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ENHANCING CROP YIELDS IN THE DEVELOPING COUNTRIES THROUGH RESTORATION OF THE SOIL ORGANIC CARBON POOL IN AGRICULTURAL LANDS

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ABSTRACT

Food production in developing countries, estimated at 1223 million metric tons (Mg), must be increased by 778 million Mg or 2·5 per cent y^{-1} between 2000 and 2025 to meet the needs of an increased population and projected change in diet. Among numerous options, the one based on enhancing soil quality and agronomic productivity per unit area through improvement in soil organic carbon pool has numerous ancillary benefits. The available data show that crop yields can be increased by 20–70 kg ha^{-1} for wheat, 10–50 kg ha^{-1} for rice, and 30–300 kg ha^{-1} for maize with every 1 Mg ha^{-1} increase in soil organic carbon pool in the root zone. Adoption of recommended management practices on agricultural lands and degraded soils would enhance soil quality including the available water holding capacity, cation exchange capacity, soil aggregation, and susceptibility to crusting and erosion. Increase in soil organic carbon pool by 1 Mg ha^{-1} y^{-1} can increase food grain production by 32 million Mg y^{-1} in developing countries. While advancing food security, this strategy would also off-set fossil fuel emissions at the rate of 0·5 Pg C y^{-1} through carbons sequestration in agricultural soils of developing countries.

KEY WORDS: soil quality; global food security; developing countries; climate change; soil carbon sequestration

INTRODUCTION

World hunger is an overarching issue and will remain a major concern during most of the 21st century. Global hot spots of hunger include sub-Saharan Africa (SSA) and South Asia (Rhodes, 1995; Somerville and Briscoe, 2001; Sanchez, 2002; Rosegrant and Cline, 2003; Conway and Toenniessen, 2003). Wild (2003) estimated that the annual food production of 1223 million Mg (1 Mg = 10 g^6 = 1000 Kg = 1 metric ton) in developing countries must be increased at the rate of 2·5 per cent y^{-1} by an additional 778 million Mg to meet the food demands and projected change in diet. This increase will have to come from increases in productivity of the existing land through restoration of degraded soils and improvement in soil quality. On the contrary, the rate of increase in crop yields is projected to decrease, especially in developing countries where natural resources are already under great stress, because of soil degradation that may be exacerbated by the projected climate change, (Broad and Agrawala, 2000; Kaiser, 2000) and which may reduce yield of rice in Asia because of higher night temperatures from global warming (Peng *et al.*, 2004). The projected global warming may also limit the agricultural yield in the USA (Lobell and Asner, 2003), which can adversely affect emergency grain supplies to regions with food deficit. Yet, high and sustainable yield increase will have to be achieved (Fischer *et al.*, 2000), just to maintain a status quo in

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per capita food availability (Wild, 2003). Decline in agronomic productivity of soils in developing countries is partly attributed to human-induced soil degradation and the attendant decline in soil quality (Lal, 2004). There is a strong link between soil quality and agronomic productivity on the one hand, and soil organic carbon (SOC) and soil quality on the other. Extractive practices widely used by resource-poor farmers in developing countries deplete the SOC pool, degrade soil quality and adversely affect agronomic productivity. Thus, agricultural sustainability is contingent upon land use and management systems that enhance and maintain high levels of SOC pool. This manuscript collates and synthesizes existing information linking the SOC pool and the agronomic yields of important food crops in developing countries. The focus is on soils of the tropics and subtropics, where the SOC pool has been the most severely depleted. In these areas, crop yields are low, and productivity must be increased to meet the food demands of the growing population. The hypothesis is that improvement in soil quality through increase in the SOC pool can achieve the desired rate of increase in crop yield to ensure food security by 2025.

SOIL ORGANIC CARBON POOL AND SOIL QUALITY

Soil carbon (C) pool, estimated at 2500 Pg (Pg = petagram = 1×10^{15} g = 1 billion tons) to 1 m depth comprising both soil organic carbon (SOC) and soil inorganic carbon (SIC) (Batjes, 1996; Eswaran *et al.*, 2000), is an important component of the global C cycle. World soils have lost 55 to 90 Pg of C because of conversion from natural to agricultural ecosystems, tillage, and soil degradation caused by erosion and other processes (IPCC, 2001; Lal, 2004). Some estimates of SOC loss since the advent of agriculture 10 000 years ago vary from 55 Pg (IPCC, 2001), via 243 Pg (Rozanov *et al.*, 1990) to 320 Pg (Ruddiman, 2003). In addition to degrading quality of soil and water resources, most SOC lost from agricultural soils and degraded ecosystems is emitted into the atmosphere as CO_2 or CH_4. Thus, restoration of degraded soils and ecosystems and adoption of recommended management practices (RMPs) is considered a viable option to reducing the rate of enrichment of atmospheric CO_2 by 0·4 to 1·2 Pg C y^{-1} (5 to 15 per cent of the fossil fuel emissions in 2000) for the next 20 to 50 years (Lal, 2004). While reducing the risk of climate change by enrichment of atmospheric CO_2 concentration, the SOC sequestration has numerous ancillary benefits, which must also be objectively addressed while implementing any regional or global policies towards sustainable management of soil resources. Important among these is the strong positive effect of SOC pool on soil quality, agronomic/biomass productivity, and advancing global food security.

The SOC pool comprises two predominant components: (1) the inert or recalcitrant component, which is not involved in the mineralization process and depends on the soil type, climate, land-use history and the landscape position; and (2) the labile or the active fraction, which depends on the management. The change in the SOC pool because of changes in land use and management is mostly because of changes in the labile fraction. There also exists a strong link between the concentration of the labile fraction of the SOC and soil quality, especially so in impoverished soils of the tropics and subtropics, which have lost 60 to 80 per cent of their SOC pool due to extractive practices of subsistence farming. Some cultivated soils in Kenya have lost their SOC stock by 50 to 75 Mg C ha^{-1} within 30 years of cultivation (Moshi *et al.*, 1974; Van Wissen, 1974; Tiffen *et al.*, 1994; Cole *et al.*, 1993; Swift *et al.*, 1994). In Senegal, Siband (1974) reported that SOC concentration of the surface 0–10 cm layer decreased from 28 g kg^{-1} to 10 g kg^{-1} following 90 years of cultivation, with severe adverse effects on soil quality and ability to resist drought.

Increasing the SOC pool of degraded soils would increase crop yields by influencing three mechanisms: (1) increasing available water capacity; (2) improving supply of nutrients; and (3) enhancing soil structure and other physical properties (Figure 1). There exists a strong relationship between the SOC pool and the plant available water capacity (AWC) and the ability of soils to withstand drought (Hudson, 1994; Emerson, 1995; Gupta and Larson, 1979; Hollis *et al.*, 1977; Salter and Williams, 1969; Salter and Haworth, 1961). In general, the soil available moisture content increases by 1 to 10 g for every 1 g increase in soil organic matter (SOM) content (Emerson, 1995). The increase may be small, but it may suffice to help maintain crop growth between periods of rainfall of 5 to 10 days. For some soils, however, several researchers have also reported either no or slight effect of SOC on AWC (Bauer and Black, 1992; Haynes and Naidu, 1998; Thomasson and Carter, 1989).

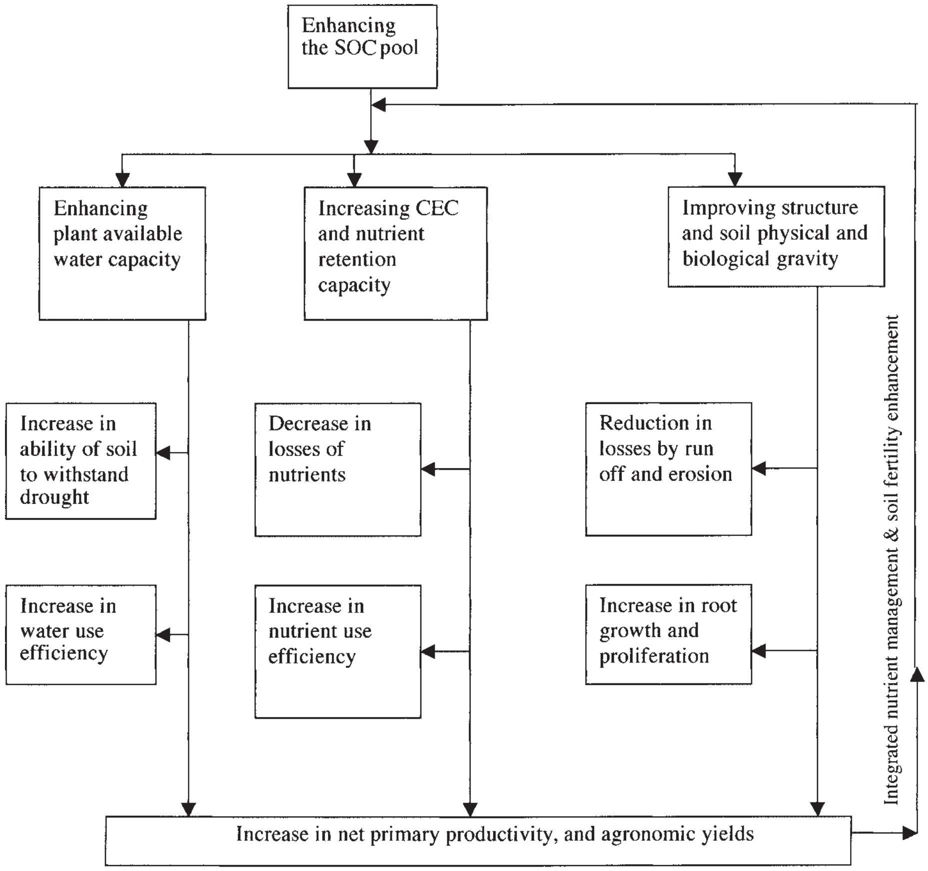

Figure 1. Improvement in soil quality by increasing the soil organic carbon content.

Reversing degradation and desertification through enhancement and preservation of SOC would enhance cation exchange capacity (CEC), improve biotic activity of micro-organisms and improve the supply of nutrients. Soil biota are ecosystem engineers, and their importance to ecosystem restoration cannot be overemphasized (Lavelle *et al.*, 1997). The SOC pool is the driving force for biological activity, and it is the primary source of energy and nutrients for soil biota (Powlson *et al.*, 2001). Soils with improved quality respond more to fertilizers and other input than those depleted of their SOC pool. Increase in the SOC pool also increases CEC (Johnston, 1986). Decline in 1 g kg^{-1} of SOC decreased effective CEC by 4·3 mmol kg^{-1} in soils of low activity clays (e.g., the West African Sahel) reducing the ability of the soil to retain nutrients (DeRidder and VanKeulen, 1990; Bationo and Mokwunye, 1991). There exists a significant positive correlation of the SOC pool with exchangeable bases and extractable K in red Ferrosols of Tasmania, Australia (Cotching *et al.*, 2002). Therefore, an increase in SOC concentration would produce the same level of crop yield with a reduced level of fertilizers (Vallis *et al.*, 1996; Aggarwal *et al.*, 1997) because of an increase in fertilizer-use efficiency and a decrease in nitrate leaching (Vallis *et al.*, 1996). Increases in the SOC pool also enhance soil structure and aggregation (Tisdall and Oates, 1982; Stengel *et al.*, 1984; Haynes and Swift, 1990; Feller and Beare, 1997; Haynes and Naidu, 1998; Gardner *et al.*, 1992; Hamblin and Davies, 1997; Karlen *et al.*, 1994), making soils less prone to crusting and compaction (Diaz-Zorita and Grosso, 2000) and soil erosion (Schertz *et al.*, 1994; Benito and Diaz-Fierros, 1992).

Experiments in Canada showed that a decrease in SOC by 1 Mg ha^{-1} in the 0 to 7·5 cm layer decreased wheat yield by 39 kg ha^{-1} in Lethbridge and 19 kg ha^{-1} at Hill Spring location (Larney *et al.*, 2000). In comparison, wheat grain yield declined by 26·5 kg ha^{-1} for each 1 Mg ha^{-1} loss in the SOC pool at 0–50 cm depth in North

Dakota, USA (Bauer and Black, 1994). Experiments in Russia showed that an increase in the humus content of soil by 1 per cent resulted in a corresponding increase in yield of cereal by 1 Mg ha^{-1} (Ganzhara, 1998), which is equivalent to 42 kg ha^{-1} y^{-1} of SOC for a plow depth of 20 cm and a mean soil bulk density of 1·2 Mg m^{-3}. At Rothamsted, UK, Johnston (1991) reported that the yield of wheat and other crops increased with an increase in humus content from 0·7 to 0·9 per cent. For a Podzolic loamy-sand soil in Russia, Zhukov *et al.* (1993) reported that the yields of wheat and barley (*Hordeum vulgare*) increased with an increase in soil humus content. The yield of wheat (Mg ha^{-1}) and the corresponding humus content (%), respectively, were 3·86 and 0·7, 3·92 and 1·5, 4·20 and 2·4 and 4·15 and 3·0. Thus, the rate of increase in yield was 13 kg ha^{-1} for every 1 Mg increase in the SOC pool at 0–20 cm depth.

SOIL ORGANIC CARBON AND CROP YIELDS

Productivity gains with an increase in the SOC pool are large, especially when combined with judicious input of fertilizers, irrigation and other amendments. Increases in SOC concentration enhance crop productivity in soils with a clay content lower than 20 per cent, and in soils of sandy-loam and loamy-sand texture. In most soils, the relation between SOC content and crop yield is linear up to a limit (2·0 per cent of SOC) beyond which it levels off (Janzen *et al.*, 1992; Olson and Janzen, 1992). In some soils, an increase in crop yield due to an increase in the SOC pool is primarily related to an increase in the labile fraction, which may have a narrow ecological optimum, 0·2 to 0·6 per cent for central Germany (Körschens, 1997). The critical limit of total SOC content, below which crop yield declines by about 20 per cent is 1·1 per cent for most soils of the tropics (Aune and Lal, 1997), and 2·0 per cent for soils of the temperate regions (Kemper and Koch, 1966; Greenland *et al.*, 1975; Loveland and Webb, 2003). In unfertilized soils, in which breakdown of soil organic matter is necessary to supply nutrients and maintain yields, there may be a critical level of SOC below which insufficient nutrients are mineralized to sustain satisfactory yields (Grace *et al.*, 1995).

Latin America

Numerous experiments conducted in Latin America have documented that enhancing and maintaining a high level of SOC pool is important to sustaining productivity of soils. In Argentina Pampas, Diaz-Zorita *et al.* (1999) observed that wheat (*Triticum aestivum*) yields were linearly related to a SOC concentration lower than 17·5 g kg^{-1}. Losses of 1 Mg of SOM decreased wheat yield by about 40 kg ha^{-1}. Therefore, use of no-till soil management and incorporation of pastures in the rotation cycle are recommended for sustainable use of the soils of the Pampas (Diaz-Zorita *et al.*, 2002).

There are several land-use and management practices that can enhance the SOC pool in soils of Latin America. Growing deep-rooted grasses with a high Net Primary Productivity (NPP) (Fisher *et al.*, 1994), improved pastures (Neill *et al.*, 1997), conversion from plow-till to conservation tillage (Bayer *et al.*, 2000, 2001; Sa *et al.*, 2001), and afforestation with fast-growing tree species (Zinn *et al.*, 2002; Smith *et al.*, 2002), all enhance SOC concentrations in the soils of Latin America. Beneficial effects of conversion from plow-till to conservation-till have been widely documented in the Pampas (Buschiazzo *et al.*, 1998; Alvarez and Lavado, 1998; Diaz-Zorita and Grosso, 2000).

South Asia

Several experiments have demonstrated the positive impact of residue retention on SOC concentration and increase in crop yield in South Asia. In Rajsthan, India, Aggarwal *et al.* (1997) reported that retention of crop residues and manure increased soil moisture content, enhanced SOC concentration and improved the yield of pearl millet (*Pennisetum typhoides*) by 0·1 to 0·2 Mg ha^{-1}. Also in India, a strong increase in crop yield with increase in SOC concentration was reported for mustard (*Brassica juncea*) by Shankar *et al.* (2002); and wheat, mustard, sunflower (*Helianthus annuus*) and groundnut (*Arachis hypogaea*) by Ghosh *et al.* (2003). Seed grain yield of mustard increased at the rate of 360 kg ha^{-1} for each 1 Mg increase in the SOC pool in the surface 15 cm layer within the SOC range of 6 to 12 Mg C ha^{-1} (Shankar *et al.*, 2002). Decreases in SOC pools in agricultural soils is reportedly more in unfertilized compared to fertilized soils, and there is a gradual build up in the SOC pool in those soils receiving recommended rates of fertilizers (Ghosh *et al.*, 2003), especially when combined with manure application (Yadav *et al.*, 2000; Reddy *et al.* 2000; Kanchikerimath and Singh, 2001). For Vertisols in central India, integrated soil management (e.g., conservation tillage for erosion control, water harvesting, soil-fertility management, and legume-based rotations), increased grain yield from 1 Mg ha^{-1} y^{-1} under traditional systems to 4·7 Mg ha^{-1} with an attendant increase in the SOC pool and improvement in soil quality (Wani *et al.*, 2003). The rate of growth in productivity between 1977 and 2002 was 77 kg ha^{-1} y^{-1} under the improved system *vis-à-vis* 26 kg ha^{-1} y^{-1} under the traditional systems. The long-term sustainability of rice (*Oryza sativa*)-wheat systems of South Asia, the basis of the Green Revolution of the 1970s, which averted mass starvation in the region, depends on the SOC pool of these intensively managed soils. Grace *et al.* (2003) observed that a decline in yield of the rice–wheat system was also associated with an attendant decline in the SOC pool at the rate of 200 to 624 kg ha^{-1} y^{-1}. Experiments on maize in Thailand showed that grain yield increased by 2·9 Mg ha^{-1} for each 1 per cent increase in SOM content (Petchawee and Chaitep, 1995). Sustainable use of structurally weak Vertisols in Australia also strongly depends on the SOC pool (Dalal *et al.*, 1995; Cotching *et al.*, 2002). In Tasmania, Australia, Cotching *et al.* (2002) reported a significant correlation between the SOC pool and yields of spring vegetables.

Africa

Experiments conducted in tropical Africa have also produced encouraging results with regards to the positive impact of SOC on crop yields and agronomic productivity. In Niger, Bationo and Ntare (2000) observed that legume–millet rotation with 30 kg N ha^{-1} maintained a high level in the SOC pool and sustained crop yields. Across several sites in West Africa, Becker and Johnson (2001) observed that a reduction in yield of upland rice on continuously cultivated soils was also associated with a decline in the SOC concentration. Decline in rice yield (Mg ha^{-1}) in relation to reduction in SOC concentration (%), respectively, was 0·19 and 0·47 in the Guinea Savanna zone, 0·33 and 0·21 in the derived savanna zone, 0·53 and 0·11 in the bimodal forest zone, and 0·40 and 0·26 for the monomodal forest zone. Decline in the SOC concentration by 19 per cent across sites resulted in a 26 per cent yield decline (Becker and Johnson, 2001). In the West African Sahel, Yamoah *et al.* (2002) reported that a combination of crop residues and fertilizer produced the highest millet grain and straw yields, water and fertilizer use efficiencies, and SOC concentration. Similar observations for the Sahel were made by Subbarao *et al.* (2000), Andreas *et al.* (2000), and Rebafka *et al.* (1994). A long-term experiment conducted on a Kikuyu red clay in Kenya showed that total crop yield of maize and beans (*Phaseolus vulgare*) ranged from 1·4 Mg ha^{-1} y^{-1} when residue was removed and without external input to 6·0 Mg ha^{-1} y^{-1} when straw was retained and fertilizers and manure (120 kg N, 52 kg P and 10 Mg ha^{-1} manure y^{-1}) were applied. The SOC pool to 15 cm depth ranged between 23·6 Mg ha^{-1} for straw removal to 28·7 Mg ha^{-1} with manuring and residue retention. Every Mg of C ha^{-1} conserved in soil through adoption of RMPs increased grain yield by 243 kg ha^{-1} for maize and 50 kg ha^{-1} for beans (Kapkiyai *et al.*, 1999). In Western Nigeria, Lal (1981) observed that grain yield increased linearly with increase in the SOC content at the rate of 2·9 Mg ha^{-1} for maize and 0·23 Mg ha^{-1} for cowpea (*Vigna unguiculata*) for each 1 per cent increase in SOC concentration in the 0–10 cm layer. In the West African humid forest and savanna zones, Larbi *et al.* (2002) observed that average grain yield increased positively with the increasing amount of crop residues applied as mulch due to the corresponding increase in SOC, total N and available P concentrations. Several experiments throughout tropical Africa, North Africa and West Africa have shown that SOC concentration can be increased by conversion from plow-till to conservation-till (Lal, 1976; Mrabet, 2002; Jenkinson *et al.*, 1999), manuring and soil fertility management (Pieri, 1992; Vlek, 1993), afforestation and agroforestry measures (Breman and Kessler, 1997; Guillaume *et al.*, 1999), and crop residue retention as mulch (Lal, 1998; Adeoye, 1990; Mbagwu, 1991).

POTENTIAL OF INCREASING CROP YIELDS THROUGH ENHANCING THE SOIL ORGANIC CARBON POOL

The increase in crop yield with increase in SOC can be substantial especially in impoverished soils that are severely depleted of their SOC pool. On the contrary, decline in the SOC concentration is not always associated

Table I. Soil organic carbon impacts on crop yields in the tropics and subtropics

Country	Crop	Soil/region	Yield increase ($Kg\,ha^{-1}\,y^{-1}\,Mg^{-1}$ of SOC)	Reference
Kenya	Maize	Kikuyu red clay	243	Kapkiyai *et al.* (1999)
Kenya	Beans	Kikuyu red clay	50	Kapkiyai *et al.* (1999)
Nigeria	Maize	Egbeda/Alfisol	254	Lal (1976)
Nigeria	Cowpea	Egbeda/Alfisol	20	Lal (1976)
Argentina	Wheat	Haplundolls/Haplustoll	64	Diaz-Zorita *et al.* (1999)
Thailand	Maize	Northeastern	408	Petchawee and Chaitep (1995)
India	Mustard	Inceptisol/UP	360	Shankar *et al.* (2002)
India	Maize	Inceptisol/Haryana	210	Kanchikerimath and Singh (2001)
India	Wheat	Inceptisol/Haryana	38	Kanchikerimath and Singh (2001)
Sri Lanka	Rubber	Alfisol/Ultisol	66	Samarppuli *et al.* (1999)

with a decrease in crop yields (Beyer *et al.*, 1999). In some cases, crop yield may increase despite a notable decline in SOC concentration (Hairiah *et al.*, 2000), because of other managerial inputs whose efficiency may increase in soils with low SOC, N and other nutrients (Ganzhara, 1998). In others, an increase in SOC may not increase the crop yield as has been reported for the rice–wheat system of South Asia (Duxbury, 2001).

Increases in crop yield with increase in the SOC concentration in the root zone through adoption of RMPs in developing countries is impressive (Table I). There are three possible scenarios relating crop yield or agronomic productivity to SOC pool: (1) increase in crop yield with increase in the SOC pool; (2) no or little decrease in crop yield with reduction in the SOC pool, and (3) increase in crop yield with decrease in the SOC pool. These apparently conflicting responses depend on soil texture (clay content), antecedent SOC pool, severity of degradation, land use, and management with regards to the use of fertilizer and irrigation. Empirical data relating crop yields to the SOC pool are scanty, especially for depleted and degraded soils of the developing countries. Meager data, summarized in Table I, show that every $1\,Mg\,ha^{-1}$ increase in the SOC pool can increase crop yield by $20–70\,kg\,ha^{-1}$ for wheat, $10–50\,kg\,ha^{-1}$ for rice, $30–300\,kg\,ha^{-1}$ for maize, $20–30\,kg\,ha^{-1}$ for cowpea, and $40–60\,kg\,ha^{-1}$ for beans. There exists a strong need to improve the data base for principal crops and predominant soil types through well designed and properly implemented long-term experiments.

Scaling up from the plot scale data to regional/global scale over a 25-year period requires an understanding of the functional relationship between the SOC pool and crop yield at a given point in time, and of the temporal changes in such relationships over the 25-year period. Experimental data describing such functional relationships are not available, especially for degraded soils of the tropics and subtropics. The relationship between SOC concentration and crop yield, in addition to being soil and crop specific, may be sigmoidal, linear or exponential.

The extrapolation of the plot data in Table I to the global scale presented in Table II is based on several assumptions: (1) yields of all crops increase linearly with increase in SOC concentration over the 2-year period; (2) adoption of RMPs may enhance the SOC pool either by $0{\cdot}5\,Mg\,ha^{-1}\,y^{-1}$ or by $1\,Mg\,ha^{-1}\,y^{-1}$, corresponding to an increase in SOC concentration at 20 cm depth by $0{\cdot}02$ per cent y^{-1} and $0{\cdot}04$ per cent y^{-1}, respectively; (3) the rate of increase in the SOC pool can be sustained for 50 years with a cumulative increase in SOC concentration by 1 per cent or 2 per cent in 50 years; and (4) such an increase would be independent of any increase in crop yield by other managerial input.

The global increase in crop yields are computed assuming that every $1\,Mg\,ha^{-1}$ increase in the SOC pool would increase crop yield by $20–70\,kg\,ha^{-1}\,y^{-1}$ in wheat, $30–300\,kg\,ha^{-1}\,y^{-1}$ in maize, $10–50\,kg\,ha^{-1}\,y^{-1}$ in rice, $50–60\,kg\,ha^{-1}\,y^{-1}$ in millet, $20–30\,kg\,ha^{-1}\,y^{-1}$ in soybean, $20–25\,kg\,ha^{-1}\,y^{-1}$ in beans and $5–10\,kg\,ha^{-1}\,y^{-1}$ in cowpeas (Table II). Restoration of the SOC pool may lead to a total increase in food-grain production in the tropics and sub-tropics by $(16 \pm 6) \times 10^6\,Mg\,y^{-1}$ for a $0{\cdot}5\,Mg\,C\,ha^{-1}$ increase in the SOC pool and $(32 \pm 11) \times 10^6\,Mg\,y^{-1}$ for a $1\,Mg\,C\,ha^{-1}$ increase in the SOC pool (Table II). Increases in food-grain production attributed to increases in the SOC pool can be $(2{\cdot}3 \pm 0{\cdot}8) \times 10^6\,Mg\,y^{-1}$ in Africa, $(4{\cdot}2 \pm 1{\cdot}2) \times 10^6\,Mg\,y^{-1}$ in

Table II. Potential of increase in food grains in the tropics and subtropics through improvement in soil quality by adopting recommended management practices which enhance the SOC pool

Crop	Region	Area	Yield ($kg\,ha^{-1}$)	Increase in SOC pool by 0·5 $Mg\,C\,ha^{-1}\,y^{-1}$		Increase in SOC pool by 1 $Mg\,C\,ha^{-1}\,y^{-1}$	
				Increase in yield ($kg\,ha^{-1}\,y^{-1}$)	Productivity increase ($10^6\,Mg\,y^{-1}$)	Increase in yield ($kg\,ha^{-1}\,y^{-1}$)	Productivity increase ($10^6\,Mg\,y^{-1}$)
Wheat							
	Africa	8·9	1571	10–20	0·09–0·18	20–40	0·18–0·36
	Latin America	9·0	2515	25–35	0·225–0·315	50–70	0·45–0·63
	Asia	97·1	2535	15–25	1·455–2·43	30–50	2·91–4·86
					1·77–2·925		3·54–5·85
Maize							
	Africa	26·6	1677	15–25	0·40–0·65	30–50	0·80–1·30
	Latin America	22·6	3124	100–150	2·26–3·435	200–300	4·52–6·87
	Asia	41·1	3566	50–150	2·05–4·11	100–300	4·11–8·22
					4·71–8·195		9·43–16·39
Rice							
	Africa	7·8	2211	5–20	0·04–0·115	10–30	0·08–0·23
	Latin America	6·5	3585	15–25	0·10–0·165	30–50	0·20–0·33
	Asia	137·6	3964	15–25	2·06–3·425	30–50	4·13–6·85
					2·20–3·72		4·41–7·44
Sorghum							
	Africa	21·6	862	40–60	0·86–1·295	80–120	1·73–2·59
	Latin America	4·1	3163	50–70	0·20–0·285	100–140	0·41–0·57
	Asia	12·5	1073	50–70	0·625–0·875	100–140	1·25–1·75
					1·69–2·46		3·39–4·91
Millet							
	Africa	20·1	670	15–25	0·30–5·00	30–50	0·60–1·00
	Latin America	0·2	1516	25–35	0·005–0·005	50–70	0·01–0·01
	Asia	14·6	820	15–25	0·22–0·365	30–50	0·44–0·73
					0·52–0·87		1·05–1·74
Beans (*Phaseolus* and *Vigna* spp.)							
	Africa	3·1	668	20–30	0·06–0·095	40–60	0·12–0·19
	Latin America	8·0	743	20–30	0·16–0·24	40–60	0·32–0·48
	Asia	14·7	640	15–25	0·22–0·37	30–50	0·44–0·74
					0·44–0·70		0·88–1·41
Soybean							
	Africa	0·92	973	10–15	0·01–0·015	20–30	0·02–0·03
	Latin America	24·0	2389	15–25	0·36–0·60	30–50	0·72–1·20
	Asia	16·9	1398	10–15	0·17–0·25	20–30	0·34–0·51
					0·54–0·87		1·08–1·74
Total					11·89–19·74	—	23·78–39·48
					(15·8 ± 5·6)	—	(31·6 ± 11·1)

1 $g\,ha\,y^{-1}$ increase in SOC equals 0·02 per cent increase in SOC pool at 20 cm depth per year in soil with a bulk density of 1·3 $Mg\,m^{-3}$. The data on area and crop yield are from FAO (2000).

Latin America, and $(9{\cdot}3 \pm 3{\cdot}5) \times 10^6\,Mg\,y^{-1}$ in Asia for a 0·5 $Mg\,C\,ha^{-1}\,y^{-1}$ increase in the SOC pool. The corresponding increase in food production for 1 $Mg\,C\,ha^{-1}\,y^{-1}$ increase in the SOC pool would be $(4{\cdot}6 \pm 1{\cdot}6) \times 10^6\,Mg\,y^{-1}$ in Africa, $(8{\cdot}4 \pm 2{\cdot}4) \times 10^6\,Mg\,y^{-1}$ in Latin America and $(18{\cdot}6 \pm 7{\cdot}1) \times 10^6\,Mg\,y^{-1}$ for Asia. The actual increase may be soil and region specific and vary with a wide range of socio-economic and biophysical factors, and may be much greater because of the synergistic effects of the overall improvement in soil quality.

STRATEGIES FOR ENHANCING THE SOIL CARBON POOL

While the benefits of SOC sequestration in mitigating climate change are important to developed economies (Powell and Hons, 1991; Powell and Unger, 1998; Rasmussen and Parton, 1994; Wilhelm *et al.*, 2004), improvements in agronomic yield and reduction in hunger and poverty are critical to degradation-prone developing countries. It is the agronomic yield, not SOC sequestration, that is the goal of all farmers, especially resource-poor farmers who consider SOC as a source of nutrients to be exploited in risk-prone environments. Subsistence farmers in the tropics are not directly concerned about the depletion of SOC, but rather with the reduction in crop yields caused by SOC-induced degradation in other soil properties (Sanchez, 2002). Not being a plant nutrient, SOC is not essential to plant growth *per se*, and the benefits derived from it are substitutable by external input, albeit to a certain limit. Yet, there is a close relationship between increases in crop yield and increase in SOC (Reilly and Fuglie, 1998), especially through increase in root biomass and residues returned to the soil. An important question is whether it is theoretically possible to reverse downward trends in the SOC pool in agricultural soils of SSA and South Asia by adopting RMPs, thereby increasing productivity and improving the environment.

Several experiments in the tropics have demonstrated that the SOC pool can be enhanced by a combination of no-till farming, residue retention, manuring, N fertilization, incorporation of grass and legume in the rotation cycle and use of agroforestry systems (Dalal *et al.*, 1991, 1995; Yadav, 1996; Pal, 2003; Rautaray *et al.*, 2003). Within a specific management system (e.g., conservation tillage, mulching, manuring, agroforestry, etc.), the rate of SOC increase depends on several interacting factors including the quantity and quality of residue retained, soil moisture and temperature regimes, intensity and frequency of cropping systems, etc. Legume-based crop rotations (e.g., soybean–sunflower, cowpea–mustard–sunflower) and the use of compost and manure are preferred as viable alternatives to the rice–wheat system in South Asia for increased productivity, and improvements in the SOC pool and soil quality (Moore, 1994; Pal, 2003; Dwivedi *et al.*, 2003). However, the retention of crop residues and use of compost, animal manure and other biosolids on agricultural soils can happen only if alternative sources for competing uses of such materials (for fodder, fuel and construction, etc.) are identified and made available. Under the prevailing socio-economic and policy environments, practices such as no-till, agroforestry, diversified/mixed farming systems, precision farming and judicious use of these options do not meet the social and economic needs that determine farmer behavior. Therefore, there is a need for a radical change in mindset at all levels of the societal hierarchy. There must be a drastic paradigm shift so that soil resources are not taken for granted. It is important that sustainable management of soil resources (through no-till farming, retention of crop residue as mulch and use of manure and compost to enhance soil fertility) is an integral component of any government program related to improving agricultural productivity, achieving food security, enhancing water quality and mitigating climate change. The time for this important action is now.

There are two principal socio-economic and cultural traditions, throughout the developing world in the tropics and subtropics, which are the driving forces responsible for depletion of the SOC pool and which lead to degradation of soil, pollution of water, and emission of GHGs and particulate material in to the air. These are: (1) the removal of crop residue for use as fodder for cattle; and (2) the use of animal dung as household dung for cooking. Consequently, soil nutrient balance is negative, the SOC pool is depleted, soils are prone to crusting and compaction because of a decline in soil structure, and are subject to severe erosion by wind and water due to bare, unprotected surfaces and high erodibility (Figure 2). These degradative processes reduce agronomic/biomass productivity, decrease response to inputs such as fertilizers and irrigation, and require additional labor (plowing) to prepare a desirable seedbed/tilth. In addition to reduced production, there are serious problems of soil degradation, water pollution, and decline in air quality.

Lack of a suitable fuel for household cooking is another social factor driving the complex process of soil and environmental degradation. Rather than using it as a soil amendment, animal dung is used as a cooking fuel in developing countries of Asia and Africa. In addition to being a serious health hazard to young mothers and the children with them, not returning the dung to the soil disrupts the nutrient cycling, accelerates the depletion of SOM and plant nutrients, reduces agronomic/biomass productivity and jeopardizes sustainability of the specific land-use system.

Such extractive systems were sustainable practices for millennia in ancient countries such as India, and were ecologically compatible as long as the population was low, the land:people ratio was high, and the demands on natural resources were low. With high demographic pressures, a low land:population ratio and high demands for natural resources that have been severely stressed, these extractive practices are causing severe environmental degradation.

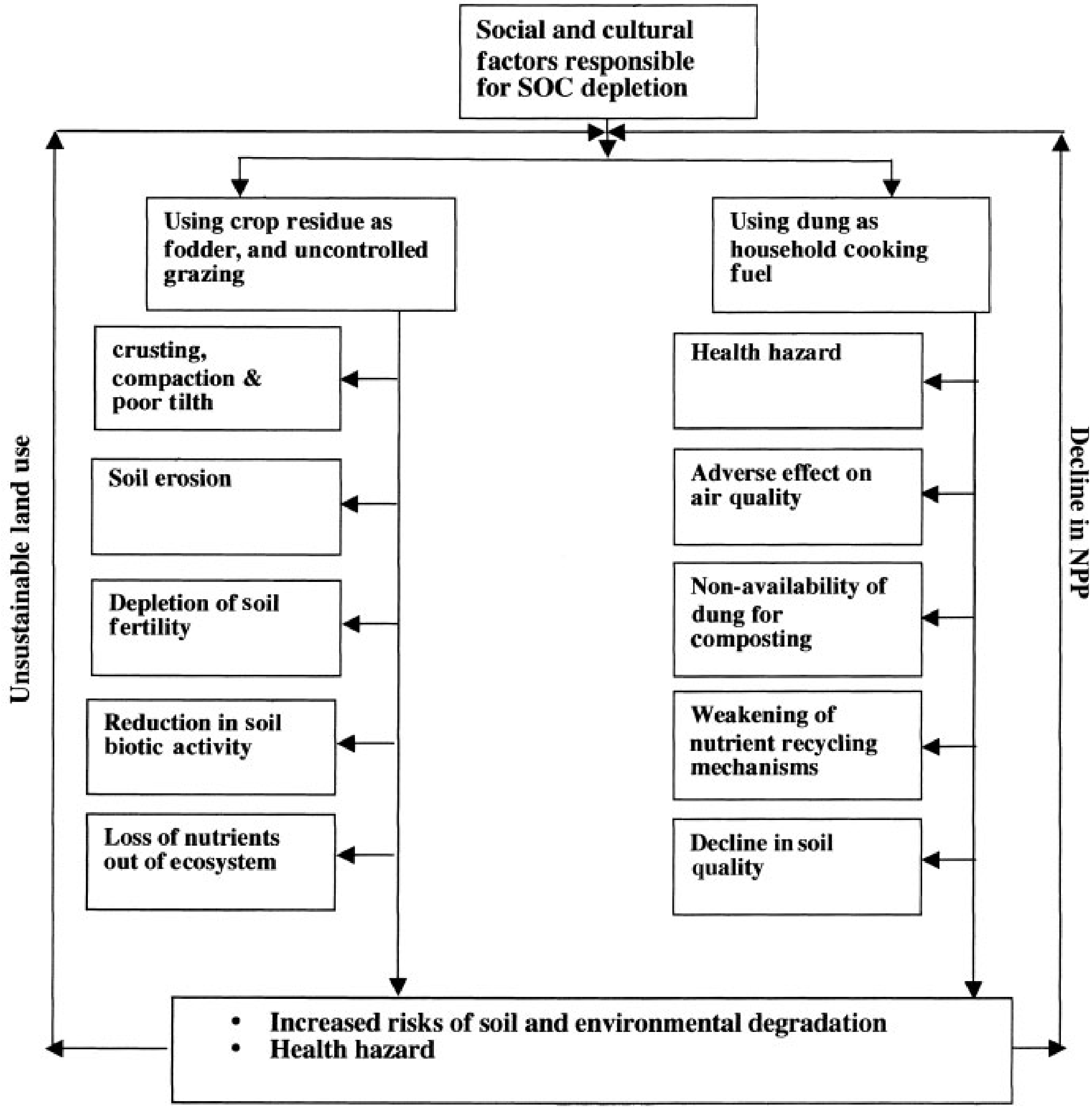

Figure 2. Two important social and cultural factors responsible for soil and environmental degradation in developing countries.

The reversal of this degradation process requires a paradigm shift in traditional systems of using natural resources. Livestock management, an important component of any agrarian society, must be based on viable forage-based rotations and sound pastoral systems. Cattle cannot be raised on crop residues and uncontrolled grazing without jeopardizing natural resources, which are already under great stress, and without making common village land prone to the 'tragedy of the commons'. The system of removing residues from cropland to feed cattle must be stopped. Similarly, development/identification of clean sources of household fuel is essential to reducing risks to the health of women and children, and making it possible to use dung/compost as a soil amendment. Establishment of biofuel plantations (e.g., *Prosopis*, (**mesquite**) *Jatropha*, *Leucaena*, etc.) on degraded/wastelands, village common land, etc., is an important strategy to restoring degraded soils and ecosystems, improving the SOC pool, enhancing the environment and improving the standard of living.

CONCLUSION

Food-grain production in developing countries can be increased by 24–39 (32 ± 11) million $Mg\,y^{-1}$ through improving soil quality by increasing the SOC pool and reversing degradation processes. This increase is about 2·5 per cent r^{-1} of the total annual cereal production of 1223 million Mg of grain in developing countries. However, the synergistic effects of increase in yield due to enhanced fertilizer and water use efficiencies are likely to be much greater. Mulch farming, retention of crop residues, use of manures and biosolids are essential to enhancing and maintaining the SOC pool in the soils of the tropics. In addition to advancing food security, an increase in the SOC pool at $1\,Mg\,C\,ha^{-1}\,y^{-1}$ over 500 million hectares would lead to carbon sequestration of $0{\cdot}5\,Pg\,C\,y^{-1}$ with a strong impact on off-setting fossil fuel emissions. Achieving these goals, however, requires identifying alternative sources for competing uses of crop residues (for fodder, fuel and construction, etc.). Under the prevailing socio-economic and policy environments, practices such as no-till farming, agroforestry, diversified/mixed farming systems, precision farming and judicious use of these options do not meet social and economic needs that determine farmer behavior. Therefore, there is a need for a radical change in mindset at all levels of the societal hierarchy. There must be a radical paradigm shift so that soil resources are not taken for granted. The sustainable management of soil resource—through no-till farming, retention of crop residue as mulch and use of manure and compost to enhance soil fertility—must be an integral component of any government program related to improving agricultural productivity, achieving food security, enhancing water quality and mitigating climate change. The time for this important action is now.

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REFERENCES

Adeoye KB. 1990. Effects of amount of mulch and timing of mulch application on maize at Samaru, Northern Nigeria. *Samaru Journal of Agriculture Research* **7**: 57–66.

Aggarwal RK, Kumar P, Power JF. 1997. Use of crop residue and manure to conserve water and enhance nutrient availability and pearl millet yields in an arid tropical region. *Soil & Tillage Research* **41**: 43–51.

Alvarez R, Lavado RS. 1998. Climate, organic matter and clay content relationships in the Pampa and Chaco soils, Argentina. *Geoderma* **83**: 127–141.

Andreas B, Bationo A, Dossa K. 2000. Mechanisms of residue mulch-induced cereal growth increases in West Africa. *Soil Science Society of America Journal* **64**: 346–358.

Aune JB, Lal R. 1997. Agricultural productivity in the tropics and critical limits of properties of Oxisols, Ultisols and Alfisols. *Tropical Agriculture* **74**: 96–103.

Bationo A, Mokwunye AU. 1991. Role of manures and crop reissued in alleviating soil fertility constraints to crop production with special reference to Sahelian zones of West Africa. *Fertilizer Research* **29**: 125–177.

Bationo A, Ntare BR. 2000. Rotation and nitrogen fertilizer effects on pearl millet, cowpea and groundnut yield and soil chemical properties in a sandy soil in the semi-arid tropics, West Africa. *Journal of Agriculture Science (Cambridge)* **134**: 277–284.

Batjes NH. 1996. The total C and N in soils of the world. *European Journal of Soil Science* **47**: 151–163.

Bauer A, Black A. 1992. Organic carbon effects on available water capacity of three soil textural groups. *Soil Science Society of America Journal* **56**: 248–254.

Bauer A, Black AL. 1994. Quantification of the effect of soil organic matter content on soil productivity. *Soil Science Society of America Journal* **58**: 185–193.

Bayer C, Martin-Neto L, Mielniczuk J, Pillon CN, Sangoi L. 2001. Changes in soil organic matter fractions under sub-tropical no-till cropping systems. *Soil Science Society of America Journal* **65**: 1473–1478.

Bayer C, Mielniczuk J, Amado TJC, Martin-Neto L, Fernandes SV. 2000. Organic matter storage in a sandy clay loam Acrisol affected by tillage and cropping systems in southern Brazil. *Soil & Tillage Research* **54**: 101–109.

Becker GM, Johnson DE. 2001. Cropping intensity effects on upland rice yield and sustainability in West Africa. *Nutrient Cycling in Agroecosystems* **59**: 107–117.

Benito E, Diaz-Fierros F. 1992. Effects of cropping on the structural stability of soils rich in organic matter. *Soil & Tillage Research* **23**: 153–161.

Beyer L, Sieling K, Pingpank K. 1999. The impact of low humus level in arable soils on microbial properties, soil organic matter quality and crop yield. *Biology and Fertility of Soils* **28**: 156–161.

Breman H, Kessler JJ. 1997. The potential benefits of agroforestry in the Sahel and other semi-arid regions. *European Journal of Agronomy* **7**: 25–33.

Broad K, Agrawala S. 2000. The Ethiopian food crisis—Uses and limits of climate forecasts. Science **289**: 1693–1964.

Buschiazzo DE, Panigatti JL, Unger PW, 1998. Tillage effects on soil properties and crop production in the subhumid and semiarid Argentinean Pampas. *Soil and Tillage Research* **49**: 105–116.

Cole CV, Paustien K, Elliott ET, Metherell AK, Ogime DS, Parton NJ. 1993. Analysis of agroecosystem carbon pools. *Water, Air and Soil Pollution* **70**: 357–371.

Conway G, Toenniessen G. 2003. Science for African food security. *Science* **299**: 1187–1188.

Cotching WE, Hawkins K, Sparrow LA, McCorkell BE, Rowley W. 2002. Crop yields and soil properties on eroded slopes of red Perrobols in north-west Tasmania. *Australian Journal of Soil Research* **40**: 625–642.

Dalal RC, Henderson PA, Glasby JM. 1991. Organic matter and microbial biomass in a Vertisol after 20 years of zero tillage. *Soil Biology and Biochemistry* **23**: 435–441.

Dalal RC, Strong WM, Weston EJ, Cooper JE, Lehane KJ, King AJ, Chicken CJ. 1995. Sustaining productivity of a Vertisol of Warra, Queensland, with fertilizers, no-tillage or legumes. I. Organic matter status. *Australian Journal of Experimental Agriculture* **35**: 903–913.

DeRidder N, Van Keulen H. 1990. Some aspects of the role of organic carbon in sustainable intensified arable farming systems in West Africa semi-arid tropics. *Fertilizer Research* **26**: 299–310.

Diaz-Zorita M, Duarte GA, Grove JH. 2002. A review of no-till systems and soil management for sustainable crop production in the sub-humid and semi-arid Pampas of Argentina. *Soil & Tillage Research* **65**: 1–18.

Diaz-Zorita M, Grosso GA. 2000. Effect of soil texture, organic carbon and water retention on the compatibility of soils from the Argentinean Pampas. *Soil & Tillage Research* **54**: 121–126.

Diaz-Zorita M, Buschiazzo DE, Peinemann N. 1999. Soil organic matter and wheat productivity in the semi-arid Argentina Pampas. *Agronomy Journal* **91**: 276–279.

Duxbury JM. 2002. Long-term yield trends in the rice-wheat cropping system: results from experiments in Northwest India. *Journal of Crop Production* **3**: 27–52.

Dwivedi BS, Shukla AK, Singh VK, Yadav RL. 2003. Improving nitrogen and phosphorus use efficiencies through inclusion of forage cowpea in the rice–wheat systems in the Indo-Gangetic Plains of India. *Field Crops Research* **80**: 167–193.

Emerson WW. 1995. Water retention, organic carbon and soil texture. *Australian Journal of Soil Research* **33**: 241–251.

Eswaran H, Van den Berg E, Reich P. 2000. Organic carbon in soil of the world. *Soil Science Society of America Journal* **57**: 192–194.

FAO 2000. *Production Yearbook in Agriculture*. FAO: Rome.

Feller C, Beare MH. 1997. Physical control of soil organic matter dynamics in tropical land use systems. *Geoderma* **79**: 49–67.

Fischer KS, Barton J, Khush GS, Leung H, Cantrell R. 2000. Collaborations in rice. *Science* **290**: 279–280.

Fisher MJ, Rao IM, Ayarza MA, Lascano CE, Sanz JI, Thomas RJ, Vera RR. 1994. Carbon storage by introduced deep-rooted grasses in the South American Savannas. *Nature* **371**: 236–238.

Ganzhara NF. 1998. Humus, soil properties and yield. *Eurasian Soil Science* **31**: 738–745.

Gardner WK, Fawcett RG, Steed GR, Pratley JE, Whitfield DM, Van Rees H. 1992. Crop production on duplex soils in south-eastern Australia. *Australian Journal of Experimental Agriculture* **32**: 915–927.

Ghosh PK, Dyal D, Mandal KG, Wanjari RH, Hati KM. 2003. Optimization of fertilizer schedules in fallow and groundnut based cropping systems and an assessment of system sustainability. *Field Crops Research* **80**: 83–98.

Grace PR, Oades JM, Keith H, Hancock TW 1995. Trends in wheat yield and soil organic carbon in the permanent rotation trial at the Waite Agricultural Research Institute, South Australia. *Australian Journal of Experimental Agriculture* **35**: 857–864.

Grace PR, Harrington L, Jain MC, Robertson GP. 2003. Long-term sustainability of the tropical and sub-tropical rice–wheat system: an environmental perspective. In *Improving the Productivity and Sustainability of Rice–Wheat Systems: Issues and Impacts*. ASA Special Publication No. **65**. ASA: Madison, WI; 27–43.

Greenland DJ, Rimmer D, Payne D. 1975. Determination of the structural stability class of English and Welsh soils, using a water coherence test. *Journal of Soil Science* **26**: 294–303.

Guillaume K, Abbadie L, Marriott A, Nario H. 1999. Soil organic matter dynamics in tiger bush (Niamey, Niger): Preliminary results. *Acta Oecologia, International Journal of Ecology* **20**: 185–195.

Gupta SC, Larson WE. 1979. Estimating soil water retention characteristics from particle size distributions, organic matter content and bulk density. *Water Resources Research* **15**: 1633–1635.

Hairiah K, Van Noordwijk M, Cadisch G. 2000. Crop yield, C and N balance of the three types of cropping systems on an Ultisol in northern Lampung. *Netherland Journal of Agricultural Science* **48**: 3–17.

Hamblin AP, Davies DB. 1997. Influence of organic matter on the physical properties of some East Anglian soils of high silt content. *Journal of Soil Science* **28**: 11–22.

Haynes RJ, Naidu R. 1998. Influence of lime, fertilizer and manure applications on soil organic matter content and soil physical conditions: a review. *Nutritient Cycling in Agroecosystems* **51**: 139–153.

Hollis JM, Jones RJA, Palmer RC. 1977. The effects of organic matter and particle size on the water retention properties of some soils in the west midlands of England. *Geoderma* **17**: 225–231.

Hudson BD. 1994. Soil organic matter and available water capacity. *Journal of Soil and Water Conservation* **48**: 188–193.

IPCC. 2001. *Climate Change 2001. Scientific Basis*. IPCC, Cambridge University Press: Cambridge; 851 pp.

Janzen HH, Larney FJ, Olsen BM. 1992. Soil quality factors of problem soils in Alberta. Proceedings of the 29th Annual. Alberta Soil Science Workshop, 19–20 February, 1992. Lethbridge: Alberta.

Jenkinson DS, Harris HC, Ryan J, McNeil A, Pilbeam CJ, Coleman K. 1999. Organic matter turnover in calcareous soil from Syria under a two-course cereal rotation. *Soil Biology & Biochemistry* **31**: 643–648.

Johnston AE. 1986. Soil organic matter: effects on soils and crops. *Soil Use and Management* **2**: 97–105.

Johnston AE. 1991. Soil fertility and soil organic matter. In *Advances in Soil Organic Matter Research: The Impact on Agriculture and the Environment*, Wilson WS (ed.). The Royal Society of Chemistry: Cambridge; 274–314.

Kaiser J. 2000. Global warming, insects take stage at Snowbird. *Science* **289**: 2030–2031.

Kanchikerimath M, Singh D. 2001. Soil organic matter and biological properties after 26 years of maize–wheat–cowpea cropping as affected by manure and fertilization in a Cambisol in semi-arid region of India. *Agriculture, Ecosystems & Environment* **86**: 155–162.

Kapkiyai JJ, Karanja NK, Qureshi JN, Smithson PC, Woomer PL. 1999. Soil organic matter and nutrient dynamics in a Kenyan Nitisol under long-term fertilizer and organic input management. *Soil Biology & Biochemistry* **31**: 1773–1782.

Karlen DL, Wollenhaupt NC, Erbach DC, Berry NC, Swain JB, Eash NS, Jordahl JL. 1994. Crop residue effects on soil quality following 10-years of no-till corn. *Soil & Tillage Research* **31**: 149–167.

Kemper WD, Koch EJ. 1966. *Aggregate Stability of Soils from Western United States and Canada*. USDA Technical Bulletin No. 1355. Washington, DC.

Körschens M. 1997. *Possibilities and Limits of Carbon Accumulation in Arable Soils*. Processes of Ecological Agriculture and Sustainable Development. Indian Ecological Society: Ludhiana; 536–543.

Lal R. 1976. No-tillage effects on soil properties under different crops in Western Nigeria. *Soil Science Society of America Proceedings* **40**: 762–768.

Lal R. 1981. Soil erosion problems on Alfisols in Western Nigeria VI. Effects of erosion on experimental plots. *Geoderma* **25**: 215–230.

Lal R. 1998. Mulching effects on runoff, soil erosion and crop response on Alfisols in Western Nigeria. *Journal of Sustainable Agriculture* **11**: 135–140.

Lal R. 2004. Soil carbon sequestration impacts on global climate change and food security. *Science* **304**: 1623–1627.

Larbi A, Smith JW, Adexumleg IO, Agyare WA, Gbaraneh LD, Tanko RJ, Akinlaide J, Omokaye AT, Karbo N, Aboh A. 2002. Crop residues for mulch and feed in crop-livestock systems: impact on maize grain yield and soil properties in the West African forest and savanna zones. *Experimental Agriculture* **38**: 253–264.

Larney FJ, Janzen HH, Olson BM, Lindwall CW. 2000. Soil quality and productivity response to simulated erosion and restorative amendments. *Canadian Journal of Soil Science* **80**: 515–522.

Lavelle P, Bignell D, Lepage M, Wolters V, Roger P, Ineson P, Healow P, Dhillon S. 1997. Soil function in a changing world: the role of invertebrate ecosystem engineer. *European Journal of Soil Biology* **33**: 159–193.

Lobell DB, Asner GP. 2003. Climate and management contributions to recent trends in agricultural yields. *Science* **299**: 1032.

Loveland P, Webb J. 2003. Is there a critical level of organic matter in the agricultural soils of temperate regions: a review. *Soil & Tillage Research* **70**: 1–18.

Mbagwu JSC. 1991. Mulching an Ultisol an southern Nigeria: effects on physical properties and maize and cowpea yields. *Journal Science Food and Agriculture* **57**: 517–526.

Moore SD. 1994. Effect of farm waste and organic manures on soil properties, nutrient availability and yield of rice–wheat grown on Sodic Vertisol. *Journal of the Indian Society of Soil Science* **42**: 253–256.

Moshi AO, Wild A, Greenland DJ. 1974. Effect of organic matter on the charge and phosphate adsorption characteristics of Kikuyu red cay from Kenya. *Geoderma* **11**: 275–285.

Mrabet R. 2002. Stratification of soil aggregation and organic matter under conservation tillage systems in Africa. *Soil & Tillage Research* **66**: 119–128.

Neill C, Melillo JM, Steudler PA, Cerri CC, DeMoraes JFL, Piccolo MC, Brito M. 1997. Soil carbon and nitrogen stocks following forest clearing for pasture in the southwest Brazilian Amazon. *Ecological Applications* **7**: 1216–1225.

Olson BM, Janzen HH. 1992. Influence of topsoil quality parameters on crop yield. In *Management of Agricultural Soils*. Proceedings of the Soils and Crops Workshop, 20–21 February 1992. Saskatoon; 137–143.

Pal MS. 2003. Alternative crop production strategies for rice–wheat cropping systems in the Indo-Gangetic Plains of India. *Australian Journal of Experimental Agriculture* **43**: 605–615.

Peng S, Huamg J, Sheehy JE, Laza RC, Visperas RM, Zhong X, Centeno GS, Khush GS, Cassman KS. 2004. Rice yield declines with higher night temperatures from global warming. *Proceedings of National Academy of Sciences. Washington, DC* **101**: 997–999.

Petchawee S, Chaitep W. 1995. Organic matter management for sustainable agriculture. In *Organic Matter Management in Upland Systems in Thailand*, LeFroy RDB, Blaci GJ, Craswell ET (eds). ACIAR: Camberra; 21–26.

Pieri CMMG. 1992. *Fertility of Soils: A Future of Farming in West African Savannah*. Springer Verlag: Berlin.

Powell JM, Hons FM. 1991. Sorghum stover removal effects on soil organic matter content, extractable nutrients, and crop yield. *Journal of Sustainable Agriculture* **2**: 25–39.

Powell JM, Unger PW. 1998. Alternatives to crop residues for sustaining agricultural productivity and natural resource conservation. *Journal of Sustainable Agriculture* **11**: 59–84.

Powlson DS, Hirsch PR, Brookes PC. 2001. The role of soil micro-organisms in soil organic matter conservation in the tropics. *Nutritional Cycling in Agroecosystems* **61**: 41–51.

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

Rautaray SK, Ghosh BC, Mittra BN. 2003. Effect of fly ash, organic wastes and chemical fertilizers on yield, nutrient uptake, heavy metal content and residual fertility in a rice–mustard cropping sequence under acid lateritic soils. *Bioresource Technology* **90**: 275–283.

Rebafka FP, Hebel A, Bationo A, Stahr H, Marschner H. 1994. Short- and long-term effects of crop residues and of phosphorus fertilization on pearl millet yield on an arid sandy soil in Niger, West Africa. *Field Crops Research* **36**: 113–124.

Reddy DD, Subba Rao A, Rupa TR. 2000. Effects of continuous use of cattle manure and fertilizer phosphorus on crop yield and soil organic phosphorus in a Vertisol. *Bioresource Technology* **75**: 113–118.

Reilly JM, Fuglie KO. 1998. Future yield growth in field crops: Wheat evidence exists. *Soil & Tillage Research* **47**: 275–290.

Rhodes ER. 1995. Nutrient depletion by food crops in Ghana and soil organic nitrogen management. *Agriculture Systems* **48**: 101–118.

Rosegrant MW, Cline SA. 2003. Global food security: challenges and policies. *Science* **302**: 1917–1919.

Rozanov BG, Tarjulian V, Orlov DS. 1990. Soils. In *The Earth as Transformed by Human Action*, Turner BL, Clark WC, Kates RW, Richards JF, Mathews JT, Meyer WB (eds). Cambridge University Press: Cambridge.

Ruddiman W. 2003. The anthropogenic greenhouse era began thousands of years ago. *Climatic Change* **61**: 261–293.

Sa JCD, Cerri CC, Dick WA, Lal R, Venske SP, Piccolo MC, Feigl BE. 2001. Organic matter dynamics and carbon sequestration rates for a tillage chronosequence in a Brazilian Oxisol. *Soil Science Society of America Journal* **65**: 1486–1499.
Salter PJ, Haworth F. 1961. The available water capacity of a sandy loam soil II. The effect of farmyard manure and different primary cultivations. *Journal of Soil Science* **12**: 335–342.
Salter PJ, Williams JB. 1969. The moisture characteristics of some Rothamsted, Woburn and Saxmundham soils. *Journal of Agriculture Science (Cambridge)* **73**: 155–158.
Samarppuli IN, Ekanayake A, Samarppuli L. 1999. Modeling the effects of land degradation on rubber yield. *Journal of Plantation Crops* **27**: 179–186.
Sanchez PA. 2002. Soil fertility and hunger in Africa. *Science* **295**: 2019–2020.
Schertz DL, Moldenhauer WC, Livingston SJ, Weeisies GA, Hintz AE. 1994. Effect of past soil erosion on crop productivity in Indiana. *Journal of Soil Water Conservation* **44**: 604–608.
Shankar G, Verma LP, Singh R. 2002. Effect of integrated nutrient management on field and quality of Indian mustard (*Brassica juncea*) and properties of soil. *Indian Journal of Agriculture Science* **72**: 551–552.
Siband P. 1974. Evolution des caractéres et de la fertilité d'un sol rouge de Casamance. *L'Agronomie Tropicale* **29**: 1228–1248.
Smith CK, Oliveira FD, Gholz HL, Baima A. 2002. Soil carbon stock after forest conversion to tree plantations in lowland Amazonia. *Brazilian Forest Ecological Management* **164**: 257–263.
Somerville C, Briscoe J. 2001. Genetic engineering and water. *Science* **299**: 2217.
Stengel P, Douglas JT, Guerif J, Goss MJ, Monnier G, Cannell RQ. 1984. Factors influencing the variation of some properties of soils in relation to their suitability for direct drilling. *Soil and Tillage Research* **4**: 35–53.
Subbarao GV, Renard C, Payne WA, Bationo A. 2000. Long-term effect of tillage, phosphorus fertilization and crop rotation on pearl millet–cowpea productivity in the West-African Sahel. *Experimental Agriculture* **36**: 243–264.
Swift MJ, Seward PD, Frost PGH, Qureshi JN, Muchena FN. 1994. Long-term experiments in Africa: developing a database for sustainable land use under global change. In *Long-term Experiments in Agricultural and Ecological Sciences*, Leigh RA, Johnson AE (eds). CAB International: Wallingford; 229–251.
Thomasson AJ, Carter AD. 1992. Current and future user of the UK soil water retention dataset. In ''Indirect Methods for Estimating the Hydraulic Properties of Unsaturated soils'' 11–13 October 1992, Riverside, CA. USA.
Tiffen M, Mortimore M, Gichuki F. 1994. *More People, Less Erosion: Environmental Recovery in Kenya*. Wiley: Chichester.
Tisdall JM, Oates JM. 1982. Organic matter and water stable aggregates in soils. *Journal of Soil Science* **33**: 141–163.
Vallis I, Parton WJ, Keating BA, Wood AW. 1996. Simulation of the effects of trash and N fertilizer management on soil organic matter levels and yields of sugarcane. *Soil & Tillage Research* **38**: 115–132.
Van Wissen HLM. 1974. *The Influence of Cultivation Practices on the Organic Carbon Content of Some Deep Soils in Kisii District*. Winand Training Center, Agricultural University: Wageningen.
Vlek PLG. 1993. Strategies for sustaining agriculture in sub-Saharan Africa: The fertilizer technology issue. In *Technologies for Sustaining Agriculture in the Tropics*, Ragland J, Lal R (eds). ASA Publication No. 56. ASA: Madison, WZ; 265–277.
Wani SP, Pathok P, Jagawad LS, Eswaran H, Singh P. 2003. Improved management of Vertisols in the semi-arid tropics for increased productivity and soil carbon sequestration. *Soil Use and Management* **19**: 217–222.
Wild A. 2003. *Soils, Land and Food: Managing the Land During the 21st Century*. Cambridge University Press: New York, NY; 246.
Wilhelm WW, Johnson JMF, Hatfield JL, Voorhees WB, Linden DR. 2004. Crop and soil productivity response to corn residue removal: a literature review. *Agronomy Journal* **96**: 1–17.
Yadav RL. 1996. Soil organic matter and NPK status as influenced by integrated use of green manure, crop residues, cane trash and cereal in sugarcane-based crop sequences. *Bioresource Technology* **54**: 93–98.
Yadav RL, Dwivedi BS, Prasad K, Tomar OK, Shurpali NJ, Pandey PS. 2000. Yield trends and changes in soil organic-C and available NPK in a long-term rice–wheat system under integrated use of manures and fertilizers. *Field Crop Research* **68**: 219–246.
Yamoah CF, Bationo A, Shapiro B, Koala S. 2002. Trend and stability analyses of millet yields treated with fertilizer and crop residue in the Sahel. *Field Crops Research* **75**: 53–62.
Zhukov AI, Sorokina LV, Mosaleva VV. 1993. Humus and grain-crop yield on Sod-Podzolic loamy sand soil. *Pochvovedniye* **25**: 55–61.
Zinn YL, Resck DVS, da Silva JE. 2002. Soil organic carbon as affected by afforestation with *Eucalyptus* and *Pinus* in the Cerrado region of Brazilian Forestry. *Ecology Management* **166**: 285–294.

