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Crop Management for Soil Carbon Sequestration

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ABSTRACT: Reducing emissions of greenhouse gases (GHG) from agriculture is related to increasing and protecting soil organic matter (SOM) concentration. Agricultural soils can be a significant sink for atmospheric carbon (C) through increase of the SOM concentration. The natural ecosystems such as forests or prairies, where C gains are in equilibrium with losses, lose a large fraction of the antecedent C pool upon conversion to agricultural ecosystems. Adoption of recommended management practices (RMPs) can enhance the soil organic carbon (SOC) pool to fill the large C sink capacity on the world's agricultural soils. This article collates, reviews, and synthesizes the available information on SOC sequestration by RMPs, with specific references to crop rotations and tillage practices, cover crops, ley farming and agroforestry, use of manure and biosolids, N fertilization, and precision farming and irrigation. There is a strong interaction among RMPs with regards to their effect on SOC concentration and soil quality. The new equilibrium SOC level may be achieved over 25 to 50 years. While RMPs are being adapted in developed economies, there is an urgent need to encourage their adoption in developing countries. In addition to enhancing SOC concentration, adoption of RMPs also increases agronomic yield. Thus, key to enhancing soil quality and achieving food security lies in managing agricultural ecosystems using ecological principles which lead to enhancement of SOC pool and sustainable management of soil and water resources.

KEYWORDS: crop rotation, greenhouse effect, global C cycle, ley farming, soil fertility, precision farming.

INTRODUCTION

Enhancing soil organic matter (SOM) concentration is necessary to reduce agricultural emissions of greenhouse gases (GHG). Agricultural soils are a significant sink for carbon (C) through formation of SOM. Conversion of natural to agricultural ecosystems depleted the global soil organic carbon (SOC) pool by 50 to 100 Pg (billion tons) of C, and this trend is continuing by conversion of forests and savannas to agriculture in the tropics (Paustian, 2002; Wairiu and Lal, 2003). The SOC pool in natural ecosystems (e.g., forests or prairies) is in equilibrium, but losses exceed the gains in agricultural systems. The loss of SOC pool upon conversion from natural to agricultural ecosystem may be as much as 1500 g C m^{-2} with rapid rate of depletion in the first several years (Mann, 1986). Annual average rate of depletion of SOC following the change in land use to agriculture is often much greater than the rate of SOC sequestration upon adoption of recommended management practices (RMPs). Therefore, the amount of C sequestered may be much less than the total C lost (Figure 1). Restoration of the SOM pool in agricultural soils occurs through adoption of RMPs (Lal et al., 1998d), which increase C input

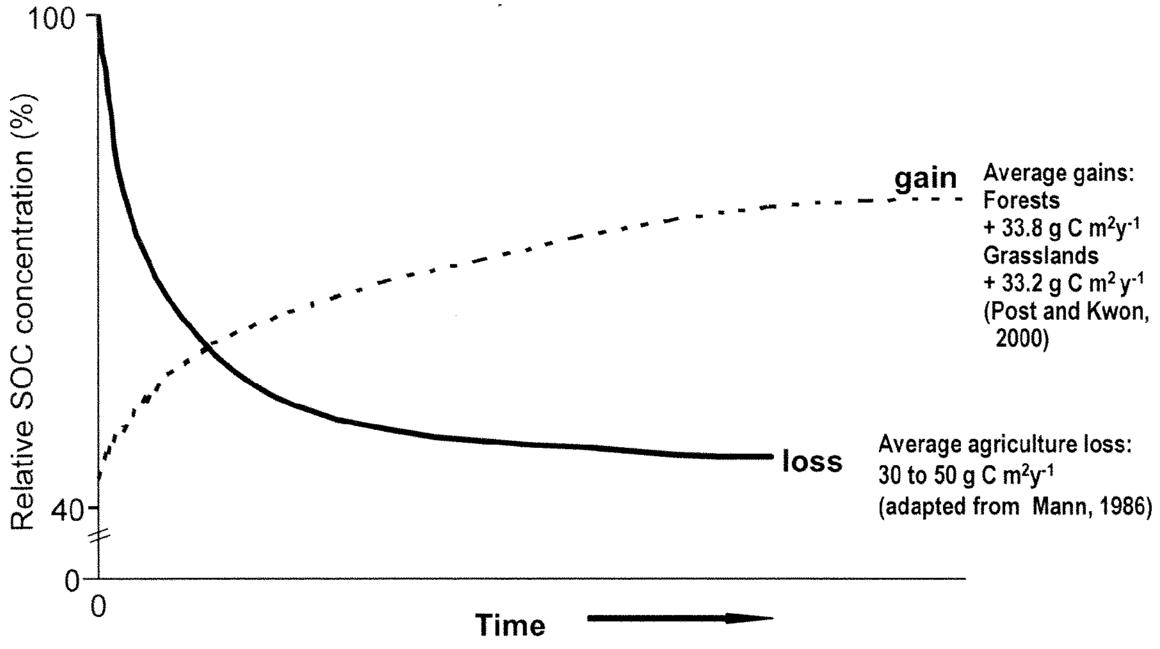

FIGURE 1. Soil carbon losses following cultivation of forests and grasslands to agricultural ecosystems, and potential C sequestration by adoption of RMPs. The time 0 on the x-axis represents the time of conversion to agricultural land use and time of adoption of RMPs.

into the soil and decrease C decomposition, thereby creating a positive C balance and making soil a net sink (Figure 2). Paustian (2000) indicated that SOC sequestration is attributed to those management systems which: (1) minimize soil disturbance and erosion, (2) maximize crop residues retained in soil, and (3) maximize water and nutrient use efficiencies of crop production systems. Changes in SOC level can be strongly affected by choice of appropriate cropping systems which increase crop productivity and enhance residue input levels (Robinson et al., 1996; Ingram and Fernandez, 2001). Adoption of reduced or no-till methods, using organic manures or biosolids, growing cover crops, and using N fertilizer are practices which promote SOC sequestration in agricultural soils (Lal, 2001). Lal et al. (1998d) estimated that in the US adoption of RMPs may lead to sequestration of 75 to 208 MMT (million metric tons) C year^{-1}, of which 50% is due to conservation tillage and residue management, 6% to supplemental irrigation and water table management, and 25% to adoption of improved cropping systems.

The purpose of this article is to collate, review, and synthesize available information on SOC sequestration by adoption of RMPs; describe ecological processes and identify management practices that enhance SOC sequestration; and identify research and development priorities for increasing the potential of RMPs for SOC sequestration.

TILLAGE AND CROP ROTATION

Tillage

Conservation tillage (CT) is “any tillage and planting system that maintains at least 30% of the soil surface covered by residue after planting to reduce water erosion; or where wind erosion is primary concern, maintain at least 1000 kg ha^{-1} of flat, small grain residue equivalent on the surface during the critical wind erosion period” (CTIC, 2002).

The influence of tillage on SOC dynamics is well documented (Doran and Smith, 1987; Paustian et al., 1997; Lal, 2001). The SOC concentration in cultivated soils declines over time with attendant increase in soil bulk density (Cameron et al., 1981). Tillage systems’ effect on soil properties, especially on SOC concentration, vary among soils, water, and temperature regimes and site-specific management. Thus, accessory overview of the literature indicates conflicting and contradictory results. For example, tillage practices invert or disturb soil surface

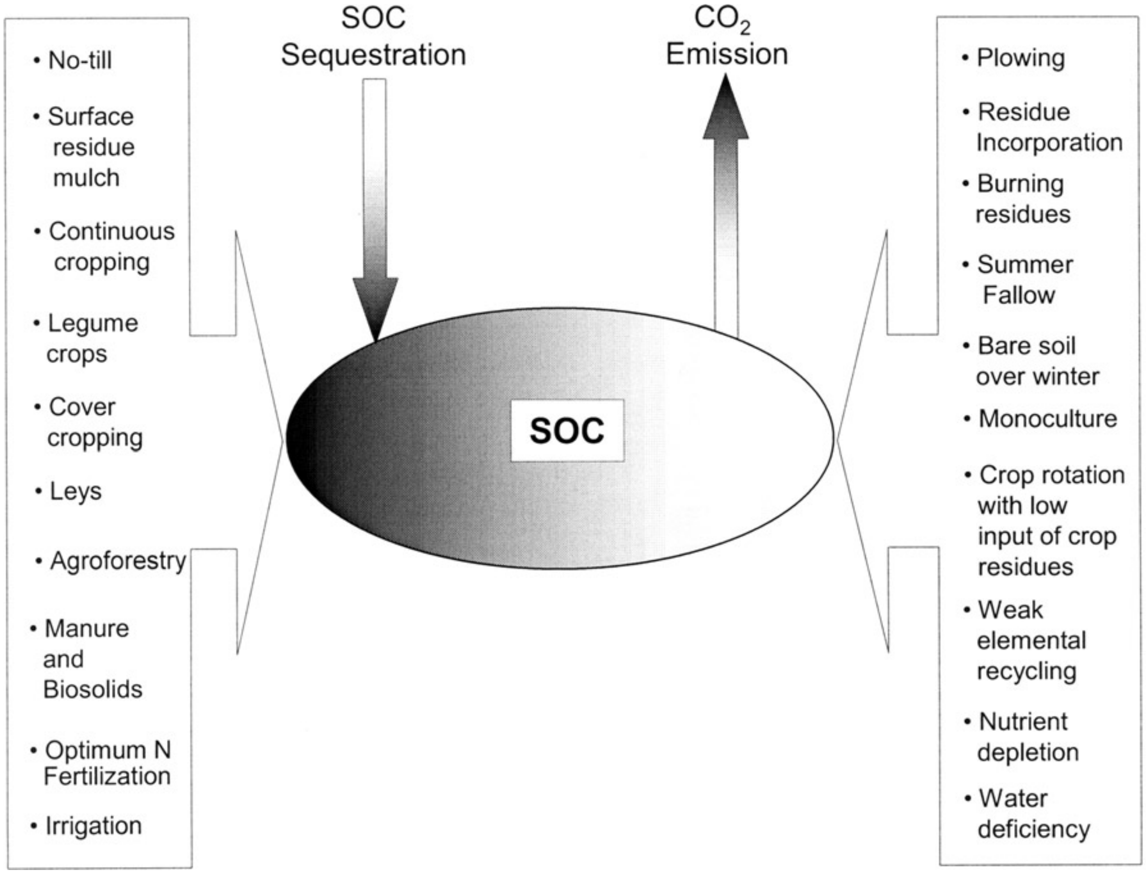

FIGURE 2. Effect of crop management practices on SOC sequestration.

(Campbell and Souster, 1982), reduce SOC concentration (Lal, 1984, 1989a), and destroy aggregates (Tisdall and Oades, 1980; Six et al., 1998). Tillage systems also affect soil biological activity, soil water and temperature regimes, and the accessibility of C and N substrates that influence elemental cycling. Russel et al. (1975) observed that reducing tillage in cultivated soils decreased total pore space and the pore-size distribution. No-till soils had more fine pores and fewer air-filled pores than plow-till soils. Dalal and Mayer (1986), based on long-term trends in soil fertility in the cereal-belt of southern Queensland in Australia, stated that total and light fraction of the SOC pool, and total and mineralizable N fractions, were greatly reduced by cultivation. In contrast, Kitur et al. (1984) and Rice and Smith (1982) reported that there is more N fertilizer immobilization and less mineralization of soil N in no-till than in the plow-till soil.

Ward et al. (1987) concluded that in the first years of introduction of the no-till or reduced-tillage system there are higher requirements of N fertilizer than in conventional tillage practices, especially when the fertilizer is broadcast on the soil surface. Doran and Smith (1987) observed that corn yields with no-till management were significantly lower than those with tillage until supplemental N was added to obtain equal yields. Tillage-induced differences in crop yield generally decrease over time (Doran and Smith, 1987).

Conventional tillage significantly reduces biological diversity in surface soil. Doran and Smith (1987) summarized data from the U.S., Canada, and England and stated that surface level of SOC, microbial biomass, and potentially mineralizable N were all significantly higher in the no-till than in the plow-till method of seedbed preparation.

Conservation practices are recommended to minimize losses of SOC and plant nutrients. Both SOC and plant nutrients are concentrated near the soil surface and therefore are prone to soil erosion (Larson, 1981). The SOC is greatly associated with the finer and more reactive clay and silt fractions. Effectiveness of soil conservation practices can be evaluated on the basis of the amount of SOC concentration associated with eroded sediments. Follett et al. (1987) showed that conservation tillage decreases SOC associated with eroded sediments by about half, and additional decrease is obtained by conversion to no-till.

Soil Organic Carbon Sequestration Rate with No Till

Results from long-term experiments show that conversion from plow-till to no-till practice is the most effective factor in crop management for SOC sequestration (Table 1). The peak rate of SOC increase by converting plow-till to no-till system may occur within 5–10 y with SOC reaching new equilibrium within 15–20 y (West and Post, 2002).

While tillage and cultivation result in a decline in SOC, conservation tillage or no-till practices increase SOC concentration. There are about 1.5 billion ha of cropland in the world (FAO, 2000). Only a small fraction of this land is currently employing conservation tillage. Therefore, conversion of even one-third of cropland to conservation tillage by the year 2020 can drastically improve SOC sequestration (Lal et al., 1998b).

Crop Rotation

Crop rotation refers to a planned sequence of crops grown in a regularly recurring succession on the same area, in contrast to continuous monoculture or growing a variable sequence of crops (SSSA, 1997). Crop rotation affects soil quality and growth and yield of subsequent crops in many ways, including changes in SOC concentration, soil structure and aggregation, nutrients cycling, and incidence of pests. In combination with minimum or no-till management, crop rotations can reduce soil erosion, enhance SOM, and sequester SOC (Lal, 2001). Thus, crop or cropping system selection has a major effect on C inputs to the soil (Ingram and Fernandes, 2001). Crop rotation is more effective in retention of C and N in soil than monoculture (Biederbeck et al., 1984). Elliot et al. (1978) reported that intensive monoculture decreases crop yield with attendant reduction in biomass returned to the soil. Buyanovsky and Wagner (1998a) reported from a long-term experiment in Missouri that monoculture of wheat (*Triticum asetivum* L.) with N fertilization accumulated 50 g C m^2 y^{-1} compared with 150 g C m^2 y^{-1} by corn *(Zea mays* L.)–wheat clover (*Trifolium* spp.) rotation with manuring and N fertilization.

The SOC sequestration depends on quantity of residues returned to the soil through crop rotation. Havlin et al. (1990) assessed SOC dynamics in: (1) continuous sorghum (*Sorghum bicolor* L.), continuous soybean (*Glycine max* L.), and sorghum-soybean rotations combined with tillage and N fertilization; and (2) continuous corn with corn-soybean rotation. The high residue-producing continuous sorghum in the first and continuous corn in the second rotation combined with reduced tillage and surface residue maintenance resulted in more SOC sequestration than grain-legume rotations. Similar results were obtained by Omay et al. (1997), who reported more SOC under continuous corn than under corn-soybean rotation. Drury et al. (1998) also compared continuous corn with continuous Kentucky bluegrass (*Poa pratensis* L.) and 4-year corn-oat (*Avena sativa* L.)–alfalfa-alfalfa (*Medicago sativa* L.) rotation. The SOC level was in the order bluegrass >4-year rotation > continuous corn.

The intensification of cropping system from spring wheat monoculture to annual cropping rotation spring wheat–winter wheat–sunflower (*Helianthus annus* L.) and introducing no-till management had a positive impact on reducing SOC loss from croplands in the northen Great Plains (Halvorson et al., 2002). In a long-term study, Collins et al. (1992) reported that the highest retention of SOC was obtained in grass pasture system, and wheat-fallow system reduced SOC and soil microbial biomass significantly.

Rotation effects on SOC sequestration are altered by tillage, antecedent SOC pool, and soil properties. For a 31-year rotation experiment in Canada on an Orthic Black Chernozem with a thick A horizon, Campbell et al. (1991) observed that fertilization or the inclusion of legume green manure or legume hay crops did not increase the SOC pool. Campbell and colleagues observed that the lack of response in increasing SOC was due to very high antecedent SOC concentration. In another report, Campbell et al. (1996) concluded that SOC sequestration is possible when crop rotation increases agronomic production. Elimination of fallow and enhancement of cropping intensity increased SOC sequestration under wheat and sorghum monoculture in Texas (Potter et al., 1997). Changing monoculture to multicrop rotation has had positive influence on SOC concentration. In semiarid regions of Spain, Lopez-Fando and Pardo (2001) compared SOC concentration in barley (*Hordeum vulgare* L.)–vetch (*Vicia sativa* L.), barley–sunflower, and barley monoculture systems and observed the lowest SOC concentration in barley monoculture. Similar results were reported by Havlin et al. (1990) and Robinson et al. (1996). Lal et al. (1998c) opined that

TABLE 1
Increase in Soil Carbon Pool by Conversion from Plow-Till to No-Till System

Location	Till to No-Till Conversion	Increase in SOC Sequestration ($kg\ ha^{-1}\ y^{-1}$)	Depth (cm)	Duration (Years)	Reference[1]
Brazil (south)	Various rotations	611	30	9	Bayer et al. (2000)
Canada	Avarage for groups: Gleysolic, Brown, Dark Brown, and Black (Century Model prediction)	200	—	10	Desjardins et al. (2001)
Europe	Assessment based on long-term experiments:				
	Europe	387[2]	25	—	Smith et al. (2000a, 2000b)
	United Kingdom	613[2]	25	—	
Spain	Various rotations on calcic luvisol	100	30	11	Lopez-Fando and Pardo (2001)
USA	Various crop rotations on:				
(1) Kansas	Grundy silty clay loam	20	30	15	Havlin et al. (1990)
	Muir silt loam	62	30	15	
(2) Nebraska	Spring wheat-fallow spring	−225	30.4	12	Halvorson et al. (2002)
	wheat-winter wheat-sunflower on silt loam	542	30.4	12	
(3) Ohio	Various rotations on clay loam	566	30	30	Dick et al. (1998)
(4) Oregon	Various crops on coarse-silty mixed mesic	94	22.5	44	Rasmussen and Rhode (1988)
(5) Oregon	Winter wheat-lentil (*Lens culinaris* Medik.)	587	20	3	Bezdicek et al. (2002)
	Winter wheat-barley with no-till management	166	20	25	
(6) Texas	Continuous corn (4y) followed continuous cotton (4y) on sandy clay loam	15–20	20	26	Salinas-Garcia et al. (1997b)
(7) Miscellaneous regions	39 paired tillage experiments	220	Various depths	5–20	Paustian et al. (1997)
World	Till to no-till 276 paired treatments excluding wheat-fallow treatments	570 ± 140	Various depths	Various time	West and Post (2002)

[1] Data obtained after recalculation from some references; bulk density, if needed, recalculated according to Post and Kwon (2000).

[2] Together with fossil fuel savings.

increasing dryland cropping intensity and N fertilization in semiarid areas is one of the ways to offset agricultural emissions and mitigate global climate change.

Using the global database containing 67 long-term agricultural experiments, West and Post (2002) estimated the potential of SOC sequestration for different crop rotations and tillage management, and assessed the duration over which SOC sequestration may occur (Table 2). The rate of SOC sequestration under changing crop rotation is relatively low since the data were recalculated from no-till treatments. They concluded that SOC enhancement due to introduction of more complex crop rotation may reach new equilibrium in approximately 40–60 years.

CROP RESIDUES AS A SOURCE OF SOIL ORGANIC CARBON

Crop residues include stems, leaves, roots, chaff, and other plant parts that remain after crops are harvested or grazed (Follett et al., 1987). Globally, 84% of residues are produced by seven major crops: wheat, rice (*Oryza sativa* L.), corn, sugar cane (*Saccharum officinarum* L.), barley, cassava (*Manihot esculenta* L. Crantz), and soybeans (Lal, 1997). The amount of crop residues is related to grain yield and is estimated by grain (or crop)-to-residue ratio or the Harvest Index (HI). Thus, a high crop yield also produces a high amount of residue. Crop residues are the main source of C in agricultural soils, and on average contain 45% of C on the dry weight basis (Lal, 1997). The amount of crop residues returned to the soil depends on the crops (Table 3), the cropping system, the soil, and crop management (Lal, 1997).

Crop residues are precursors of the SOM pool. Decomposition of plant material to simple C compounds and assimilation and repeating cycling of C through the microbial biomass with formation of new cells are the primary stages in the humus formation process (Collins et al., 1997). The rate of decomposition depends on residues' lignin: N ratio. Therefore, soybean residues decompose faster than corn and wheat residues (Wagner and Broder, 1993). Returning more crop residues is associated with an increase in SOC concentration (Larson et al., 1978; Rasmussen and Parton, 1994), and effect of rotation on SOC concentration also depends on the quantity of residues returned. Larson et al. (1972, 1978) found that different types of crop residues (e.g., wheat, corn, and alfalfa) applied in equal amounts show similar ability to maintain the SOM pool.

Proper crop residue management can reduce runoff and soil erosion, enhance water retention, and decrease summer soil temperatures (Reicosky, 1994). Residue placement impacts soil water and aeration, soil temperature, and relative predominance of certain organisms (Follett et al., 1987). Placement and incorporation are influenced by the management system. Reduced tillage methods, including conservation tillage or no till, return crop residues to the soil surface. Surface residue management prevents wind and water erosion, conserves water, and decreases evaporation. Crop residues placed on the soil surface reflect light and protect soil from high temperatures and evaporative losses of water (Franzluebbers et al., 1995; Sauer et al., 1996), and are beneficial to enhancing soil fertility and SOC concentration (Cole et al., 1987; Doran and Smith, 1987; Follett et al., 1987; Jacinthe et al., 2002). Leaving crop residues on the soil surface in no-till system decreases the rate of SOM decomposition and increases SOC concentration in comparison with tillage management, where residues are incorporated into the soil (Sain and Broadbent, 1977; Blevins et al., 1984).

Crop residues are the source of C for microbes and fauna, which stabilize soil structure and provide physical protection of the soil surface against structure-altering processes like rainfall or vehicular traffic (Angers and Caron, 1998). In undisturbed no-till soils, surface plant residues contribute indirectly to macropore/biopore formation and provide food for the earthworms (Edwards et al., 1989).

IMPACT OF LEGUMES AND OTHER CULTURES ON SUBSEQUENT CROP

Introducing legumes in rotation enhances N pool by symbiotically fixed N. Legumes reduce N fertilizer requirement for any subsequent crop (Table 4). Corn or grain sorghum generally respond by increase in yield (about 10%) when grown after a legume crop (Classen, 1982). A cropping system with leguminous crops and with sufficient N fertilizer also enhances SOC concentration (Varvel, 1994). Supplying residual N by legumes depends on climate, management, and the species grown. Heichel and Barnes (1984) and Voss and Schrader (1984) estimated that yearly fertilizer N equivalent of 10 to 70 kg of N ha^{-1} is made available to cereals grown in rotation with legumes. In legume–nonlegume crop sequences the amount of N returned

TABLE 2
Increase in Soil Carbon Pool by Changing to an Improved Crop Rotation

Location	Crop or Land Use	Increase in SOC Sequestration (kg ha^{-1} y^{-1})	Depth (cm)	Duration (Years)	Reference[1]
Canada	Corn-oat-alfalfa-alfalfa rotation compared				
(1) Ontario	to continuos corn on clay loam:				Gregorich et al. (2001)
	Unfertilized	703	70	35	
	Fertilized	403	70	35	
(2) Miscellaneous regions	Cereal-fallow versus continuous cropping:				Dumanski et al. (1998)
	Cereals in semiarid	200			
	Cereals in subhumid	170			
	Cereals in boreal	520	30	50	
	Hay in semiarid	510			
	Hay in subhumid	760			
	Hay in boreal	480			
(3) Miscellaneous regions	Conversion wheat-wheat-fallow to continuous wheat	164	20	20	Desjardins et al. (2001)
Spain	Rotation versus wheat monoculture:				Lopez-Fando and Pardo (2001)
	Barley vetch	91	30	11	
	Barley sunflower	82			
Syria	Various rotation versus wheat-fallow:				Jenkinson et al. (1999)
(International Center	Wheat-wheat	160			
for Agricultural	Wheat-vetch	220			
Research in Dry Areas)	Wheat-lentil	170	20	10	
	Wheat-chickpea	160			
	Wheat-medic (*Medicago spp.*)	380			
USA	Rotations on loam:				Halvorson et al. (2002)
(1) North Dakota	Spring wheat-winter wheat-sunflower versus				
	Spring wheat-fallow with no-till	642			
	Spring wheat-winter wheat-sunflower versus		30.4	12	
	Spring wheat-fallow with minimum till	283			
	Spring wheat-winter wheat-sunflower versus				
	Spring wheat-fallow with conventional till	−125			

(Continued on next page)

TABLE 2
Increase in Soil Carbon Pool by Changing to an Improved Crop Rotation *(Continued)*

Location	Crop or Land Use	Increase in SOC Sequestration (kg ha^{-1} y^{-1})	Depth (cm)	Duration (Years)	Reference[1]
(2) Ohio	Rotations on clay loam:				Dick et al. (1998)
	Corn-oats-meadow versus continuous corn	66	30	30	
	Corn-soybean versus continuous corn	−433	30	30	
(3) Texas	Increasing crop intensity from wheat to				Franzluebbers et al. (1994)
	Wheat/soybean with no-till management	550	20	9	
World database	Enhancing rotation:				West and Post (2002)
67 long-term agricultural experiments	Monoculture to continuous cropping, crop fallow to continuous cropping, increasing number of crops in rotation with exception of continuous corn to corn-soybean rotation	200 ± 120	Various depth	Various time	

[1] Data obtained after recalculation from some references; bulk density, if needed, recalculated according to Post and Kwon (2000).

TABLE 3
Potential of Soil Carbon Sequestration by Crop Residues

Corp	Yield (t ha^{-1})[1]	Average Harvest Index[2]	Input C with Residues (t ha^{-1})[3]	SOC Sequestration[1] (kg C ha^{-1})[3]
Barley	2.44	1.5	1.65	247
Cassava	10.7	0.7	3.35	503
Corn	4.33	1.0	1.95	292
Cotton	1.68	1.5	1.13	170
Millet (*Panicum miliaceum* L.)	0.70	1.5	0.47	71
Oats	2.05	1.0	0.92	138
Potatoes (*Solanum tuberosum* L.)	16.0	0.25	1.80	270
Rapeseed (canola)	1.42	1.5	0.96	144
Rice	3.96	1.5	2.67	401
Rye	2.17	1.5	1.46	220
Sorghum	1.31	1.5	0.88	133
Soybeans	2.27	1.0	1.02	153
Sugarbeet (*Beta vulgaris* L.)	41.0	0.25	4.61	692
Sugarcane	65.3	0.25	7.35	1102
Wheat	2.69	1.5	1.82	272

[1] Average worldwide yield in 2002 (FAOSTAT, 2003).

[2] Smil (1981), Larson et al. (1982), Stout (1990), and Mahungu et al. (1994).

[3] Mean C content in residues = 45%, and 15% of C contained in the residue can be sequestered as passive SOC (Lal, 1997).

TABLE 4
Contribution of Legume Crops and Legume Cover Crops to Supply N for Subsequent Crop

Location	Legume and Subsequent Crop	N Supply (kg ha^{-1})	Reference
Africa Guinea Savanna	N accumulation in selected fallow legumes for rice:		Becker and Johnson (1998)
	Pigeon pea *(Cajanus cajan* L.)	45	
	Jackbean *(Canavalia ensiformis* L.)	77	
	Sunn hemp *(Crotalaria juncea* L.)	49	
	Nescafe *(Mucuna pruriens* L.)	81	
	Stylo *(Stylosanthes guianensis* Aubl.)	40	
	Bambarra groundnut (*Voandzeia subterrana* L.)	20	
Humid tropics	Depending on species, soil type, and agro-ecoregion	20–200	Lal (1995)
USA Delaware	Corn following legumes (hairy vetch and crimson clover)	112	Mitchell and Teel (1977)
Georgia	N in legume cover crops:		Hargrove (1986)
	Crimson clover	170	
	Subterranean clover (*Trifolium subterraneum* L.)	114	
	Hairy vetch	153	
	Common vetch (*Vicia sativa* L.)	134	
Kentucky	Corn following hairy vetch	90–100	Ebelhar et al. (1984)
Minnesota	Soybean for green manure	90	Heichel and Barnes (1984)
	Alfalfa	192	
	Red clover (*Trifolium pratense* L.)	84	
	Birdsfoot trefoil (*Lotus corniculatus* L.)	58	

to the soil for nonlegume succeeding crop depends on (1) the quantity of legume residue returned to the soil, (2) the content of the symbiotically fixed N in the residues, and (3) the availability of the legume residue N to subsequent crop (Heichel, 1987). The majority of forage legume N returned to cropland in the U.S. is from alfalfa (Power and Papaendick, 1985). Heichel (1987) assessed that alfalfa stand turned at approximate 3-year intervals represents an average of 120 kg N ha^{-1}. The beneficial impact of legumes is not restricted to N supply alone. Legumes also improve soil structure and aeration, and minimize erosion (Heichel and Barnes, 1984).

Angus et al. (2001) summarized the effects of grain legumes and canola (*Brasica napus* ssp. *oleifera* L.) on wheat yield as a subsequent crop in comparison to continuous wheat and found that legumes increased yield of wheat by 40 to 50% and canola by 20%. The increase in yields of wheat after legumes was attributed to residual N, while canola reduced incidence of disease. Experiments conducted in Australia have shown the beneficial impact of strong narrow-leaf lupin (*Lupinus angustifolius* L.) root system in compacted soil on subsequent wheat growth and yield. Lupin acted as a "biological plow" (Henderson, 1989) and loosened the subsoil. Cotton yields doubled when followed after bahiagrass (*Paspalum notatum* Flügge), which increased large pores in compacted soil layers (Elkins et al., 1977). These examples indicate the ability of rotation to avoid or reduce tillage to alleviate soil compaction (Reeves, 1994).

COVER CROP AND GREEN MANURE

A cover crop is defined as a "crop that provides soil protection, seedling protection, and soil improvement between periods of normal crop production, or between trees in orchards and vines in vineyards" (SSSA, 2001). In contrast, green manure is defined as "a plant material incorporated into soil while green or at maturity, for soil improvement." A cover crop may be referred as a green manure when plowed under and incorporated into the soil (SSSA, 2001). Briefly, cover crop enhances soil quality while green manure impacts mainly on soil productivity. Reeves (1994) reported that green manures were widely used next to the winter cover crops in the U.S. during the early part of twentieth century. The summer annuals including cowpea (*Vigna unguiculata* L.), soybean, and velvet bean (*Mucuna deeringiana* (Bort) Merr.) were plowed under at the end of the season to improve the soil. Presently, winter cover crops are mainly grown in temperate and subtropical areas (Reeves, 1994).

Including a cover crop within a rotation cycle is also beneficial to SOC sequestration (Lal and Bruce, 1999) (Table 5), but increase in SOC concentration can be negated when the cover crop is incorporated into the soil (Utomo et al., 1987). Cover crops enhance soil protection, soil fertility, groundwater quality, pest management, SOC concentration, soil structure, and water stable aggregates (Wilson et al., 1982; Lal et al., 1991; Ingles et al., 1994; Hermawan and Bomke, 1997; Kuo et al., 1997a; Sainju et al., 2000; Dabney et al., 2001). The beneficial effects of growing cover crops on aggregation are generally more on heavy-textured than light-textured soils (Ball-Coelho et al., 2000). Cover crops promote SOC sequestration by increasing input of plant residues and providing a vegetal cover during critical periods (Franzluebbers et al., 1994; Bowman et al., 1999; Follett, 2001). A systematical use of cover crops has long-term effects, including protection of soil and environment, and uptake and storage of plant nutrients between seasons when available nutrients are susceptible to leaching (Doran and Smith, 1987).

Accruing multiple benefits of growing cover crops depends on the choice of appropriate species and proper management (Lal et al., 1991). Suitable cover crops for growing in the cold season in northern latitudes are rye (*Secale cereale* L.), clover (*Trifolium* spp.), or vetch (*Coronilla* and *Vicia* spp.). These crops are planted in the fall to provide winter cover. Cover crops which are grown during the dry season in tropical climates are legumes including *Pueraria*, *Stylosanthes*, and *Centrosema*, as well as grasses including *Brachiaria*, *Melinis*, and *Panicum* (Lal et al., 1991). Lal et al. (1998a) reported that among various cover crops grown in Ohio tall fescue (*Festuca arundinacea* Scherb.) and smooth bromegrass (*Bromus inermis* Leyss.), which have deep root systems and more root:shoot biomass ratio than other cover crops, were the most suitable for SOC sequestration, improvement in soil structure, and microaggregation. Another benefit of these grasses is erosion control. One of the management strategies is to use cover crops as a live mulch for establishing grain/food crops. Another alternative is to kill cover crops chemically or mechanically when the grain crop is planted. The live mulch system is effective when it does not compete for light, moisture, and nutrients (Lal et al., 1991). In a no-till system cover crops are mowed and the residues left

TABLE 5
Effect of Cover Crops and Green Manure on Soil Carbon Sequestration

Location	Cover Crop or Green Manure	Increase in SOC (kg C $ha^{-1}y^{-1}$)	Depth (cm)	Duration (Years)	Reference[1]
Brazil	Oat (*Avena strigosa* Scherb)-common vetch-corn-cow pea compared with oat-corn on sandy clay loam	822 no till	30	9	Bayer et al. (2000)
		622 plow till	30	9	
India	Millet-wheat-green manure-sesbania (*Sesbania aculeata* Willd.) compared with millet-wheat-fallow on sandy loam	201	15	6	Chander et al. (1997)
Sweden (Uppsala)	Wheat-barley rotation with green manure on sandy clay loam	350	20	30	Paustian et al. (1992)
USA					
(1) Alabama	Cotton-winter rye compared to cotton-fallow on silt loam	5413	30	2	Nyakatawa et al. (2001)
	Hairy vetch in tomato-silage corn on sandy loam	900	20	6	
(2) Georgia	Cover crops in tomato-eggplant (*Solanum melogena* L.) on fine sandy loam:				Sainju et al. (2002)
	Rye	633	20	5	
	Hairy vetch	517	20	5	
	Crimson clover	500	20	5	
(3) Ohio	Cover crops compared to continuous corn on silty-clay loam:				Lal et al. (1998a)
	Alfalfa	481	30	5	
	Kentucky bluegrass	−37	30	5	
	Tall fescue	2125	30	5	
	Smooth bromegrass	2083			
(4) Washington state	Winter cover crops in silage corn on silt loam:				Kuo et al. (1997a)
	Rye	527	30	7	
	Austrian winter pea (*Lathyrus hirstutus* L.)	159	30	7	
	Ryegrass	317	30	7	
	Vetch	106	30	7	
	Canola	−107	30	7	

[1] Data obtained from some references after recalculation; bulk density, if needed, recalculated according to Post and Kwon (2000).

on the soil surface. No-till of a grain crop planted directly into legume cover crop is the practice which protects soil from erosion and has a potential to reduce fertilizer requirement for the following grain crop (Follett et al., 1987).

Growing cover crops may contribute 25 to 50 kg N ha^{-1} by small grains and 36 to 226 kg N ha^{-1} by legumes (Reeves, 1994). Similar conclusions were arrived at by Hargrove (1986) and Kuo et al. (1997b), who reported that winter legume cover crops provide significant quantities of N. Establishing cover crops also reduces the rate of application of organic amendments. The residue C provided through a cover crop influences the C cycle in a manner similar to that of the manure application (Wander et al. 1996).

Lal et al. (1991) reported that following factors influence soil fertility when cover crops are grown in the rotation cycle: (1) soil and weather conditions, (2) length and time of cover crop growth, (3) quantity of biomass produced by cover crop, and (4) cover crop species. McVay et al. (1989) reported that an adapted winter legume cover crop can cover all N requirements for rain-fed grain sorghum and up to two-thirds for corn. In Kentucky, hairy vetch (*Vicia villosa* Roth) was grown as a cover crop and, besides-controlling erosion in the subsequent corn, it provided the equivalent of 90 to 100 kg ha^{-1} of fertilizer N (Ebelhar et al., 1984). Sainju et al. (2002) conducted research on a sandy loam soil in Georgia and observed that a nonlegume (rye) was a better cover crop than legumes (hairy vetch and crimson clover (*Trifolium incarnatum* L.)) in increasing SOC and N concentrations . These authors recommended growing a mixture of legumes and nonlegume cover crops.

Nyakatawa et al. (2001) reported an increase in SOC concentration in soil surface after using no-till and mulch-till system with winter rye cover. Hu et al. (1997) reported that cover crop incorporation increased labile SOC pool and coarse organic debris by two- to threefold, whereas the total SOC pool increased by 20%.

LEY FARMING

Ley farming is a system in which grasses and/or legumes are grown in short-term rotation with crops and are grazed, thus intensifying the crop-fallow system (Lloyd et al., 1991). McCown et al. (1985) described a no-till ley farming system technology for use in Australian semiarid tropics, where grain crops (corn or sorghum) were sown into a 1 to 3 years legume pasture killed by glyphosate ($C_3H_8NO_5P$). Cattle were grazed on native pastures during the wet season and on crop residues and legume leys during the dry season. This sustainable no-till system controls surface runoff, reduces nutrient losses, and minimizes soil erosion (Dilshad et al., 1996). Ley farming system enhances SOC concentration (Table 6), but with marked fluctuations, i.e., increase during the pasture phase and decrease during the crop phase (Angus et al., 2001). Greenland (1971) reviewed effects of legume-based pastures on soil properties in Australia and found that they are effective in maintaining and improving soil fertility for growing wheat. Angus et al. (2001) reported that leys based on annual legumes and crops—mostly cereals—increased SOC concentration with attendant improvements in soil aggregate stability, decrease in bulk density, and increase in water infiltration rate.

Bosma et al. (1999) reported a positive impact of ley farming system in Mali on SOC concentration because of the input of roots from ley and recycling of crop residues through animals. Ley farming is a viable alternative to burning crop residues to clear a field, which is a common practice in Africa and causes considerable loss of SOC (Bationo and Mokwunye, 1991). Data from Norway showed that ley farming had the most significant effect on SOC sequestration. A rotation with 4 years of ley and 2 years of spring grain sequestered 12 Mg ha^{-1} more SOC than all grain rotation over a 37-year period (Uhlen and Tveitnes, 1995; Singh et al., 1997).

AGROFORESTRY

Agroforestry is a collective name for land-use systems in which woody perennials (e.g., trees, shrubs, etc.) are grown in association with herbaceous plants (crops, pastures) or livestock, in a spatial arrangement, a rotation, or both. There are usually both ecological and economic interactions between the trees and other components of the system (Lundgren, 1982; Nair, 1993). Agroforestry systems, where trees maintain SOM by litter and root residues, are very effective in soil conservation, more so than traditional crops (Grewal et al., 1994) (Table 7). Soil erosion, which results in the loss of SOM and nutrients (Lal and Greenland, 1979) is controlled by trees and shrubs in agroforestry (Nair, 1993; Young, 1997). Agroforestry systems are also beneficial in reducing emission of GHGs (Dixon et al., 1994). Dixon (1995) indicated two primary beneficial attributes of agroforestry:

TABLE 6
Soil Organic Carbon Sequestration Under Grass Pasture and Ley Systems

Location	Soil Use or Management	Rate of SOC Sequestration (kg $ha^{-1}y^{-1}$)	Duration (Years)	Reference[1]
Canada (1) Ontario	Continuous blue grass compared to continuous corn on clay loam 32 years 26 cm	1316	32	Gregorich et al. (1996)
(2) Miscellaneous regions	Converting croplands to perennial grass cover (Century Model prediction over 20 years)	350	20	Desjardins et al. (2001)
Canada and USA	Conversion of cultivated land to perennial grasses (assessment)	800	20	Paustian et al. (1997) Bruce et al. (1999)
Columbia (South America)	Deep-rooted pastures in savanna soils	4316–8450[2]	6	Fisher et al. (1994)
	Deep-rooted pastures + legumes in savanna soils (in 100 cm depth)	11733	6	
Sweden (Uppsala)	Meadow fescue lay on loam with 200 kg N ha^{-1} compared to barley with 120 kg N ha^{-1}	100	2	Paustian et al. (1990)
Tropic areas	Improving grazing lands	100–200	Long term	Lal (2000c)
Mali (Africa)	Introducing leys in the crop rotation for grazing in dry season	16.7% of ley in crop rotation contributed to positive SOM balance		Bosma et al. (1999)

[1] Data obtained from some references after recalculation; bulk density, if needed, recalculated according to Post and Kwon (2000).

[2] Including particulate organic matter.

TABLE 7
Soil Organic Carbon Sequestration Under the Trees or Agroforestry System and Aboveground C Accumulation

Location	Tree or System	SOC Sequestration (kg ha^{-1}y^{-1})	Aboveground C Accumulation (kg ha^{-1}y^{-1})	Duration (Years)	Reference[1]
Canada (1) Ontario	Poplar tree (*Populus spp.*) based intercropping system	750	2920	12	Therathason (1998)
(2) Prairie	Poplar		6100		
	Green ash (*Faxinus pennsylvanica* Marsh.)	—	1360	40	Turnock (2001)
Shelterbelts	Scots pine (*Pinus silvestris* L.)		1120		
India (Saraswati)	Silvopastoral system 6-year-old trees with grasses	—	980–6500	—	Kaur et al. (2002)
Mexico (Chiapas)	Trees planted on coffee plantation, fallow, pasture lands, or corn fields	311–1578	—	150	De Jong et al. (1995)
Tropical forests	New forest	—	6200	—	Brown et al. (1993)
Tropical regions	Restoration strongly degraded soils in the tropics by planting fast growing trees	250–500	2000–4000	50	Lal (2002c)
United Kingdom	Woodland site	330	—	100	Poulton (1996)
United Kingdom	Short rotation coppice willow (*Salix spp.*) plantations on arable land	410	6700	3	Grogan and Matthews (2002)
USA	Poplar plantation on previously tilled agricultural prairie land	1600	—	18	Hansen (1993)

[1] Data obtained from some references after recalculation; bulk density, if needed, recalculated according to Post and Kwon (2000).

(1) uptake of C by trees and soils and (2) the potential to mitigate GHG emissions associated with deforestation and conversion of natural into agricultural ecosystems. Young (1997) emphasized the significance of agroforestry in tropical ecosystems and described the following ways by which such reduction in emission of GHGs could be possible: (1) uptake of C by trees on farms; (2) increase of SOC; and (3) reduction of pressure for forest clearance by providing timber, fuel wood, and other forest products on farms. Kaur et al. (2002) reported benefits of silvopastoral systems on a highly sodic soils in India, where trees were grown in association with grassess for increasing input of plant residues and enhancing SOC pool compared to the grass-only system. Experiments with corn–cowpea rotation grown on a tropical Alfisol in southwestern Nigeria containing six treatments—till, no-till, and *Leucaena* and *Gricidia* hedgerows established on the contour at 4-m and 2-m spacing—showed that SOM, total N, pH, and exchangeable basis showed decline in SOC that can be mitigated by a combination of no-till and agroforestry-based systems (Lal, 1989b). Thevanthasan and Gordon (1997) and Dyack et al.

(1999) reported that a tree-based intercropping agroforestry system had a large potential of SOC sequestration and N_2O emission reduction in intermediate regions in Canada. In the dryland ecosystems of West Asia and North Africa, an important strategy for SOC sequestration is afforestation through establishing multipurpose tree plantations (Lal, 2002a).

CROP EFFECTS ON SOIL STRUCTURE AND SOIL AGGREGATION

Soli structure according to SSSA (1997) is the combination or arrangement of primary soil particles into secondary units or peds. The secondary units are characterized on the basis of size, shape, and grade. Characterization of soil structure comprises quantification of form, stability, and resiliency. Arrangement of solids and voids existing at a given time determines structural form, and the ability to retain this arrangement under different stresses determines structural stability. Resiliency is the capacity of the soil to recover structure or stability after the stress is removed (Kay, 1990). Soil structure controls water, gas, and nutrient pools and fluxes and, therefore, influences soil biological quality (Angers and Caron, 1998). Crop rotations affect soil structure through root activity including root penetration, water extraction, anchorage, and root exudates. There is a strong interaction between plant species and management with regards to the specific effect on soil structure.

Growing plant roots compress soil around them causing enlargement of existing macropores and creation of new macropores (Gibbs and Reid, 1988). Alfalfa with large diameter and a long tap root is very efficient in creating macropore flow (Meek et al., 1990; Mitchell et al., 1995; Caron et al., 1996). Corn with a branching-type root system also can create macropore flow, but the process may be associated with earthworms' activity under no-till system (Edwards et al., 1989). Root penetration causes soil fragmentation, which loosens compact layers and enhances soil aggregation. Root exudates, together with fungal hyphae, bind and stabilize aggregates (Monroe and Kladivko, 1987; Dexter, 1991). Microaggregates are more in soils with a vegetal cover than those without it, probably because of the breakdown of large aggregates by penetrating roots (Materechera et al., 1994).

Soil water dynamics also affect soil structure. Macropore structure is modified by plant roots because of the water absorption. Grevers and De Jong (1990) reported differences in macropore structure among species with different water uptake. Grasses, legumes, and trees increase the shearing resistance of soil (Waldron and Dakessian, 1982) and shrinkage observed in cropped soils is less in alfalfa and wheat compared to uncropped bare soil (Mitchell and van Genuchten, 1992). Root length or mass are positively correlated with soil aggregation (Tisdall and Oades, 1980; Miller and Jastrow, 1990). High plant biomass production is associated with high surface area and length of macropores. Soil structure also depends on the density of root system. Dexter (1991) indicated that an increase in aggregation following sod crops is associated with the high density of roots and consequent water extraction cycles under these crops. Fine roots contribute to indirect effects by enhancing microbial activity or the release of binding materials, which increase the stability of aggregates. Miller and Jastrow (1990) ascribed the influence of fine roots on soil aggregation to association with vesicular arbuscular myccorrhiza (VAM). Mucilage released by corn roots significantly increases aggregate stability (Morel et al., 1991). Dormaar and Foster (1991) found that in the perennial ryegrass (*Lolium perenne* L.) rhizosphere microaggregate formation was enhanced by association of mineral particles, root gel, root formation, and extracellular polysaccharides. Rhizobia, in symbiosis with legumes, provide polysaccharides and promote soil aggregation (Clapp et al. 1962).

Ryegrass (*Lolium multiflorum* L.), clover (*Trifolium pratense* L.), and o ther cover crops increase aggregate stability (Dufey et al., 1986; Reeves, 1994) by producing microbial polysaccharides (Roberson et al., 1991, 1995). Perennial grasses or legumes increase water stable microaggregation (Kay, 1990; Angers, 1992). Miller and Dick (1995) compared two cropping systems: traditional vegetable rotation with winter fallow and an alternative vegetable rotation with legume crop, where a vegetable crop alternated with red clover. The latter was harvested for seeds in the summer and allowed to regrow over the winter followed by spring plow-down as a green manure. The second system with cover crop showed significant improvement in soil aggregation and exhibited high root activity and C input. Tisdall and Oades (1980, 1982) observed that structural stability can be moderated by management that includes crop rotation, and thus growing plants with extensive root systems managed with a reduced tillage can be beneficial. Angers and Caron (1998), in their review on plant-induced changes in soil structure, indicated that the

TABLE 8
Effect of Plants, Rotation, and Crop Management on Soil Aggregation

Crop Rotation or Management	Effect on Soil Aggregation	Reference
Annual ryegrass as a cover crop	Protecting aggregate breakdown, improve aggregate stability by increasing SOC	Hermawan and Bomke (1997)
Corn and soybean	Corn increase water stable aggregates by high concentration of phenol, C:N ratio, organic C, and carbohydrates; soybean can have negative effect on soil structure, throw low residue return, and low concentration of phenols	Martens (2000a, 2000b)
Crop-pasture	Increase aggregate stability during the pasture phase and decline during the arable periods Haynes et al. (1991)	
Cropping system	In long-term experiment (established 1925) wet aggregate stability decline in the order continuous pasture > wheat-pasture > wheat-fallow > continuous wheat	Kay et al. (1994)
Legumes	White clover and lupin resulted in higher aggregation stability than nonlegumes (pot experiment)	Haynes and Beare (1997)
Pasture	30 years of pasture improved soil aggregation by increasing and stabilizing large aggregation	Tisdall and Oades (1980)
Rotation with ley	Aggregate stability increased with duration of ley (timothy with or without red clover) in the rotation, whereas beet, swedes (species unknown), and potato decreased aggregate stability	Skoien (1993)
Ryegrass	Stabilize large aggregates (>1000 μm diameter) in a Red-brown earth (pot experiment)	Tisdall and Oades (1979)
Wheat-fallow or continuous wheat	50 years practice on fine sandy loam lead to breakdown water stable aggregates >1000 μm into microaggregates 50–250 and 20–50 μm	Greenland (1971)
Conventional tillage	Formation of stable microaggregates within macroaggregates is inhibited	Six et al. (1998)
Crop residue, mulching, biosolids, green manure	Increase in soil aggregation	Lal et al. (1980); Rose and Wilson (1991)

effect of various plant species on stable aggregation is associated with different SOM fractions (e.g., fungal or microbial biomass), and these fractions are closely related to the total amount of C returned as plant residues to the soil. Effects of different plants, crop rotation, tillage management, and organic amendments on soil aggregation are shown in Table 8.

SOIL FERTILITY MANAGEMENT

The principal aim of using fertilizers is to obtain high yield, increase biomass production, and return more crop residues to the soil. The quantity of residues returned is positively related to the amount of SOC sequestered (Rasmussen et al., 1980; Campbell et al., 1991; Janzen, 1987; Halvorson et al., 1999). Rochette and Gregorich (1998) reported equal CO_2 loses both from N fertilizer treatment and control. A large return of crop residue C after N fertilization increased SOC gain relative to the control. An increase in SOC after N or NPK fertilization was also reported by Blevins et al. (1983), Salinas-Garcia et al. (1997a), and Lal et al. (1998a). Studdert and Echeverria (2000) reported that N fertilization mitigated loss of C from conventional till crop rotation. The loss of C from spring wheat,

TABLE 9
Increase in Soil Organic Carbon by N and NPK Fertilizer Application

Location	Crop or rotation	Fertilization	Increase in SOC Compared to Unfertilized (%)	Depth (cm)	Duration (Years)	Reference[1]
Canada		N 90 kg ha^{-1}	−21			
(1) New Brunswick	Timothy on loam	N 180 kg ha^{-1}	−13			
		N 270 kg ha^{-1}	+29	15	35	Bèlanger et al. (1999)
(2) Ontario	Continuous corn on clay loam	NPK	16	26	32	Gregorich et al. (1996)
Denmark (Askov)	Rotation: winter cereals, root crops, spring cereals, and grass/legume mixtures on sandy loam	NPK	11	20	90	Schjønning et al. (1994)
Sweden (Uppsala)	Barley and wheat on clay loam	N	15–19	20	30	Paustian et al. (1992)
USA						
(1) Iowa	Corn on clay loam	NPK	22	15	35	Robinson et al. (1996)
(2) Missouri	Wheat on silt loam	NPK	44			
	corn on silt loam		120			
	timothy on silt loam		0	20	100	Anderson et al. (1990)
	rotation on silt loam		25			
(3) Nebraska	Corn on silty clay loam	Low N	2			
		High N	6	15	8	Varvel (1994)
(4) Texas	Wheat	N	17	22	9	Franzluebbers et al. (1994)
	Wheat-sorghum on silt clay loam	N	9	22	9	

[1] Data obtained from some references after recalculation.

soybean, sunflower, and corn was less when N fertilizer was applied. Nitrogen fertilizer placement is governed by residue placement and tillage practices. Surface-applied N can be partly immobilized by the high microbial population present in the surface of the no-till soils, thereby increasing the rate of N application to obtain the same or higher corn yield (Doran and Power, 1983). Placement of fertilizer N below the surface layer increases N availability and plant uptake (Doran and Smith, 1987).

Several experiments have confirmed an increase in SOC concentration by application of N or NPK fertilization (Table 9). Long-term experiments (over 30 years) show increase in SOC concentration by 15 to 120% depending on crop or rotation, duration of experiments, and other site-specific conditions. The Sanborn Field experiment in Missouri showed that SOC concentration was more than doubled under continuous corn but did not change under perennial continuous timothy (*Phleum pratense* L.) after 100 years of NPK fertilization (Anderson et al., 1990). Lal et al. (1998d) reported that proper soil fertility management practices on cropland can enhance SOC pool at a rate of 50 to 150 kg ha^{-1}year^{-1}.

MANURE AND BIOSOLIDS

Biosolids (organic by-products) and other organic amendments are resources that provide nutrients and C to soils. These resources in the U.S. include manure, sewage sludge and septic waste, food processing wastes, industrial organic wastes, logging and wood manufacturing wastes, and municipal refuse (Follett et al., 1987). Manuring and applying other soil organic amendments increase C inputs to soil and consequently enhance SOC concentration (Sommerfeldt et al., 1988; Smith et al., 1997; Izaurralde et al., 2001; Lal, 2001) (Table 10). Results from a long-term experiment conducted in

TABLE 10
Increase in Soil Organic Carbon by Application of Organic Amendments

Location	Crop or Rotation	Amendment	Increase in SOC (kg $ha^{-1}y^{-1}$)	Depth (cm)	Duration (Years)	Reference[1]
Denmark (Askov)	Winter cereals, root crops, spring cereals, and grass/legume mixtures on sandy loam	Manure	73	20	90	Schjønning et al. (1994)
Niger (West Africa)	Millet on low in clay soil (low initial SOC 1.7 g kg^{-1})	Manure 5t ha^{-1} 2×	366	20	5	Bationo and Mokwunye (1991)
		Manure 20t ha^{-1} 2×	1051	20	5	
Pakistan (Isfahan)	Corn on silty clay loam (low initial SOC 4.4 g kg^{-1})	Manure 30t ha^{-1}	3402	5	2	Shirani et al. (2002)
		Manure 60t ha^{-1}	4262	5	2	
Sweden (Uppsala)	Wheat-barley on sandy clay loam	Manure	600	20	30	Paustian et al. (1992)
		Sawdust	400	20		
United Kingdom	Estimation across the country based on long-term experiments	Manure 5t DM ha^{-1}	117	30	20	Smith et al. (2000a; 2000b)
		Manure 20t DM ha^{-1}	591	30	20	
		Sewage sludge 1t DM ha^{-1}	408	30	20	
		Cereal straw 2t DM ha^{-1}	350	30	20	
		Cereal straw 10t DM ha^{-1}	1091	30	20	
USA	Experiment on silt loam	Manure	404	20	25	Buyanovsky and Wagner (1998b)
(1) Missouri	continuous wheat	Manure	216	20	25	
	continuous corn corn-wheat-clover	Manure + N	656	20	25	
(2) Oregon	Wheat-fallow on silt loam	Manure	29	30	55	Rasmussen and Parton (1994)

[1] Data obtained from some references after recalculation, bulk density if needed recalculated according to Post and Kwon (2000).

Ohio showed that the continuous corn with application of NPK fertilizer and cattle manure was the best management for SOC sequestration, but without application of manure the SOC decreased dramatically (Hao et al., 2002). Follett (2001) estimated that application of manure in the U.S. would result in SOC sequestration at the rate of 200 to 500 kg C ha^{-1}year $^{-1}$. Goyal et al. (1992) and Mahmood et al. (1997), who conducted research in subtropical and tropical conditions, found that the addition of organic amendments increased microbial biomass, rhizodeposition, and plant growth even when the SOC concentration in the soil did not increase significantly. Depletion of SOC in the tropics (Salomon Islands) is additionally induced by slash-and-burn agriculture, and judicious use of chemical fertilizers and biosolids is necessary to maintain SOC concentration and soil structure (Wairiu and Lal, 2003). Soils receiving organic amendments have higher biologically active fraction compared to chemically fertilized soils (Doran et al., 1987). Organic amendments, (e.g., compost and manure) applied to soils of low SOC pool enhance N fixation by legumes (Olayinka et al., 1998). Kirchmann and Bernal (1997) compared compost after aerobic and anaerobic treatment and found that C stabilization efficiency was higher after applying aerobically treated biosolids. This information is important for developing a SOC sequestration strategy. In developing countries, cattle dung is often used as a household fuel, and the challenge is how to encourage farmers to utilize this as manure on agricultural soils (Lal, 2001).

PRECISION FARMING

Precision farming is a technique which uses the best available technologies to tailor soil and crop management to fit specific conditions found within an agricultural field (Johannsen, 1998). Precision farming is a unique tool to combine production and environmental needs in agriculture (Bouma, 1999). Soil's spatial variability, computerized soil maps, aerial photographs, spot satellite images of the field, and grid maps detailing yield potentials, soil limitations, and pest histories are widely used to identify areas of similar soil fertility (Pierce and Lal, 1991). One of the technologies used in precision farming is Global Positioning System (GPS), which is a network of satellites controlled by the U.S. Defense Department. This civilian application of GPS helps farmers return to an exact location within the field (Johannsen, 1998). Along with other measurements, GPS can be used to deliver nutrients and pest control products to a field based on the actual needs of that field. Precision farming allows farmers to match water requirements (Ferguson et al., 1999), seed type (Fagan and Schepers, 1999; Heiniger and Dunphy, 1999), fertilizer and biosolids/manure input (Yang et al.,1999; Anandacoomaraswamy and Ananthacumarswamy, 1999; Masek et al., 1999), and weed and disease control measures (Christensen et al., 1999; Eberlein et al., 1999; Fleischer et al., 1999) with soil type and topography.

All practices and inputs in precision agriculture are optimally synchronized to obtain the best economical effect. The second aspect of precision farming is the environmental effect (Ward et al., 1987). In precision farming, management practices are applied on a soil-by-soil basis, which improves efficiencies in energy and material flows (Pierce and Lal, 1991). Using the information from GPS system, farmers can apply variable rates of manure to specific locations within a field (Monson, 2000). Precision agriculture offers the most efficient use of nitrogenous fertilizers (Schnug et al., 1998; Franzen et al., 1999) and thus decreases the potential for NO_3 contamination of ground and surface waters (Ferguson et al., 1999) Using such detailed information, in most cases, results in reducing nutrient and pesticide use and therefore decreases nutrient run-off and reduces GHG emissions. Such practices also favor SOC sequestration (Li et al., 1994; Lal, 2001) (Figure 3). Precision farming, based on detailed information and a program for the specific site, is the management system that matches production expectations with environmental requirements, including SOC sequestration.

IRRIGATION AND SOIL WATER MANAGEMENT

Irrigation is a practice of increasing soil water supply under arid and semiarid conditions. Presently about 17% of world cropland (255 Mha) under irrigation (FAO, 2000) produces 40% of worlds' food. Irrigation avoids drought periods and prolongs the growing season. It is widely implemented in arid, semiarid, subhumid, and even in humid areas. Enhancing crop production increases soil C input and improves SOC concentration on irrigated vis-à-vis rainfed cropland (Table 11). High crop yields lead to more surface and root residues returned to the soil. Irrigation offers a possibility to convert less productive soils to economic croplands and, by increasing

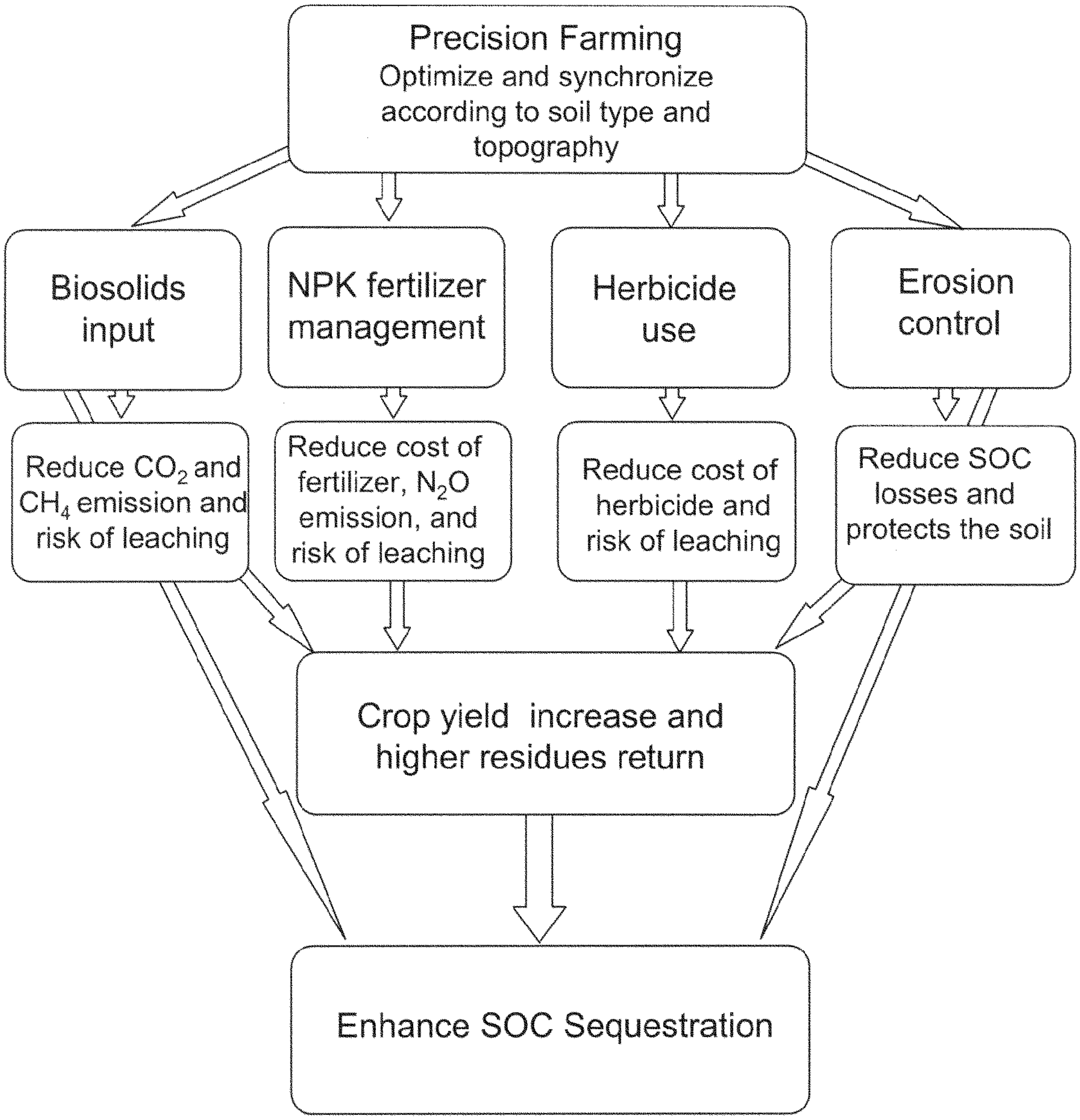

FIGURE 3. Effect of precision farming on SOC sequestration.

biomass production, enlarges the capacity for SOC storage (Lal et al., 1998d). In arid and semiarid regions where precipitation is <400 mm per year, irrigation is very important to crop production. Water used in this region often contains as much as 1% dissolved CO_2, which can precipitate in alkaline soils as secondary carbonates (Entry et al., 2002). Noncarbonated irrigation water can induce C sequestration in two ways: (1) by increasing plant biomass and enhancing soil CO_2 concentration, which can be dissolved and precipitated as secondary carbonates; and (2) by acidifying effects of plant growth and chemical fertilizers on dissolving $CaCO_3$ in calciferous soils, and translocation Ca^{+2} and HCO_3^- out of the root zone as secondary carbonate (Lal et al., 1998d; Lal and Kimble, 2000).

West and Marland (2002) indicated that irrigation requires high input of energy. Hidden C costs of irrigation include (1) fertilizer production and application, (2) fossil fuel use for lifting irrigation water, (3) fossil fuel use for farm operations such as tillage and planting, and (4) CO_2 lost as a dissolved carbonate in irrigation water. Thus, assessing the potential of irrigation to increase the SOC pool must take into account the loss of CO_2 emitted to the atmosphere though these practices. Nevertheless, by increasing

TABLE 11
Increase in Soil Organic Carbon Concentration Induced by Irrigation

Location	Irrigated Cropland	Rate of C Sequestration (kg $ha^{-1}year^{-1}$)	Reference[1]
Russia	Improvement in irrigated agriculture	93	Gurney and Neff (2000)
USA	Native sagebrush (*Artemisia spp.*)	−50	Entry et al. (2002)
(1) Idaho	vegetation converted to:	267	
	Irrigated moldboard plowed crops	1187	
	Irrigated conservation tilled crops		
	Irrigated pasture on loam and silt loam over 30 years		
(2) Nebraska	Meadow on loamy sand over 15 years	111	Lueking and Schepers (1985)
(3) General	Conversion of dryland farming to irrigated agriculture	50–150	Lal et al. (1998c)
West Asia–North Africa	Increasing plant growth on arid and semiarid areas	100–200	Lal (2002a)

[1] Data obtained from some references after recalculation.

biomass production and converting less productive soils to economical croplands, irrigation is one of the important strategies that may increase SOC pool (Lal et al., 1998d; Entry et al., 2002).

CONCLUSIONS

Key to sustainable management of soil during the twenty first century lies in using ecological principles in agricultural ecosystems (Pierce and Lal, 1991) (Table 12). Agricultural practices which promote the input of C and slow decomposition of SOM lead to SOC sequestration and improve soil quality. Crop management practices interact with one another and with the environment, and no single practice guarantees enhancement of soil quality. According to the Intergovernmental Panel on Climate Change (IPCC, 2000), improved crop management in the world scale can sequester 125 MMT by 2010 and 258 MMT of SOC in 2040. Better management of agroforestry can bring additional 26 MMT in 2010 and 45 MMT of SOC in 2040. Similarly, improved management of grazing land has the potential to sequester 168 MMT in 2010 and 474 MMT of SOC in 2040 (Table 13).

Oldeman (1994) assessed that about 2×10^9 ha of soils in the world are degraded and, therefore,

TABLE 12
Adoption of Agricultural Ecosystems to Ecological Principles from Natural Ecosystems

Natural Ecosystem	Agricultural Ecosystem
Soil is covered by plants or residues throughout the year	Continuous cropping, cover crops
Soil is protected by diverse root system, e.g., grasses, shrubs, trees	Ley farming, agroforestry
Soil remain undisturbed by cultivation	No-till or minimum-till practices
The litter is retained on the surface	Surface crop residue management
Absorbed nutrients remain on the site	Supplemental fertilization to balance nutrients uptake by crop, introducing legumes to crop rotation
Native vegetation maintains natural structure	Growing legumes, grasses, and forages, and introducing leys
SOC remains in a dynamic equilibrium with the environment	To support restoration of SOC level manure and organic wastes application

TABLE 13
Potential Net Carbon Storage Under Improved Agriculture Management

Practicies	Group[1]	Area (10^6 ha)	Adoption/Conversion (% of Area)		Increase in SOC (Mg ha^{-1} Year^{-1}	Sequestration Potential (Tg[2]/C y)	
			2010	2040		2010	2040
Cropland (reduced tillage, rotations and cover crops, fertility, erosion control and irrigation management)	AI	589	40	70	0.32	75	132
	NAI	700	20	50	0.36	50	126
Agroforestry (better management of trees on croplands)	AI	83	30	40	0.50	12	17
	NAI	317	20	40	0.22	14	28
Grazing land (herds, woody plant and fire management)	AI	1297	10	20	0.53	69	137
	NAI	2104	10	20	0.80	168	337

[1] AI; Kyoto Protocol Annex I countries (developed countries); NAI; Nonannex I countries (developing countries).

[2] Teragram = 1×10^{12} g = million metric tons.

From IPCC (2000).

depleted of their SOC pool. This land can be restored to enhance SOC concentration. Increasing the SOC pool in degraded soils at the rate of 0.01% per year (on soil weight basis) to 1 m depth at an average bulk density 1.5 Mg m^{-3} can lead to SOC sequestration of 3Pg $year^{-1}$, an amount equivalent to the net annual increase of atmospheric CO_2 (Lal, 1997). Despite this vast potential, it is important to realize that improving SOC concentration in degraded soils is a challenging task. Degraded soils exist in remote areas where land managers and farmers cannot afford the inputs needed for soil restoration. The most critical inputs are nutrient elements (e.g., N, P, and K), which must be replenished to enhance biomass production and convert cropland residue into humus.

Lal (2002b) identified three strategies to increase SOC concentrations: (1) restoration of degraded soils, (2) conversion of agriculturally marginal soils to pastures or forest lands, and (3) adoption of RMPs on cropland. Increasing SOC concentration is a long-term process. In most cultivated soils, changes in SOC are slow and may not occur over a short period of <10 years. Soil fertility management practices may not change SOC concentration by more than 10% (Jenkinson et al., 1987; Paustian et al., 1992). Restoration of depleted soils can lead to a new SOC equilibrium over 25 to 50 years through adoption of RMPs (Lal et al., 1998d). In developed areas (e.g., North America, Europe, and Australia), RMPs are being adopted to sequester SOC. The implementation of such technologies is needed in developing areas, especially in Saharan Africa, Asia, and South America (Lal, 2001). However, RMPs for SOC sequestration also improve crop yield and agronomic production, and enhance soil quality. These RMPs include conservation tillage, crop rotation, cover crops, ley farming, and precision farming. However, site-specific adaptive research is needed to identify the most suitable package of RMPs for increasing production, improving soil quality, and SOC sequestration.

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