 1167–1173.

Buyanovsky GA, Brown JR, Nelson CJ (1990) Effects of 100 years of continuous and rotational cropping on Sanborn Field. Transactions 14th International Congress of Soil Science, Kyoto, Japan, vol 4, 378–379.

Buyanovsky GA, Brown JR, Wagner GH (1996) Soil organic matter dynamics in Sanborn Field (North America). In: *Evaluation of Soil Organic Matter Models* (eds Powlson DS, Smith P and Smith J). NATO ASI Series I, 38, 295–300. Springer, Berlin.

Buyanovsky GA, Kucera CL, Wagner GH (1987) Comparative analyses of carbon dynamics in native and cultivated ecosystem. *Ecology*, **68,** 2023–2031.

Buyanovsky GA, Wagner GH (1986) Post-harvest residue input to cropland. *Plant& Soil*, **93,** 57–65.

Buyanovsky GA, Wagner GH (1987) Carbon transfer in a winter wheat ecosystem. *Biology and Fertility of Soils*, **5,** 76–82.

Buyanovsky GA, Wagner GH (1997a) Crop residue input to soil organic matter on Sanborn Field. In: *Soil Organic Matter in Temperate Agroecosystems* (ed. Paul EA), pp. 73–83. CRC Press, Boca Raton, FL.

Buyanovsky GA, Wagner GH (1997b) Sanborn Field: Effect of 100 years of cropping on soil parameters influencing productivity. In: *Soil Organic Matter in Temperate Agroecosystems* (ed. Paul EA), pp. 205–225. CRC Press, Boca Raton, FL.

Buyanovsky GA, Wagner GH, Gantzer CJ (1986) Soil respiration in a winter wheat ecosystem. *Soil Science Society of America Journal*, **50,** 338–344.

Campbell CA, McConkey BG, Zentner RP, Selles F, Curtin D (1995) Tillage and crop rotation effects on soil organic C and N in a coarse-textured Typic Haploboroll in southwestern Saskatchewan. *Soil & Tillage Research*, **37,** 3–14.

Cole CV, Paustian K, Elliot ET, Metherell AK, Ojima DS, Parton WJ (1993) Analysis of ecosystems carbon pools. *Water, Air, and Soil Pollution*, **70,** 357–371.

Cole CV, Stewart JWB, Ojima DS, Parton WJ, Schimel DS (1989) Modeling land use effects on soil organic matter dynamics in the North America Great Plains. In: *Ecology of Arable Land* (eds Clarholm M and Bergstrom L), pp. 89–98, Kluwer, Dordrecht.

Detwiler RP (1986) Land use change and the global carbon cycle: The role of tropical soils. *Biogeochemistry*, **2,** 67–93.

Donigan AS, Pathwardhan AS, Jackson RV, Barnwell TO, Weinrich KB, Rowell AL (1995) Modeling the impacts of agricultural management practices on soil carbon in the Central U.S. In: *Soil Management and Greenhouse Effect* (eds Lal R, Kimble J, Levine E, Stewart BA), pp. 121–135. CRC – Lewis Publishers, Boca Raton, FL.

Esser G (1990) Modeling global terrestrial sources and sinks of CO_2 with special reference to soil organic matter. In: *Soils and the Greenhouse Effect* (ed. Bouwman AF), pp. 247–261. Wiley, Chichester.

Gantzer CJ, Anderson SH, Thompson AL, Brown JR (1989) Evaluation of soil loss after 100 years of soil and crop management. *Agronomy Journal*, **83,** 74–77.

Haas HJ, Evans CE, Miles EF (1957) Nitrogen and carbon changes in Great Plains soils as influenced by cropping and soil treatment. *U.S. Department of Agriculture Technical Bulletin*, **1164**.

Hobbs JA, Brown PL (1965) Effects of cropping and management on nitrogen and organic carbon contents of a Western Kansas soil. *Kansas Agricultural Experiment Station Technical Bulletin*, 144.

Houghton RA (1995) Balancing the global carbon cycle with terrestrial ecosystems. In: *The Role of Nonliving Organic Matter* *in the Earth's Carbon Cycle* (eds Zepp RG, Sonntag Ch), pp. 133–152. Wiley, Chichester.

Hunt PG, Karlen TA, Matheny TA, Quisenberry VL (1996) Changes in carbon content of a Norfolk loamy sand after 14 years of conservation or conventional tillage. *Journal of Soil and Water Conservation*, **51** (3), 255–258.

Johnson MG, Levine ER, Kern JS (1995) Soil organic matter: distribution, genesis, and management to reduce greenhouse gas emissions. *Water, Air and Soil Pollution*, **82,** 593–615.

Kern JS, Johnson MG (1993) Conservation tillage impacts on national soil and atmospheric carbon levels. *Soil Science Society of America Journal*, **57,** 200–210.

Kucera CL (1987) The tallgrass prairie. In: *Ecosystems of the World* (ed. Coupland RT), chapter 18, Vol. 8. Elsevier, Amsterdam.

Mann LK (1985) A regional comparison of carbon in cultivated and uncultivated Alfisols and Mollisols in the continental United States. *Geoderma*, **36,** 241–253.

Mann LK (1986) Changes in soil carbon storage after cultivation. *Soil Science*, **142,** 279–288.

Nelson DW, Sommers LE (1982) Total carbon, organic carbon, and organic matter. In: *Methods of Soil Analysis*, *Part 2*, Second edn (ed. Page AL). ASA – SSSA, Madison, Wisconsin, USA.

Rasmussen PE, Parton WJ (1994) Lond-term effects of residue management in wheat-fallow: I. Inputs, yield, and soil organic matter. *Soil Science Society of America Journal*, **58,** 523–530.

Rassmussen PE, Allmaras RR, Rohde CR, Roager NC (1980) Crop residue influences on soil carbon and nitrogen in a wheat – fallow system. *Soil Science Society of America Journal*, **44,** 596–600.

Sauerbeck D (1993) CO_2 Emission from Agriculture: Sources and Mitigation Potentials. *Water, Air and Soil Pollution*, **70,** 381–388.

Schimel DS (1996) Terrestrial ecosystems and the carbon cycle. *Global Change Biology*, **1,** 77–91.

Schlesinger WH (1984) Soil organic matter: A source of atmospheric CO_2. In: *The Role of Terrestrial Vegetation in the Global Carbon Cycle. Measurement by Remote Sensing* (ed. Woodwell GM), pp. 111–127. Wiley, New York.

Schlesinger WH (1986) Changes in soil carbon storage and associated properties with disturbunce and recovery. In: *The Changing Carbon Cycle: A Global Analysis* (eds Trabalka JR, Reichle DE), pp. 124–220. Springer-Verlag, New York.

Tans PP, Fung IY, Takahashi T (1990) Observational constraints on the global atmospheric CO_2 budget. *Science*, **247,** 1431–1438.

Unger PW (1968) Soil organic matter and nitrogen changes during 24 years of dryland wheat and cropping practices. *Soil Science Society of America Proceedings*, **32,** 427–429.

Upchurch WJ, Kinder RJ, Brown JR, Wagner GH (1985) Sanborn Field, historical perspective. *Missouri Agricultural Experiment Station Technical Bulletin*, 1054.

US Dept. of Agriculture (1971–94) *Agricultural Statistics*. US Government Printing Office, Washington, DC.

US Dept. of Commerce (1975) *Historical Statistics of the United States. Colonial Times to 1970*. US Bureau of Census, Washington, DC.