Agricultural soils as a sink to mitigate CO_2 emissions

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Abstract. Agricultural soils, having been depleted of much of their native carbon stocks, have a significant CO_2 sink capacity. Global estimates of this sink capacity are in the order of 20–30 Pg C over the next 50–100 years. Management practices to build up soil C must increase the input of organic matter to soil and/or decrease soil organic matter decomposition rates. The most appropriate management practices to increase soil C vary regionally, dependent on both environmental and socioeconomic factors.

In temperate regions, key strategies involve increasing cropping frequency and reducing bare fallow, increasing the use of perennial forages (including N-fixing species) in crop rotations, retaining crop residues and reducing or eliminating tillage (i.e. no-till). In North America and Europe, conversion of marginal arable land to permanent perennial vegetation, to protect fragile soils and landscapes and/or reduce agricultural surpluses, provides additional opportunities for C sequestration.

In the tropics, increasing C inputs to soil through improving the fertility and productivity of cropland and pastures is essential. In extensive systems with vegetated fallow periods (e.g. shifting cultivation), planted fallows and cover crops can increase C levels over the cropping cycle. Use of no-till, green manures and agroforestry are other beneficial practices. Overall, improving the productivity and sustainability of existing agricultural lands is crucial to help reduce the rate of new land clearing, from which large amounts of CO_2 from biomass and soil are emitted to the atmosphere.

Some regional analyses of soil C sequestration and sequestration potential have been performed, mainly for temperate industrialized countries. More are needed, especially for the tropics, to capture region-specific interactions between climate, soil and management resources that are lost in global level assessments.

By itself, C sequestration in agricultural soils can make only modest contributions (e.g. 3–6% of total fossil C emissions) to mitigating greenhouse gas emissions. However, effective mitigation policies will not be based on any single 'magic bullet' solutions, but rather on many modest reductions which are economically efficient and which confer additional benefits to society. In this context, soil C sequestration is a significant mitigation option. Additional advantages of pursuing strategies to increase soil C are the added benefits of improved soil quality for improving agricultural productivity and sustainability.

Keywords: Carbon, retention, carbon dioxide, emission, agricultural soils

INTRODUCTION

Greenhouse gas emissions and climate change are important issues to agriculture both because of their potential impacts on agricultural production and because agriculture is a major contributor to the build-up of greenhouse gases in the atmosphere. In the 1995 Intergovernmental Panel on Climate Change (IPCC) Assessment, agriculture was estimated to be responsible for 20% of the annual increase in anthropogenic greenhouse gas emissions, expressed as radiative forcing potential (Cole *et al.*, 1996). Methane and nitrous oxide account for most of this and their emissions from soil and their mitigation is discussed elsewhere in this volume. The increase in radiative forcing due to agricultural CO_2 emissions, excluding that associated with land use change (see Erickson & Keller, 1997 this issue), is relatively modest, *c.* 5% of the total.

The conversion of native ecosystems to agriculture almost invariably results in a net loss of soil C (Haas *et al.*, 1957; Mann, 1986; Schlesinger, 1986; Davidson & Ackermann, 1993). The rapid increase in the world's agricultural area over the past 300 years (Wilson, 1978; Houghton & Skole, 1990) was responsible for large CO_2 emissions in the past. Prior to 1920, land use change (mainly conversion to agriculture) was the predominant anthropogenic source of CO_2 emissions, exceeding that of fossil fuels (Houghton & Skole, 1990). Because these agricultural soils are now relatively C-depleted, they represent a potential CO_2 sink if part of the lost carbon can be regained.

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Several recent studies have begun to assess the potential for C sequestration on agricultural soils, primarily in industrialized countries (Barnwell *et al.*, 1992; Kern & Johnson, 1993; Lee *et al.*, 1993; Cole *et al.*, 1996; Smith *et al.*, 1997a,b; Dumanski *et al.*, 1998). Our objective in this paper is to discuss the controls on soil C in agricultural soils, how they are influenced by management, and to review and synthesize field data and recent assessments pertaining to managing soil as a sink for CO_2.

C STOCKS IN AGRICULTURAL SOILS: PRESENT AND PAST

The global soil organic carbon (SOC) inventory is estimated to be 1200–1600 Pg, which is equal to or slightly greater than the amounts stored in terrestrial vegetation (550–700 Pg) and the atmosphere (750 Pg), combined (Post *et al.*, 1990; Sundquist, 1993). Estimates of 1456 Pg SOC by Schlesinger (1977) and 1395 Pg by Post *et al.* (1982), were based on land area classified by major vegetation types or life zones, while estimates of 1576 Pg by Eswaran *et al.* (1993) and 1220 Pg by Sombroek *et al.* (1993) were based on global soils maps. There has been no detailed determination of global C stocks specifically for agriculture. However, rough estimates have been obtained using information from the global soil C inventories. Based on data compiled by Bouwman (1990) of the distribution of FAO soil groups on cultivated lands, C contents by soil group from Sombroek *et al.* (1993), and additional data for cultivated Histosols, Cole *et al.* (1996) estimated precultivation C stocks of 222 Pg on the present area of cultivated land (Table 1). Accounting for C losses due to cultivation, they estimated current agricultural soil C stocks at 168 Pg, very close to the 167 Pg estimated by Post *et al.* (1982) using C inventories based on Holdridge life zones.

The estimated historic losses of C from agricultural soils (Table 1) amount to 54 Pg C for all soils under agriculture, of which 43 Pg C stems from upland soils and 11 Pg C from cultivated 'wetland' soils, i.e. Histosols and poorly-drained mineral soils (Gleysols). Similar soil C losses due to past land conversion to agricultural use were estimated by Houghton & Skole (1990). They estimated a net reduction in terrestrial organic C stocks of 275 Pg since the beginning of settled agriculture, of which 41 Pg was attributed to soils. Carbon losses

from organic soils (Histosols) were not specifically included in their estimates.

These global estimates of historic C losses from cultivated soils (40–60 Pg) provide a reference level for C sequestration potential. In most cases, C levels in agricultural soils, even with improved management, are unlikely to exceed their native condition. Thus, the C levels of native soils (i.e. precultivation conditions) can be viewed as a practical upper limit to C storage potential. However, there are notable exceptions to this, such as the 'Plaggen' soils of NW Europe and the 'Terra Preta-do-Indio' soils of the Amazon, where intensive management and high levels of organic matter additions were practiced over many years, resulting in greatly enhanced soil C (Sombroek *et al.*, 1993). Other examples include improved pastures in Australia where P fertilization greatly stimulated plant productivity, resulting in soil organic matter levels much higher than in the original native condition (Russell, 1960).

The potential to increase C levels in soils under permanent cultivation will be largely restricted to upland soils. Restoring C sinks in artificially-drained wetland soils (i.e., Histosols and Gleysols) is unlikely unless they are taken out of agricultural production and reverted to natural wetlands. Cole *et al.* (1996) assumed a recovery of one-half to two-thirds of historic C losses (43 Pg C from upland soils; Table 1) as a reasonable upper limit, yielding a global potential for C sequestration in agricultural soils over the next 100 years of the order of 20–30 Pg C. Including the potential for soil C sequestration in surplus agricultural lands which are reverted to grasslands and wetlands, increases the annual estimate to 0.2–0.4 Pg/y (Cole *et al.*, 1996).

For purposes of mitigating CO_2 increases in the atmosphere, we define C sequestration as any persistent net increase in organic C storage. One might argue that only the formation of very recalcitrant soil C should be considered as sequestered soil C. However, the decomposability of soil organic matter varies along a continuous gradient and there is no biological process which renders organic C completely inert. Thus, any definition of sequestered C based on a particular residence time would be purely arbitrary. Because SOC responds dynamically to management, a policy to promote C sequestration presupposes a maintenance of the practices which promote the accumulation of organic matter. If man-

Table 1. Areas and organic C inventories of agricultural soils worldwide, derived from Cole *et al.* (1996). Global distribution of cultivated soils (excluding Histosols) are from Bouwman (1990), with mean C contents by FAO soil groups, representing uncultivated soils, from Sombroek *et al.* (1993). Estimated area of artificially-drained Histosols is 10% of total area (Armentano, 1980) and mean C content is from Armentano & Menges (1986). Carbon in cultivated mineral soils is estimated assuming an average 26% decrease of C in the top 30 cm (Davidson & Ackerman, 1993). Carbon loss due to conversion of Histosols for cropland and pasture is based on Armentano & Menges (1986). Calculations were done separately for each soil group after which the data were grouped for clarity. However, soil types can occur in more than one grouping

Soil Groups	Cultivated area ($\times 10^6$ ha)	Soil C (kg/m^2 to 1 m)	C mass – virgin (Pg C)	C mass – cultivated (Pg C)
Temperate Forest Soils (Podzoluvisol, Luvisol, Podzol, Chromic Luvisol)	308	6.9–14.2	24.4	18.1
Temperate Grassland Soils (Chernozem, Phaeozem, Kastanozem, Greyzem)	352	12.5–18.4	49.8	36.9
Tropical Forest Soils (Typic Acrisols, Ferralsol, Cambisol, Nitosol, Planosol)	439	7.1–14.5	47.3	35.1
Tropical Grasslands/Savanna Soils (Humic Acrisol, Vertisol)	161	9.4–17.8	21.4	15.9
Shallow, Saline, Sodic and Arid Soils (Regosol, Lithisol, Arenosol, Solonchak, Solonetz, Xerosol)	308	2.6–7.1	17.7	13.1
Wetlands/Paddy Soils (Gleysols)	89	11.9	10.6	7.8
Histosols	39	112	43.6	35.6
Andosols	31	23.7	7.3	5.4
Total	1727	n.a.	222	168

agement reverts to its previous state, net losses of CO_2 will result. In situations in which C stocks fluctuate significantly over a management cycle, such as in shifting cultivation, we define C sequestration as any increase in mean C stocks over the entire course of the management cycle. This definition is consistent with that used for forest C sequestration, i.e. the average increase in the standing stocks of biomass C.

CONTROL ON SOIL C LEVELS

Carbon levels in soil are determined by the balance of inputs, as crop residues and organic amendments, and C losses through organic matter decomposition. Thus, management to sequester C requires increasing C inputs, decreasing decomposition, or both. In the context of managing soils to sequester C, we view erosion as a transport process rather than as a loss or a gain of SOC. It is unclear whether erosion, at the regional level, increases or decreases C stocks in soils and sediments (Paustian et al., 1997a; Van Noordwijk et al., 1997) and therefore effects of erosion are not considered. There is a clear need for research on the fate of C in depositional sites in agricultural landscapes.

Most management practices seek to increase the productivity of a crop and therefore nearly all management practices directly affect the input of C to the soil. A number of longterm experiments show a direct proportionality between C input rates and soil C levels (Paustian et al., 1997a). While increasing productivity may result in an increase in the rate of crop residue return, the magnitude will depend on residue management practices (i.e. straw retention vs. removal) and the C allocation pattern within the crop. For example, a substantial part of the yield increases in wheat over the past several decades has been achieved through increasing allocation to grain (Cox et al., 1988). Thus, residue production has increased more slowly than yields. Management practices which enhance production, such as fertilization and irrigation, may also influence decomposition rates (Andrén et al. 1993). Thus, the relationship between management as it affects productivity and SOC is complex.

Organic matter decomposition is influenced by numerous physical, chemical and biological factors controlling the activity of microorganisms and soil fauna (Swift et al., 1979; Andrén et al., 1990). Soil temperature and moisture are the most important environmental controls and their influence is fairly well understood. The increase in decomposition rates with increasing temperature, usually described by a power function (e.g. Q_{10}, Arrhenius equation), is well documented. Optimal moisture conditions in most soils are around 55–60% water-filled pore space (Doran et al., 1988) with decomposition decreasing as the soil dries. Water contents near or at saturation inhibit decomposition due to reduced diffusion and availability of oxygen. Both temperature and moisture are affected by management including cropping intensity (e.g. bare fallow frequency), crop type (e.g. water use, shading), residue management (e.g. surface mulching), irrigation and tillage.

Tillage affects decomposition processes through the physical disturbance and mixing of soil, by exposing soil aggregates to disruptive forces, and through the distribution of crop residues in the soil (Oades, 1984; Elliott, 1986; Beare et al., 1994a). Tillage also affects soil temperature, aeration and water rela-

tions by its impact on surface residue cover and soil structure (Paustian et al., 1997a). By increasing the effective soil surface area and continually exposing new soil to wetting/drying and freeze/thaw cycles at the surface, tillage makes aggregates more susceptible to disruption and physically-protected inter-aggregate organic material becomes more available for decomposition (Elliott & Coleman, 1988; Beare et al., 1994a). Numerous field studies show increases in macroaggregate stability with reduced tillage, especially with no-till (Kladivko et al., 1986; Beare et al., 1994b).

Crop residues vary in their inherent decomposability due to differences in their physiochemical characteristics (Andrén & Paustian, 1987). Thus, the use of different crop types represents a potential management control on decomposition. Lignin and certain polyphenolic substances are the most commonly used chemical measures of litter quality (Paustian et al., 1997b). Several studies have shown a strong correlation between lignin content and short-term decomposition rates of fresh residues (Melillo et al., 1982; Tian et al., 1992). The effects of litter quality also seem to have a more lasting effect on total soil C levels. Experiments with 20-30 years of organic amendments of differing qualities, but in the same amounts, have shown significant long-term effects of litter quality on soil C levels (Sowden & Atkinson, 1968; Paustian et al., 1992). For conventional cropping systems, manipulation of litter quality may not be a major option, since most crop residues do not differ greatly in their relative amounts of recalcitrant substances. Most forage and annual crop residues have lignin contents in a relatively narrow range, usually between 5 and 15% (Theander & Åman, 1984). However, in less conventional systems, such as agroforestry, additions of recalcitrant woody tissues and tree leaves, having high C:N ratios and high lignin content, have been proposed as a means of building soil C stocks and regulating soil nutrient availability (Myers et al., 1997).

Animal manure is also effective in building soil C stocks (Jenkinson & Rayner, 1977; Sommerfeldt et al., 1988; Sauerbeck, 1992). Animal manures have a high proportion of recalcitrant materials because labile compounds have been selectively removed in digestion. Not all the gain in soil C from manure applications represents a net removal of atmospheric CO_2; much is simply a redistribution of C from plant materials used as feed and bedding. Through benefits to soil fertility and structure, however, manure application can increase crop growth and thereby contribute to C gains from higher plant litter input.

Nutrient levels and soil pH affect decomposition rates and SOM turnover and both are influenced by management practices such as fertilization and liming. However, manipulation of nutrient and pH levels to reduce decomposition rates are unlikely to be effective strategies in most instances. In most agricultural soils, significant nutrient limitation of decomposition would only occur at low nutrient levels, where crop production would be far below the optimum. Similarly, optimal pH levels for decomposition coincide with those best suited for crop production (i.e. 6–7) and decomposition is usually not significantly repressed except in quite acid conditions (Dyal et al., 1939), where crop growth is similarly inhibited. It has been suggested that the development and use of acid tolerant crops (i.e. high Al tolerance) in acid tropical soils would be useful in reducing the need for liming, which

can stimulate soil respiration and CO_2 losses from these soils (Van Noordwijk *et al.*, 1997). Overall, the main effects of fertilization and liming on the soil C balance are likely to be manifested through influencing crop production and C inputs to soil.

INCREASING SOIL C THROUGH MANAGEMENT

The adoption of agricultural management practices that sequester C will be constrained both by environmental conditions such as climate and soil types as well as by economic and socio-political factors. The latter constraints, including the supply and demand for agricultural products, production costs, subsidies, incentives to reduce environmental impacts (including reducing CO_2 emissions), and social, aesthetic and political acceptance for changes in the agricultural landscape, may well be the most important factors affecting adoption rates. However, analysis of these factors is highly complex and such studies, in the context of mitigation of CO_2 emissions, are only now beginning (Cole *et al.*, 1996). Therefore, we will focus primarily on environmental constraints on managing soils as a CO_2 sink. Thus our assessments reflect more of an agro-ecological potential for C sequestration. In doing so, we consider agriculture in temperate and tropical regions separately, because of broad differences in climatic and soil conditions, and because of some distinct differences between the major types of agricultural systems in temperate and tropical environments.

Agriculture in Temperate Regions

Temperate zone agriculture includes Europe, N. America, parts of East Asia (including northern China, Japan, Korea), New Zealand, much of Australia, and southern parts of Africa and S. America. Agriculture is for the most part intensive, with a high degree of mechanization and high chemical inputs. Low temperatures generally preclude active crop growth during winter, with the exception of some irrigated agriculture in Mediterranean climates. Another important distinction from tropical regions is that there is little new land being converted to agriculture and in some of the most economically developed areas (Canada, USA, W. Europe) there is currently a surplus of arable land which is being converted to other uses (urban, forest, grassland) or placed in set-aside programmes. Climatically, broad distinctions can be made between semi-arid and more humid regions and between cool and warmer temperature regimes. These differences influence both the kinds of management practices which can be used to sequester C and the magnitude of the responses.

In temperate semi-arid regions annual precipitation is less than *c.* 500 mm and the main production systems are annual cropping of cereals (wheat, barley, millet, sorghum) and oil seed and extensively managed pastures/rangeland. In irrigated areas a variety of high yielding (e.g. maize, sugarbeet, hay) and high value (e.g. vegetables) crops are grown. Since water is the main limiting factor for non-irrigated systems, a dominant practice has been the use of lengthy bare fallow periods to accumulate soil water for subsequent crops. Shortage of water also limits the importance of perennial forages in rotation with annual crops, particularly in warm climates with high evapotranspiration potential. Conventional prac-
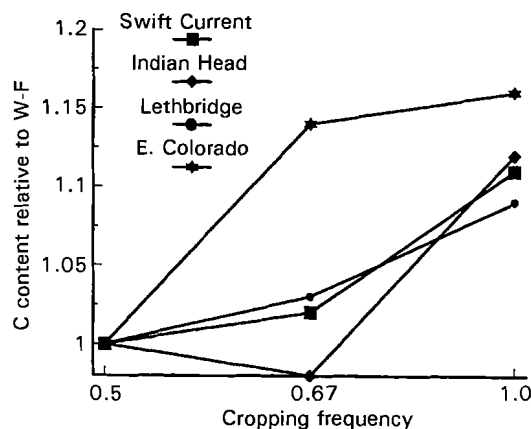

Fig. 1. Changes in soil organic carbon (SOC) as a function of cropping frequency, i.e. number of crops per year, for long-term sites in semi-arid cropping sysems in southern Alberta (Bremer *et al.* 1994) and Saskatchewan (Campbell *et al.*, 1997; Campbell & Zetner, 1997) and eastern Colorado (Peterson *et al.*, 1998). Values are scaled relative to C contents in wheat-summer fallow (W–F) rotations (i.e. cropping frequency = 50%). Values for E. Colorado are means for experiments at three sites.

tices in these regions have not been conducive to maintaining soil C, with low rates of C return, frequent tillage, degradation of soil structure and favourable conditions for decomposition during fallow periods.

In semi-arid environments, numerous field experiments have demonstrated the potential for enhancing soil C levels through increasing the frequency of cropping (i.e reducing fallow), together with improved water and nutrient management (Fig. 1). Overall, C inputs tend to increase with continuous cropping, particularly where fertilizers are applied (Paustian *et al.*, 1997a). Of equal or greater importance is the reduced time in fallow, during which decomposition is enhanced due to higher soil moisture and temperature. In warmer semi-arid regions, the use of no-till enhances water storage and water use efficiency, enabling increased cropping frequency (Peterson & Westfall, 1997).

More humid temperate regions are characterized by predominantly continuous cropping, with cooler climates supporting small grains, oil seed and root crops while dominant systems in warmer climates include row crops, feed grains (e.g. maize, sorghum) and grain legumes (e.g. soyabean, groundnut). Grass and legume forages are important and can be incorporated within grain-based rotations. Generally, there is potential for high C inputs to soil but conditions for decomposition are also favourable during much of the year. Strategies to increase C inputs to soil in these environments include use of high residue yielding crops, including perennial forages in rotations (ley farming), intensifying rotations with winter cover crops and double cropping where possible, and increasing production with fertilization.

Among annual crops, cereals generally produce the most residues while crops such as grain legumes, dry beans and root crops produce less. Thus, for example, soil C levels tend to be lower under maize-soyabean rotations compared with continuous maize (Paustian *et al.*, 1997a). Zielke & Christenson (1986) found that changes in soil C for six rotations including maize, sugarbeet, navy bean, oats and lucerne were directly correlated to amounts of residue returned and the frequency of maize in the rotation. Havlin *et al.* (1990) found similar results for two sites in eastern Kansas, with continu-

Table 2. Soil C responses to N fertilizer additions for long-term field experiments in subhumid temperate regions. Soil C levels are given as % of the unfertilized (or least fertilized) treatment

Site	Yrs	Treatment	N Levels (kg/ha) Soil C (% of control)			
Eastern Kansas	8		0	252		
(Havlin et al., 1990)		continuous soyabean	100	95		
		maize/soybean	100	101		
		continuous maize	100	102		
Purdue, Indiana	12		0	67	200	
(Barber, 1979)		continuous maize	100	106	107	
Lamberton, Minnesota	19		0	45	90	180
(Bloom et al., 1982)		continuous maize	100	104	103	105
Lexington, Kentucky	20		0	84	168	336
(Ismail et al., 1994)		continuous maize –ploughing	100	115	115	126
		continuous maize –no-till	100	105	106	120
Askov, Denmark	78		0	35	70	105
(Kofoed & Nemming, 1976)		cereal/root crop rotation—loam	100	106	109	111
		cereal/root crop rotation—sand	100	111	121	–
Southern Sweden	15		0	50	100	150
(Jansson, 1975)		mixed cropping	100	107	108	111
Uppsala, Sweden	30	cereal/root crops	0	80		
(Paustian et al., 1992)		straw removed	100	118		
		straw added	100	116		
		sawdust added	100	115		
Ås, Norway	20	cereals	0	34	68	136
(Uhlen, 1991)		straw added	100	98	101	103
		straw removed	100	101	104	103
Øsaker, Norway	20	cereals	0	34	68	136
(Uhlen, 1991)		straw added	100	102	100	104
		straw removed	100	100	99	107
Ås, Norway	31		60	120		
(Uhlen, 1991)		cereals	100	102		
		cereal + row crops	100	102		
		2 ley + 4 arable	100	108		
		4 ley + 2 arable	100	104		
Halle/Saale, Germany	80		0	40		
(Welte & Timmerman, 1976)		continuous rye	100	108		
Gottingen, Germany	81		0	30–50		
(Timmerman & Welte, 1976)		mixed rotation	100	111		
Rothamsted, UK			0	144		
(Jenkinson et al., 1994)	135	continuous wheat	100	123		

ous maize and continuous sorghum maintaining higher C levels than rotations including soyabeans.

The inclusion of perennial forages (i.e. leys) in rotations increases soil C levels relative to rotations with annual crops alone. Experiments in Europe with three or more years of ley within annual crop rotations had up to 25% more soil C compared to rotations including only annual crops (Johnston, 1973; Van Dijk, 1982; Nilsson, 1986). Carbon accumulation by perennials is attributable to the high relative allocation of C below-ground, greater transpiration leading to drier soils, the formation of stable aggregates within the extensive network of grass roots, and the absence of soil disturbance by tillage (Anderson & Coleman, 1985; Paustian et al., 1990; Haynes et al., 1991).

Fertilization enhances crop production and C inputs, with many experiments showing a positive effect of N additions on the soil C balance (Glendining & Powlson, 1995; Paustian et al., 1997a), particularly in mesic environments where nutrients are the primary growth limiting factor (Table 2). In addition to direct effects of fertilization on C inputs, high N availability may also enhance the formation of recalcitrant humic substances in soil (Fog, 1988).

Reduced tillage, in particular no-till, can increase soil C in annual crop systems, provided that crop production is not adversely affected by reducing tillage (Paustian et al., 1997a). To quantify tillage effects on soil C stocks it is necessary to account for differences in the depth distribution of SOC and bulk density, both of which are affected by tillage type (Doran, 1987). Using published data from long-term experiments, comparisons of no-till and ploughed treatments were made in which C levels were summed to below the depth of ploughing and adjusted to an equivalent soil mass basis (Fig. 2). All comparisons, whether or not they were reported to be statistically significant, were included in the analysis.

For the 39 paired comparisons, the average soil C level was 285 g/m^2 more under no-till compared with conventional tillage. On a relative basis, soil C was 8% higher in no-till than in conventional tillage. These data are for the mineral soil only and exclude coarse (e.g > 2 mm) residues. For the majority of the experiments included in Figure 2 the conventional tillage practice is mouldboard ploughing, which incorporates all residues into the soil. In contrast, no-till systems can accumulate a substantial standing stock of surface residues (i.e. > 100 g C/m^2) which should be included in comparing the C balance for different tillage systems (Peterson et al., 1998). However, since most studies of tillage effects on soil properties were not originally intended to address questions of C sequestration, surface (and coarse) residue C pools have
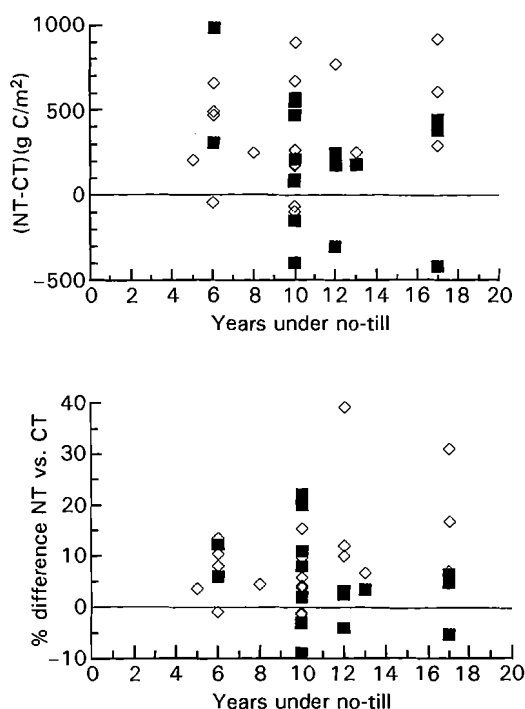
Fig. 2. Differences in soil C between paired no-till (NT) and conventional till (CT) treatments from several temperate zone long-term experiments. Values show absolute (NT-CT) and percent relative ((NT-CT)/CT*100) differences versus duration of the experiment (i.e. time under NT). All calculations were done on an equal soil mass basis, to below the depth of tillage, to adjust for tillage-induced differences in bulk-density. Filled symbols are for heavy-textured soils (clay and clay loam), open circles are for all other soil textures. Data from Balesdent *et al.* (1990), Chan *et al.* (1992), Dalal (1989), Dick (1983), Dick *et al.* (1986a,b), Doran (1987), Groffman (1984), Havlin *et al.* (1990), Ismail *et al.* (1994), Peterson *et al.* (1998), Potter *et al.* (1998), and Powlson & Jenkinson (1981).

generally not been measured or reported. Thus, the values shown in Figure 2 should be regarded as under-estimates of the effects of reduced tillage on C storage.

The reversion of cultivated land to perennial grassland, wetland or forest are land use changes which can contribute to C sequestration. Establishment of a perennial cover and the absence of tillage disturbance generally leads to a recovery of soil C stocks depleted as a result of cultivation. Rates of recovery tend to increase in proportion to plant productivity. Therefore, C accumulation rates tend to increase going from dry to more mesic environments and C sequestration is usually enhanced for managed conversions (i.e. with seeding,

fertilization) compared with land abandonment (Table 3). Significant land areas in industrialized countries (i.e. USA, Canada, W. Europe) have been taken out of crop production mainly due to problems with over production and crop surpluses and/or to reduce environmental problems (e.g. erosion, water quality, wildlife habitat loss) on marginal or environmentally sensitive areas. For the US Conservation Reserve Program which provides land set-asides to grassland or forest for periods of ten years or more, Paustian *et al.* (1998) estimated C sequestration rates of 14 Tg/y averaged over a ten-year period, for the *c.* 14 Mha in the programme. If such lands are maintained under perennial vegetation, sequestration of C will continue for up to several decades (although at a diminishing rate) until new equilibrium C levels are reached. However, if set-aside lands are returned to annual crop production, most of the accumulated C is likely to be lost within a few years. Thus, short-term, transient set-asides are likely to be ineffective as a C sequestration strategy. However, research on direct conversions to no-till for lands taken out of set-aside, suggests that some of the accumulated C could be maintained and C losses reduced (Karlen, 1998).

Agriculture in the Tropics

Tropical agriculture is highly diverse, ranging from intensive, highly developed management systems to extensive, low input subsistence production. Agriculture is practised on all major soil types, over a wide array of climatic conditions differentiated mainly by the amount and distribution of rainfall.

The constraints on agriculture's potential to sequester C in tropical environments differs from those in temperate regions in several ways. A large proportion of agriculture in the tropics is subsistence-based, with low production inputs and low average yields. Such systems often require an extensive land base (i.e. shifting cultivation) and there is high demand for alternative uses of crop residues (e.g. fodder, fuel). In contrast to most of the temperate zone, food demand exceeds supply in much of the tropics and the agricultural land base is expanding, resulting in large losses of biomass and soil C due to deforestation.

As in the temperate zone, practices which can contribute to C sequestration and the magnitude of the potential C sink vary greatly by climate and by soil type. In assessing management options to increase soil C stocks we consider three broad tropical environments: the semi-arid, sub-humid and humid tropics.

Table 3. Examples of C sequestration rates with conversion of agricultural land to forest and grasslands in some temperate locations

Region	Land use conversion	Time period (years)	Soil depth (cm)	Mean soil C accumulation $(g/m^2/y)$	Reference
USA	Abandoned to native shortgrass prairie	50	10	3	Burke *et al.* (1995)
Canada	Abandoned to native shortgrass prairie	25	15	7–13	Dormaar & Smoliak (1985)
USA	Grassland seeded for set-aside programme	5	20	2–40	Gebhart *et al.* (1994)
UK	Abandoned to forest—Geescroft	81	23	25	Jenkinson (1971)
	Abandoned to forest—Broadbalk	83	23	52	
	Abandoned to grass—Broadbalk	83	23	55	
UK	Planted grassland	15	15	75	Tyson *et al.* (1990)
USA	Abandoned to tall grass prairie	17	10	~100	Jastrow (1996)
New Zealand	Planted grassland	18	20	100	Haynes *et al.* (1991)

Semi-arid Tropics The semi-arid tropics include parts of Central and South America (e.g. northeastern Brazil), extensive areas in West, East and Southern Africa and on the Indian subcontinent. Annual precipitation is less than *c.* 1000 mm/y and the predominant native ecosystems are savanna and dry forest. The predominant agricultural systems include grazing, shifting cultivation and permanent dryland agriculture. Grazed savannas consist of isolated trees and shrubs and native or introduced grasses, grazed and browsed by ruminant livestock. They are subjected to annual or periodic burning to reduce tree and shrub cover. Continuous heavy grazing may result in reduced vegetation cover, soil degradation and desertification.

Shifting cultivation includes small-scale agriculture by pastoralists as well as more sedentary agricultural communities. Land is prepared by clearing and burning, usually with minimal hand tillage, and small grains (e.g. millet, sorghum) and drought-tolerant or quick-maturing field legumes (e.g. pigeon pea, cowpea, groundnuts) are cultivated, typically as intercrops for 1–3 years. Fallows are often slow to reestablish and may result in shrubby, delayed succession.

Continuous cropping is practised where land availability no longer permits fallow cycles. Land is tilled by hand or with livestock, water harvesting is often an important feature of land preparation and crop selection is similar to that for shifting cultivation. In some cases, a higher population density may allow for greater market opportunities (e.g. production of cotton, sisal). Feeding of crop residues to livestock results in reduced C additions to soils. Also, these areas often suffer from lack of fuelwood and therefore livestock manures, crop residues and even crop roots may be recovered and burned.

Soil C values in semi-arid tropical systems are inherently low, a 'global average' value for the A horizon (0–20 cm) in native savanna is about 15 g/kg which translates to around 25 Mg C/ha (Tiessen *et al.*, 1998). Fires are frequent such that much of the biomass and litter carbon inventory is lost to the atmosphere several times per decade. Agricultural systems are extensive in nature, have low productivity, and a low capacity for utilizing fertilizer or other production inputs.

For example, in northeastern Brazil the predominant crop production systems are shifting cultivation with five years of arable use followed by 20 or more years of bush fallow (Tiessen *et al.*, 1998). Soil C levels in the native 'caatinga' savanna are around 8 g/kg or 15 Mg C/ha. Losses of soil C following clearing are rapid, 30–50% within the first six years of cultivation (Tiessen & Santos, 1989; Tiessen *et al.*, 1992). However, C levels on cultivated land rarely drop below 50% (in the absence of erosion or irreversible degradation), because declining fertility causes the land to be abandoned to bush fallow.

In semi-arid West Africa about 3 million km^2 are used for arable agriculture and animal husbandry. Cultivation is based on millet–groundnut cropping with extensive livestock use on degraded bush savanna. The agricultural area is cultivated continuously, with a portion (10–30%) receiving animal manure additions (Tiessen *et al.*, 1998). Soil C varies between land use systems, with values of 2.5–6.0 g/kg for grazed savannas (with the lower C contents found on degraded sites) and 1.5–4.5 g/kg on cropped areas without manure. Cultivated areas receiving animal manure have up to 40% greater soil C in some locations. On most cultivated

land, straw is collected or burned, resulting in minimal C returns to soil. Improved production through better manure management, extended bush fallows and fertilizer additions could raise soil C levels from 2.5 to 4 g/kg, which would add up to 1 Pg C over the 2 million km^2 of presently unfertilized cropland in the region (Tiessen *et al.*, 1998). However, such measures are currently beyond the economic and social capabilities of the region.

Overall, there appears to be limited opportunity for managing semi-arid tropical soils as C sinks. The soils have inherently low C stocks and a limited capacity to increase these through improved management. Water is the fundamental factor which restricts productivity and C inputs to soil. Low productivity also constrains the economics for marginal improvements through increased fertilization. Despite these limitations, the maintenance and improvement of soil C are important goals and to that end improved grazing management to reduce degradation/desertification and improved fertility management on arable land must be pursued.

Sub-humid Tropics The sub-humid tropics include large areas of Africa, the majority of the Indian subcontinent and continental SE Asia, and parts of Latin America and Australia. Tropical sub-humid environments are characterized by annual precipitation in the range of *c.* 1000–2000 mm with extended dry seasons. Native vegetation is tropical deciduous, or tropical dry forests, the canopy becoming more completely deciduous and more open as the length of the dry season increases. Fires are common in drier habitats.

Agricultural production systems overlap between the semi-arid to sub-humid zones with an increasing importance of high input, mechanized agriculture in the more humid areas on suitable soils. Grazing remains an important land use. In less favourable environments, extensive livestock grazing is practised, often in combination with crop production on adjacent areas in subsistence agriculture, where manure from grazing livestock is utilized. At the higher end of the rainfall range, pastures may be improved through species selection, weed control and fertilization, thus reaching higher productivity. Shifting cultivation and fallow rotation systems are also practised, especially in SE Asia and India. In some cases, lands have been degraded due to shortening fallow intervals, and derived savannas have replaced the natural succession to deciduous forest. Mixed continuous cropping, with little or no mechanization, is the most prevalent land use in sub-humid regions of Africa and has replaced large areas of land previously used for shifting agriculture over the past 50 years. These farming systems occupy some of the most densely populated agricultural landscapes in the tropics, consisting of mixtures of annual field crops (maize, beans) and perennials (banana, coffee, sugarcane). Crop residues are an important component of yield as feed to confined livestock but manure and composting strategies are often very advanced. Continuous mechanized cropping became a major land use in Asia with the advent of the Green Revolution, with the introduction of improved varieties, fertilizers and pesticides. Parts of Latin America have more recently converted large areas of land in this zone to high-input continuous cultivation of soyabean, rice, and maize. Other important production systems include plantations (e.g. coffee, tea and pineapple) and irrigated cropping, including paddy rice.

The principal soils of the tropical sub-humid zone are Alfisols, Ultisols, Oxisols, and Psamments. Under native vegetation, the surface horizon of these soils typically contains 20–30 g SOC/kg (Moormann *et al.*, 1975; Sanchez *et al.*, 1982). Continuous cropping with plough-based methods of seedbed preparation causes a rapid decline in SOC content to as low as 5–10 g/kg for the plough layer within 5 to 10 years of cultivation (Lal, 1989; Feller *et al.*, 1996). The decline in SOC content also occurs with shifting cultivation and bush fallow rotation, but recovery of soil C can be rapid during the fallow phase (Nye & Greenland, 1960). Cultivation leads to a decline in soil structure, from crumbly or polyhedral under native vegetation to single-grain, massive, or platy structure within 1 to 3 years of cultivation. This change in soil structure is often accompanied by the formation of surface crusts and soil compaction (Casenave & Valentin, 1989; Feller *et al.*, 1996).

In the sub-humid tropics, decomposition can be very rapid due to extended periods with high soil temperature and moisture. Hence, an important factor for carbon sequestration in these soils is the formation and maintenance of soil aggregation (Monnier, 1965), which is enhanced by root and soil fauna activities (Dalal & Bridge, 1996). Aggregates are stabilized in organomineral complexes involving stabilized (persistent) organic matter, clay colloids, hydrous oxides of Fe and Al, and polyvalent metal cations. Low-activity clay soils predominate in the sub-humid tropics and SOC contents are correlated with the amount of soil in clay and silt-sized (0–20 μm) fractions (Feller, 1993). Soil biota, especially earthworms and termites, play an important role in aggregation and aggregate stabilization (Lavelle *et al.*, 1992; Brussaard
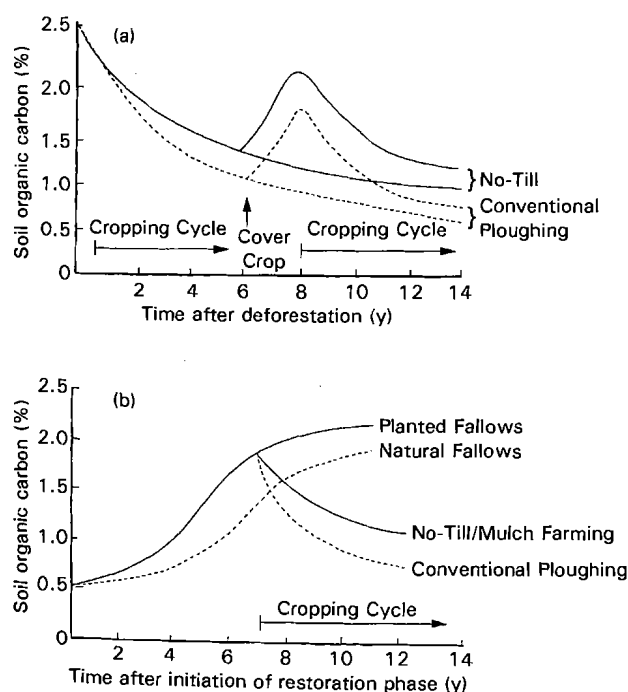

Fig. 3. Conceptualized pattern of (a) soil C losses following forest clearance and cultivation and (b) C accumulation during the vegetated fallow phase, followed by subsequent re-cropping. Different management practices implemented before (i.e. cover crops, planted fallows) and during (i.e. no-till vs. ploughing) the cropping cycle affect the trajectory and levels of SOC.

et al., 1993). Cultural practices that promote high C inputs to soil and enhance root and faunal activity include mulch farming, conservation tillage, agroforestry, cover crops, and manures.

Increasing population pressures have led to shortened fallow cycles in traditional shifting cultivation systems. A conceptual view of soil C changes over time, as affected by different management practices, is given in Figure 3. Typically, deforestation of a secondary forest of 15 to 20 years regrowth leads to a rapid decline in SOC content in surface horizons after cultivation to annual crops. However, the rate of decline of SOC is usually significantly lower with the use of no-till, mulch farming and/or agroforestry practices than with plough-based systems and continuous annual crop monocultures (Fig. 3a). Establishment of short-term cover crops can lead to improvements in SOC content and extend the length of the annual cropping phase (Fig. 3a). A longer term (5–10 year) restoration by establishing planted fallows and cover crops can improve SOC content more rapidly than with natural fallowing (Fig. 3b). Once the SOC content is sufficiently restored, the cultivation phase can be restarted and subsequent C losses are reduced with conservation tillage, mulch farming or agroforestry systems (Fig. 3b).

Conservation tillage is a viable practice for soils of the humid and sub-humid tropics (Ike, 1986; Lal, 1989). Experiments in the sub-humid and humid tropics have demonstrated the potential for no-till systems to maintain higher soil C levels compared to conventional cultivation (Aina, 1979; Juo & Lal, 1979; Agboola, 1981). Reduced soil erosion and lower soil temperatures with surface mulches are particularly important attributes of no-till systems in the tropics (Lal, 1986; Fernandes *et al.*, 1997). Agboola (1981) reported organic matter losses of < 10% with no-till compared with 19–33% losses in tilled treatments, after four years of continuous maize. Juo & Lal (1979) reported nearly doubled C contents in no-till vs. ploughed treatments in the top 10 cm (and no significant differences below 10 cm) under maize. They attributed much of the difference to reduced erosion under no-till. No-till may also contribute to a more effective use of increased C inputs (e.g. from crop residues or mulches) in maintaining soil C levels. Under no-till, Juo & Kang (1989) reported that SOC levels were up to two times higher where residues were added compared to where residues were removed (Fig. 4a). In ploughing experiments, Kang (1993) showed less of an effect of residue retention in both fertilized (Fig. 4b) and non-fertilized (not shown) continuous maize.

The use of improved (planted) fallows and cover crops within cropping sequences and woody species in agroforestry systems shows promise for increasing soil C. Alley cropping systems have been shown to be effective on Alfisols and Psamments in sub-humid and humid regions of tropical Africa. Where applicable, these practices maintain higher levels of SOC and nutrients than under conventional cropping (Kang *et al.*, 1981, 1991). Natural fallows with shifting cultivation and related bush fallow systems restore SOC, soil structure and soil fertility (Nye & Greenland, 1960). However, natural fallowing is slow and cannot be practised in regions with land shortage. Growing cover crops and planted fallows can be more efficient in increasing SOC content, improving aggregation and soil fertility (Monnier, 1965; Lal *et al.*, 1979; Wilson *et al.*, 1982). In experiments with planted fallows, comparing three different species of grass and five species of
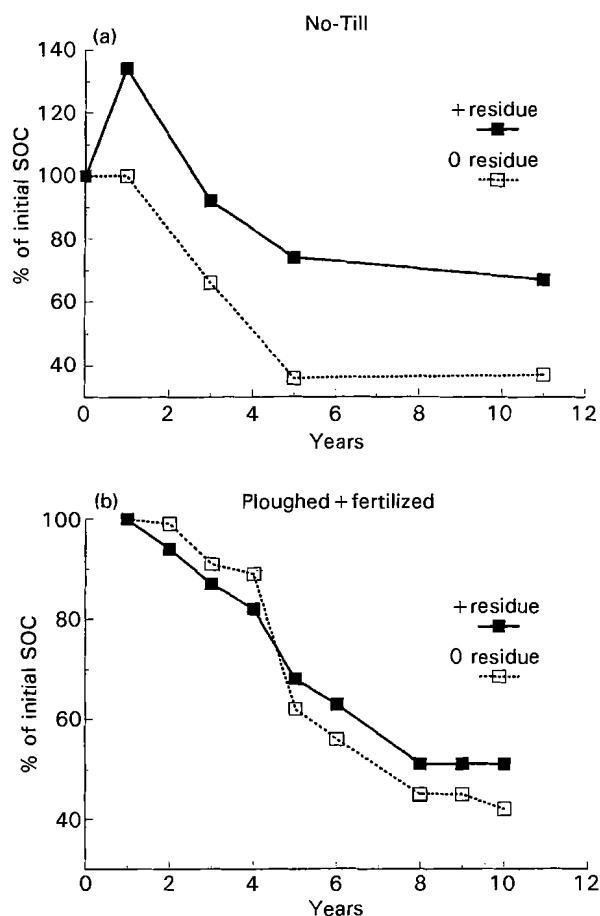
Fig. 4. Effects of residue retention on soil C changes following bush clearance and cultivation to continuous maize, for two field experiments in the sub-humid tropics of Nigeria: (a) with no-till in an Alfisol soil (from Juo & Kang, 1989) and (b) with ploughing in an Entisol soil (from Kang, 1993).

legumes, SOC (0–10 cm) increased by 18–30% (average 25%) after two years, on an eroded Alfisol in Nigeria (Lal *et al.*, 1979). With good management, cover crops can also be grazed and still increase SOC (Mbakaya *et al.*, 1988).

The need for improved cropping systems, with high biomass production and continuous groundcover to control erosion and to promote C sequestration cannot be over-emphasized (Okigbo, 1990). Cropping systems that produce large biomass, provide quick ground cover and have appropriate crop combinations that conserve soil and water resources, can better maintain productivity and SOC levels over time. Improved fertility management is a key component in intensifying cropping systems. Nutrient depletion is a major form of soil degradation on soils managed by resource-poor farmers that cannot or do not use chemical fertilizers (Stoorvogel *et al.*, 1993). Use of chemical fertilizers can enhance soil fertility (Juo & Kang, 1989; Vlek, 1990), increase biomass production, and increase soil C levels.

To summarize, many agricultural soils of the sub-humid tropics are highly weathered, with low C and fertility status. Their low fertility is further compounded by poor soil physical properties leading to crusting, compaction, and accelerated soil erosion. However, there is potential for C sequestration in these soils. The best strategies are to improve soil physical conditions by conservation tillage, mulch farm-

ing, improved fallows, cover crops and agroforestry. Soil fertility and C inputs to soil will also be enhanced by the use of chemical fertilizers and manures.

Humid Tropics   The humid tropics cover substantial parts of S. America (the Amazon basin), Equatorial Africa and SE Asia. Annual precipitation exceeds 2000 mm and there is no significant dry season. Tropical evergreen forest is the natural climax vegetation while non-climax natural vegetation often occurs in mosaics with 'shifting cultivation'. Crop production is generally limited by low soil fertility and soil acidity on heavily leached soils and/or by rapid invasion of weeds. Exceptions are the fertile soils of recent volcanic origin and the rice paddies, which benefit from sediments eroded from the uplands. The major types of agricultural production systems in the humid tropics are briefly described below.

Shifting cultivation and fallow rotation systems include a broad group of land use systems based on a few years of crop production with declining soil organic matter contents and a recovery fallow period of a few years (i.e. bush fallow) or for longer periods (i.e. classical shifting cultivation, based on secondary forest succession). In SE Asia this system can be an early stage of 'agroforest' development, but can also lead to the invasion of grassy weeds such as *Imperata*. Agroforests and other mixed perennial (multi-strata) systems are among the most sustainable types of system for the humid tropics (e.g. Gouyon *et al.*, 1993). Many of their ecological functions, such as soil C storage, are close to those of natural secondary forests of similar age. Monoculture plantations of perennial crops including industrial trees, rubber, oil palm, coconut, sugarcane and pineapple are another major land use. On suitable soils, notably on upland Andosols and rice paddies, intensive food crop production systems exist. If crop residues are returned and supplemented with nutrient inputs, these systems maintain adequate soil organic matter and production levels.

Large scale conversions of forest to pasture land, such as in the Amazon region, are a comparatively recent land use change. The degree to which improved pasture management techniques are practised (i.e. use of introduced grasses, a sufficient legume component, adequate soil fertility maintenance) has a major impact on their sustainability and on soil C levels. In many instances, poor management has resulted in overgrazing and nutrient deficiencies, leading to land degradation with weed invasions, increased soil erosion and soil C losses (Eden *et al.*, 1991; Feller 1993; Woomer *et al.*, 1994). In contrast, well-managed pastures may be able to maintain or even increase soil C levels compared with native forest (Cerri *et al.*, 1991; Lugo *et al.*, 1986). In comparing more than 25 sets of paired pasture and mature forest sites, Lugo & Brown (1993) found that soil C stocks under pasture varied from 60 to 140% of those under forests and that on average, soil C under pasture was not significantly different than under mature forest. In detailed studies of a number of sites in Rondonia, western Amazonia, Neill *et al.* (1997) found similar or higher C levels under pasture compared to the native forest from which they were derived. With good pasture management, they calculated a potential increase in soil C storage of 10–23 t/ha compared to forest. However, this amount is less than 10% of the 140–180 t C/ha lost from forest biomass with conversion to pasture (Neill *et al.* 1997).

In Colombia, Fisher *et al.* (1994) reported very large below-ground C increases of 25–70 t/ha within 5–10 y after establishing pastures of deep-rooting African grasses. While further research is needed to substantiate these very large values, it seems clear that the C sequestration potential in moist tropical pastures can be significant under favourable conditions and that sound management practices are essential to realize this potential for reducing C losses from land use conversions.

Many of the other practices described for sub-humid regions (e.g. improved fallows, cover crops, conservation tillage, agroforestry) can promote C sequestration in the humid tropics. In the sub-humid zone, most of the suitable land is already in agriculture whereas much of the humid tropics remains under forest vegetation. However, current rates of deforestation are high (Houghton 1994; Skole *et al.*, 1994) with large CO_2 emissions associated with the loss of biomass and soil C (Dixon *et al.*, 1994). Thus, the single most significant mitigation option related to agriculture in the tropics is to reduce the pressure for converting new (forested) land to agriculture. While factors other than food demand, such as political and social pressures, are among the causes of deforestation (Fearnside, 1993), breaking the cycle of deforestation and land degradation requires that the productivity and sustainability of existing agricultural lands be improved (Sanchez *et al.*, 1990), together with better protection of native ecosystems.

REGIONAL ESTIMATES OF C SEQUESTRATION POTENTIAL

A number of regional and country-level assessments of the potential for C sequestration in agricultural soils have been made recently. The majority of these are for temperate zone, industrialized agriculture and a variety of methods, including simulation models and empirical data from long-term field experiments, have been employed.

Smith *et al.* (1997a,b, 1998) estimated potential C sequestration for agricultural land in Europe. Using data from long-term European field experiments in the IGBP/GCTE Soil Organic Matter Network (SOMNET; Smith *et al.*, 1996a,b), they developed relationships between various agricultural practices and changes in SOC contents. The practices used in the assessment included adoption of no-till on cultivated land, animal manure and sewage sludge applications, straw incorporation, afforestation of surplus arable land and increased ley-arable crop rotations (Fig. 5).

Calculations were based on a high degree of implementation of the various practices. No-till assumed conversion of all arable agriculture to no-till. Rates of animal manure application were 10 t/ha/y to all arable land. Sewage sludge values were for application of sludge at 1 t/ha/y, sufficient to cover about 11% of arable land in Europe. Straw values were for the incorporation of all cereal straw into the land on which the crops were grown (about 5 t/ha/y) (Smith *et al.* 1997a). Afforestation included natural woodland regeneration on 30% of arable land, which is the upper limit predicted to be surplus to arable requirements by 2010. Allowance is made for the C mitigation potential of the wood produced, assuming 50:50 biofuel:bioproduct utilization (Smith *et al.* 1997b). Alternatively, the predicted 30% surplus of arable land by 2010 could remain in agriculture, allowing a less intensive use of all
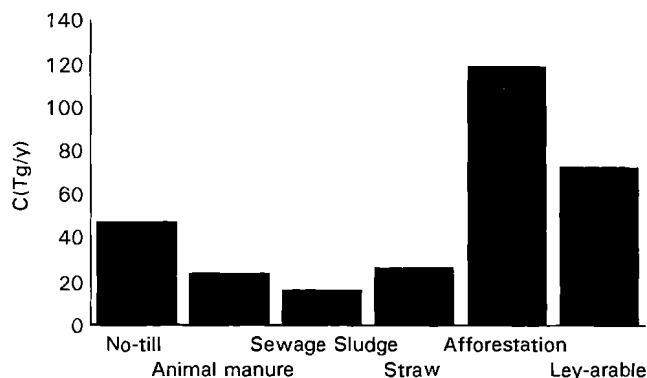

Fig. 5. Potentials for CO_2 emission mitigation for different management/policy scenarios in Europe, excluding most of the former Soviet Union but including Belarus and Ukraine. Values were estimated using SOC contents and relationships between changes in SOC and management practices from European field experiments, as described in Smith *et al.* (1997a, 1998). See text for description of assumptions on management implementation.

land. The values for ley-arable (or mixed cropping) are for extensification of arable agriculture (leaving current grassland at the present level), including less intensive animal production by raising pigs and poultry in outdoor units.

The estimated potential CO_2 mitigation was of the order of 165–210 Tg C/y, depending on the proportional use of surplus arable land for ley/pasture increases versus afforestation. This is equivalent to about 15–20% of the annual CO_2 emissions from fossil fuels in the region. The values for these scenarios are of nearly the same magnitude as the global C sequestration estimate (200–400 Tg/y) of Cole *et al.* (1996). However, as much as half of the mitigation potential estimated by Smith *et al.* is not related to C sequestration in the soil, i.e. forest biomass C sequestration, fossil C offsets from biofuels produced on afforested land and reduced fuel consumption from no-till, are included in the overall estimate. Also the estimates by Smith *et al.* represent a maximum upper limit to potential mitigation, in that full implementation of all the practices was assumed.

Dumanski *et al.* (1998) calculated C sequestration for Canadian agriculture, through adoption of practices to reduce summer fallow, increased use of forage crops, increased adoption of minimum and no-till and more intensive use of fertilizers. In preparing their estimates, they based the rate of adoption of these practices on historic trends — thus the values represent more of a conservative forecast than an estimate of the potential. They used geographically-referenced land use and soils data, together with results from long-term experiments and Century model (Parton *et al.*, 1987; Metherell *et al.*, 1993) simulations. They estimated C sequestration rates of around 2 Tg C/y, over a 50-year period, from reduction of summer fallow through the use of more continuous rotations, including more hay production. This would require about a 50% decrease in the current area of summer fallow land. An additional saving of about 0.8 Tg C/y was calculated from reduced fuel consumption with greater adoption of no-till and minimum till practices. Changes in soil C stocks associated with adoption of reduced tillage were not included in the calculations.

Donigian *et al.* (1994) assessed potential changes in soil C stocks for the main agricultural area in the Central USA. They divided the area (90 Mha) into 80 subregions (based on

climate and land use) and within each subregion several man-
agement systems, soil types and policy alternatives were
defined. The Century model was used to simulate past
changes in soil C and current soil C stocks for each combina-
tion of climate, soil and management conditions. Future
changes in soil C over a 40-year period (1990–2030) were
then simulated for a variety of management options. Their
analysis projected that soil C levels under the present mix of
management were increasing by 25–50 Tg/y, mainly driven by
an annual increase in crop production of 0.5–1.5% per year
(based on historic trends). A key assumption was that C
inputs to soil were increasing in direct proportion to total
productivity. Relative to the baseline scenario (i.e. present
management), increased adoption of reduced till and no-till
practices (on up to 53% of cultivated area) would increase C
storage by an additional 5–6 Tg C/y for the study area.
Increased use of cover crops, where appropriate (on 12% of
land in the region), was predicted to yield an additional 4–5
Tg C/y over the period.

In a somewhat similar study, Lee et al. (1993, 1998) esti-
mated the potential sequestration of C in US croplands,
using the EPIC model (Sharpley & Williams, 1990). His analy-
sis suggested that surface layers (0–15 cm) of agricultural
soils are currently a net C sink of 2–5 Tg C/y, but that greater
soil depths are a net source of CO_2. Maintaining current
trends of increased use of conservation tillage and increased
yields could sequester an additional 30–50 Tg C/y. Conversion
of 400 000 ha of agricultural land to forestry, maintaining
land in the Conservation Reserve Program and reverting
200 000 ha of cultivated bottomland to natural wetland areas
could sequester an additional 13, 12 and 4 Tg C/y, respectively.

Kolchugina & Vinson (1996) calculated current C inven-
tories and fluxes for agriculture in the former Soviet Union
(FSU). They estimated that on the present 232 Mha of agri-
cultural land in the FSU there is a net emission of 76 Tg C/y
as CO_2. They also estimated the potential for C sequestration
with the adoption of several mitigation strategies, including
conversion to no-till, agroforestry for shelterbelts and tree
plantations, and changes in crop rotations to include more
perennial forages. A total of 181 Mha were judged suitable
for conversion to no-till, for which a total C sequestration
potential of 3.3 Pg C was estimated (Gaston et al., 1993; Kol-
chugina & Vinson, 1996). This equates to an average SOC
increase of about 1800 g C/m^2, which is considerably higher
than the average difference of c. 300 g C/m^2 between no-till
and ploughed treatments discussed earlier (Fig. 2). The
higher rates used by Gaston et al. were based on % increases
under no-till, as estimated by Kern & Johnson (1993) from
mainly N. American experiments, which were applied to Rus-
sian soils with much higher SOC levels (up to 250 t C/ha).
Thus, these rates of increase remain somewhat speculative
until more results are obtained from no-till experiments in
soils with high SOC levels. However, given the large area for
which no-till practices could potentially be applied, lower
rates of C gain (e.g. 300 g C/m^2) would still imply a large C
sequestration potential of 500–600 Tg. The establishment of
71 Mha of shelterbelts and other forest plantations was esti-
mated to have a potential to sequester 5 Pg C in soil and an
additional 4.7 Pg C in biomass and forest litter, over a 40 year
period (Kolchugina & Vinson, 1996). The rate of soil C accu-
mulation following establishment of forest on arable land was
calculated assuming an increase of 35% in the average soil C

contents (200 t/ha), based on several field observations. How-
ever, much of the C accumulation (60–95%) in these reports
was attributed to 'abiotic accumulations', presumably deposi-
tion of eroded material. Thus, the interpretation of these
increases as C sequestration (as defined in the present paper)
depends on a difficult assessment about how the CO_2 emis-
sions from this eroded soil would differ with or without the
forest plantations. The optimal strategy for C sequestration
through altered crop rotations was 26 Tg C/y, achieved by
increasing the amount of perennial grass production (relative
to grain) in fodder crop rotations, occupying 73 Mha (c. 30%
of the total agricultural area).

For sub-tropical and tropical agricultural areas of China,
Li & Zhao (1998) estimated the scope for C sequestration
through improved agricultural management and wasteland
reclamation. Of the 218 Mha in the region, about 41 Mha is
cultivated and 42 Mha is classified as wasteland, of which
only 7 Mha is considered suitable for reclamation to cropland
and pasture uses. They calculated that achievable production
increases from higher crop yields and decreased bare-fallow
frequency could raise C inputs to soil, resulting in soil C
sequestration rates of around 1 Tg/y. Soil C increases follow-
ing reclamation of wasteland to agriculture was calculated to
sequester an additional 1.2 Tg/y, at the current reclamation
rate of 95 000 ha/y.

CONCLUSION

There is good evidence that many if not most agricultural
soils have the capacity to sequester C under proper manage-
ment. Information from long-term field experiments and
simulation modelling shows that the key strategies are to
increase the time under which the soil is vegetated, reduce
or eliminate soil tillage, boost primary production and the
return of organic matter to soil and increase the use of peren-
nial grasses and legumes, as forage crops, cover crops, and
green manures. At the present time, temperate industrialized
countries have the greatest capability to pursue C sequestra-
tion strategies based on their technology and infrastructure,
including well-developed extension and farm programmes
and their associated administrative capacities. However, the
greatest need, and perhaps the greatest long-term potential,
for C sequestration is in the tropics.

How significant is soil C sequestration in the overall pic-
ture of mitigating CO_2 increases in the atmosphere? The
IPCC estimates for the global mitigation potential of C
sequestration in agricultural soils are 0.4–0.6 Pg/y over 100
years, which is less than 10% of the current annual C emis-
sions from fossil fuels. Moreover, the capacity of soils to
store additional C is finite so that mitigation benefits will be
realized over a limited time span, of the order of 50–100
years, until a new and higher SOC equilibrium level is
reached. From this perspective, soil C sequestration can
make only modest contributions to the overall need for miti-
gation of atmospheric CO_2 build-up.

However, it is increasingly clear that no single action is
likely to mitigate atmospheric CO_2 increases in the short-
term. Effective policies should include many modest reduc-
tions (e.g. the US Climate Action Plan contains over 40 indivi-
dual measures to reduce greenhouse gas emissions; DOE,
1994) which are economically efficient and which confer
additional benefits (i.e. so-called 'no regrets' policies). A
major advantage in pursuing strategies to increase soil C is

that the increase in soil organic matter will also benefit agricultural productivity and sustainability. Practices that increase SOC are being increasingly implemented for these reasons, quite apart from issues relating to climate change. However, various economic and social factors such as initial capital investment needs, government subsidies for certain crops, insufficient extension information, resistance to change traditional practices, etc. may slow the rate and extent of adopting C sequestering practices. Thus, adopting policies to encourage C sequestration, e.g. through tax benefits, subsidies, joint implementation projects, improved extension and information dissemination, could help to overcome the barriers to adopting new practices. Given the small net income margins that many farmers face, even in developed countries, and 'value-added' benefits of SOC, it may well be that C sequestration strategies are among the cheapest mitigation options available. To assess this better, economic analyses of the kind that have been done to evaluate forest C sequestration options (e.g. Richards, 1992; Nilsson & Schopfhauser, 1995) and further ecological research, particularly in the tropics, is needed.

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