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Beyond Copenhagen: mitigating climate change and achieving food security through soil carbon sequestration

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Abstract This article explains the technical potential of C (carbon) sequestration in world soils for mitigating climate change and describes its positive impacts on agronomic productivity and global food security through the improvement of soil quality. It also supports the idea of economic development through the provision of payments to farmers in developing countries for their stewardship and enhancement of ecosystem services. These would be generated by their use of recommended management practices for improved agriculture. The technical potential of C sequestration in soils of terrestrial ecosystems and restoration of peat soils is ~3 Petagram (Pg) C/yr (i.e. 3×10^{15} g=3×10^{9} tonnes C/yr) or 50 ppm draw down of atmospheric CO_2 by the end of the 21st century by increasing the soil C pool at a rate of 1 Mg/ha/yr. Depending upon climate and other variables, this could increase cereal and food legume production in developing countries by 32 million Mg/yr and roots and tubers by 9 million Mg/yr. It is precisely this strategy which would have received broad political support at the COP-15 meeting in Copenhagen in December 2009 from developing countries, emerging economies and the industrialized world. Addressing the issue of food-insecurity and global warming through sequestration of C in soils and the biota, along with payments to resource-poor farmers for the ecosystem services rendered, would be a timely win-win strategy.

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Introduction

There are more than 1 billion food-insecure people in the world, mostly in developing regions of Asia/Pacific, Sub-Saharan Africa, South/Central America, and the Caribbean (FAO 2009). The gap in cereal requirement in Sub-Saharan Africa, i.e. the difference between production and demand, was about 16 million Mg (Mg = tonne) in 2001 and is projected to increase to 52 million Mg in 2015 (Roy 2010). India must also increase its food grain production by 60% by 2030 over that produced in 2007. The question “can India produce enough wheat and other food grains by 2030” (Nagarajan 2005) was the main theme of India’s Prime Minister Man Mohan Singh’s inaugural address to the 97th Indian Science Congress held in Kerala from 4th to 7th January, 2010. He listed three serious issues facing the nation of >1.1 billion: hunger, malnutrition and drinking water quality. Farmers of developing countries, predominantly small landholders (<2 ha), use extractive farming practices, and harvest low grain yields (~1 Mg/ha). Most agricultural soils used by the small landholders of the tropics and sub-tropics are severely depleted of their soil organic carbon (SOC) pool (Dang and Klinnert 2001; Lal 2004). These soils are also highly prone to degradation by erosion, structural breakdown, decline in biodiversity and overall deterioration in quality. Under these conditions, crop yields depend on the vagaries of rainfall and must cope with additional biotic (pest and pathogen) and abiotic (drought, high temperature) stresses. Failure of even one monsoon season, as was the case in India in 2009, may mean crop failure with serious consequences.

Global potential of carbon sequestration in soils

Soils are important for the moderation of numerous ecosystem services such as net primary production, food and fibre production, water storage and quality, and maintaining biodiversity. Soil quality, the ability of soils to provide ecosystem services, depends, to a great extent, on the amount and quality of the SOC pool in the root zone. Most soils in managed ecosystems contain a lower SOC concentration/pool than those under natural environments because of the higher rates of mineralization accelerated by changes in soil temperature and moisture regimes, lower input of biomass C, and higher losses caused by accelerated erosion and leaching (Lal 2004). The loss of SOC pool, attributed to historic land misuse and soil mismanagement, can yet be remediated by conversion to a restorative land use and adoption of recommended management practices (RMPs). The natural C sink capacity is in the range of 10–30 Mg C/ha. However, not all RMPs are adapted to all soils and ecoregions. Those RMPs which create positive C and nutrient budgets, conserve water, control soil erosion, improve soil structure and minimize soil disturbances should be suitable for enhancing the SOC pool and sustaining agronomic productivity under most conditions. These practices include appropriate afforestation of degraded/desertified soils, conversion of degraded croplands to pastures and tree cover, conservation agriculture with no-till farming and crop residue mulching along with cover cropping, integrated nutrient management based on appropriate use of organic and inorganic sources of plant nutrients, use of compost/manure and biochar in conjunction with other soil amendments, and complex crop rotations including agroforestry. The humification efficiency, the fraction of biomass C converted into humus with long residence time, is about 20% (Majumdar et al. 2007; Cai and Qin 2006), with a biomass-C input for steady state SOC pool of 3 to 4 Mg C/ha/yr (5 to 7 Mg of dry biomass/ha/yr). Depending on soils and climate, the technical potential of these RMPs is in the range of 100 to 1,000 kg C/ha/yr, and may be as much as 3 Pg C/yr (1.8–4.4 Pg C/yr$=1.8\text{–}4.4\times10^9$ tonnes C/yr) on a global scale (Table 1). This low hanging fruit, a win-win option of C sequestration in terrestrial ecosystems with a sink capacity of reducing the atmospheric CO_2 concentration by 50 ppm by 2100 (Hansen et al. 2008), should have been high on the agenda of the COP-15 meeting in Copenhagen in December 2009. Despite high estimates of the technical potential of SOC sequestration, some have argued about the limited C storage capacity of terrestrial ecosystems in general and soils in particular (Schlesinger and Lichter 2001).

Table 1 Technical potential of carbon sequestration in world soils for about 50 to 100 years

Ecosystem	Technical potential (Gt[a] C/yr)	References
1. Croplands	0.6–1.2	Lal (2004)
2. Grazing lands (Grasslands and Rangelands)	0.5–1.7	Conant et al. (2001); DOE (1999)
3. Restoration of salt affected soils	0.4–1.0	Lal (2010)
4. Desertification control	0.3–0.5	Lal et al. (1999)
Total	1.8–4.4	

[a] Gt (Gigatonne = 10^9 tonnes)

Soil carbon and ecosystem services

Rather than a critical level, there is an optimum range of SOC concentration of 2% to 3% in the root zone covering a wide spectrum of soils (Barrow 1991; Kemper and Coach 1966; Greenland et al. 1975; Aune and Lal 1997; Loveland and Webb 2003). Enhancing the SOC pool to the level of optimal range improves agronomic yields of crops and pastures through several processes such as: (i) increasing available water capacity (Huntington 2003; Lal 2000; Emerson 1995; Salter and Haworth 1961), (ii) improving plants' nutrient supplies (Johnston 1986; Larbi et al. 2002; Diels et al. 2002; Rhodes 1995; Quansah et al. 2001; Aggarwal et al. 1997; Bationo and Ntare 2000; Duxbury 2001; Mando et al. 2005a, b), (iii) restoring soil structure (Roose and Barthès 2001; Carter 2002), and (iv) minimizing risks of soil erosion (Lal 1981; Fahnestock et al. 1995; Wang et al. 2009; Craswell and Lefroy 2001). These and other proven beneficial impacts of the SOC pool on soil quality form the basis of numerous RMPs to enhance and sustain high crop yields of small landholders for whom chemical fertilizers are either prohibitively expensive or their effectiveness is uncertain because of harsh climates and degraded soils (Lal 2004; Lal et al. 1999).

Crop yield response to concentrations of soil organic carbon

Agronomic response of crops to SOC concentration in the root zone depends on numerous factors (e.g., active or mineralizable fraction, antecedent level, and the managerial inputs, especially of nutrients and water). There are few experiments specifically conducted to establish the relationship between SOC concentration and agronomic yield. Most of the available data relating crop yields with SOC concentration comprise indirect information from other studies conducted to assess the impact of agronomic practices on soil properties. The available information collated and synthesized in Table 2 shows a strong relation between crop yields and the amount of SOC in the root zone for diverse soils in several countries including Argentina, China, India, Nigeria, Russia, Thailand and the semi-arid areas of West Africa. For the alluvial soils of New Delhi, India, increase in grain + straw yield (biomass production) with increase in SOC concentration by 1% in the root zone was 1.6 Mg/ha for cowpea (*Vigna unguiculata* L.), 7.9 Mg /ha for maize (*Zea mays* L.), and 12.7 Mg/ha for wheat (*Triticum aestivum* L.) (Fig. 1). However, an increase in SOC concentration by 1% in the root zone for soils of a semi-arid region of India is rather dramatic. An increase in SOC concentration by even 0.1% over a decade would be a significant improvement. The data in Fig. 2 show an interesting interaction between SOC concentration and fertilizer use on grain yield of wheat in a semi-arid and sub-tropical region of India. Chemical fertilizer application increased the maximum grain yield from 3.5 t/ha to 5.2 t/ha (compare upper and lower panels). Without fertilizer, grain yield increased from 1.5 t/ha in soils with an SOC concentration of 0.2% to 3.5 t/ha in soils with an SOC concentration of 0.9%. With application of chemical fertilizer, however, grain yield increased to 4.6 t/ha even in soils with SOC concentration of 0.2%, and to a maximum of

Table 2 Regression equations relating agronomics yields of a range of crops to the concentration of soil organic carbon in the root zone (Y = yield in Mg/ha, SOC = % on weight basis)

Country	Region/Soil	Regression equation		Crop	Reference
Argentina	Pampas	$Y=2.24X+0.44$,	$R^2=0.44$	Wheat	Quiroga et al. (2006)
China	(i) Beijing, Jaingsu, Shaingai, Shandong, Lianoing, Sichan	$Y=2.038X+1.323$,	$R^2=0.93$	Cereals	Pan et al. (2009)
	(ii) Mid China, S. China	$Y=1.51X+0.752$,	$R^2=0.80$		
China	Northeast	$Y=1.764X+4.70$,	$R^2=0.91$	Maize	Qiu et al. (2009)
	North	$Y=4.541X+7.48$,	$R^2=0.99$	Wheat	
	Mid-South	$Y=1.853X+4.23$,	$R^2=0.95$	Rice	
	Eastern	$Y=2.66X+1.53$,	$R^2=0.99$	Rice	
	Southwest	$Y=2.3X+5.56$,	$R^2=0.95$	Rice-Wheat	
India	West Bengal	$Y=1.01X+3.02$,	$R^2=0.96$	Rice	Majumdar et al. (2007)
	Vertisol, Central India	$Y=9.33X-2.42$,	$R^2=0.52$	Rice	More (1994)
		$Y=9.44X-1.91$,	$R^2=0.51$	Wheat	
	Cambisol, New Delhi	$Y=1.64X-0.22$,	$R^2=0.75$	Cowpea (dry biomass)	Kanchikerimath and Singh (2001)
		$Y=7.94X+0.33$,	$R^2=0.83$	Maize (Grain + Stover)	
		$Y=12.69X+1.89$,	$R^2=0.71$	Wheat (Grain + Straw)	
	U.P., Inceptisol	$Y=-2.60X^2+5.65\times+0.47$,	$R^2=0.96$	Wheat	Benbi and Chand (2007)
	Punjab, Inceptisol	$Y=6.45X+0.94$,	$R^2=0.17$	Wheat	Sandhu et al. (1996)
Lithuania	Maz District	$Y=1.80X-1.01$,	$R^2=0.78$	Barley (*Hordeum vulgare* L.)	Jankauskas et al. (2007)
Nigeria	Alfisol/West	$Y=2.875X+0.28$,	$R^2=0.75$	Maize	Lal (1981)
		$Y=0.225X+0.04$,	$R^2=0.55$	Cowpeas	
Russia	Chernozems	$Y=0.142X+3.05$,	$R^2=0.50$	Barley	Ganzhara (1998)
		$Y=0.573X+36.4$,	$R^2=0.13$	Pea (Green biomass) (*Pisum sativum* L.)	
		$Y=1.84X+10.95$,	$R^2=0.89$	Mustard (Green biomass) (*Brassica juncea* L.)	
		$Y=8.13X+36.4$,	$R^2=0.59$	Maize (Green biomass)	
Russia	Podzolic Loamy Sand	$Y=0.33X+3.29$,	$R^2=0.78$	Wheat	Zhukov et al. (1993)
		$Y=0.29X+3.01$,	$R^2=0.58$	Barley	
Thailand	Alfisol/Northeast	$Y=4.82X+-.29$,	$R^2=0.78$	Maize	Petchawee and Chaitep (1995)
W. Africa	Semi-Arid	$Y=0.31X+0.63$,	$R^2=0.26$	Rice	Becker and Johnson (2001)

The regression equations presented in this table are computed from the recalculated data on soil organic matter content (58% C), and crop yields presented in different units (q/ha, lbs/acre, etc.) contained in the original articles listed in Table 2. However, the depth of measurement of soil organic matter content is not uniform, and ranges in most cases between 10 and 20 cm. Rather than using these equations for predicting crop yields, these empirical relations are a mere indication of the close relationship between crop yield and SOC concentration

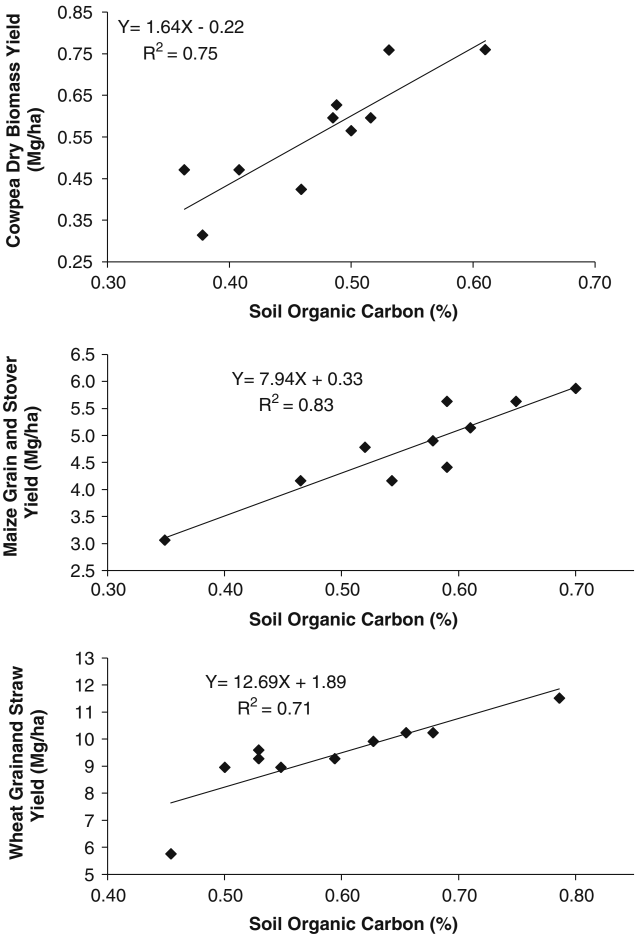


Fig. 1 Relationship between grain yield and soil organic carbon concentration in a cambisol, New Delhi, India (Redrawn from Kanchikerimath and Singh, 2001)

5.2 t/ha when SOC concentration was in the range of 0.6% to 0.7%, beyond which yield declined. The existence of an optimal range of SOC when fertilizer was used indicates the need for site-specific research to determine the concentration and quality of SOC and the optimum application of fertilizer.

For a Vertisol in Central India, increase in SOC pool by 1 Mg/ha increased grain yield by 0.174 Mg/ha for wheat and 0.235 Mg/ha for rice (*Oryza sativa* L.) (Fig. 3). Field studies conducted in West Africa indicated that a 1% increase in SOC concentration in the root zone increased grain yield of upland rice by 0.31 Mg/ha (Fig. 4). For a Podzolic loamy-sand in Russia, increase in SOC concentration by 1% increased grain yield of wheat by 0.33 Mg/ha and that of barley (*Hordeum vulgare* L.) by 0.29 Mg/ha (Fig. 5). Data from a long-term experiment in Oregon (Fig. 6) indicated that an increase in SOC pool by 1 Mg C/ha increased grain yield of wheat by 0.14 Mg/ha from 1942 to 1951, 0.38 Mg/ha from 1952 to 1966, 0.12 Mg/ha from 1967 to 1976, and 0.06 Mg/ha from 1977 to 1986: corresponding increases in straw yield of wheat were 0.09 Mg/ha, 0.15 Mg/ha, 0.12 Mg/ha and 0.06 Mg/ha, respectively (Fig. 6). The data on agronomic yield in Germany indicated a strong relationship between SOC concentration in the root zone and grain yield of wheat (Fig. 7). Regression equations in these graphs, recalculated and redrawn from the data for a wide range of ecoregions, indicate strong and positive impacts of SOC concentration on increase in agronomic yield of wheat, barley, maize, rice, cowpeas, and other food crops (Table 3). However, these empirical equations cannot be used to predict crop yield beyond the range of SOC concentration measured and for other soils and crops of diverse characteristics and edaphological requirements.

In addition to the data compiled in Tables 2 and 3, there are some other studies from the tropics and sub-tropics which have reported strong relationships between SOC pool and crop yields (Lal 2006a, b), for depleted soils of Africa (Kapkiyai et al. 1999) and India (Wani et al. 2009; Shankar et al. 2002). In the Argentinean Pampas, Díaz-Zorita et al. (1999) and Díaz-Zorita and Grosso (2000) demonstrated that losses of 1 Mg/ha of the SOC pool were associated with a decrease in wheat yield of approximately 40 kg/ha. This decline is larger than the 15.6 kg/ha reported by Bauer and Black (1994) for some soils of the USA but less than that observed by Sandhu et al. (1996) from the Punjab, India. Similarly, there are studies from temperate regions which have also reported a strong positive impact of the SOC pool on agronomic yields, including those from Australia (Cotching et al. 2002; Farquharson et al. 2003),

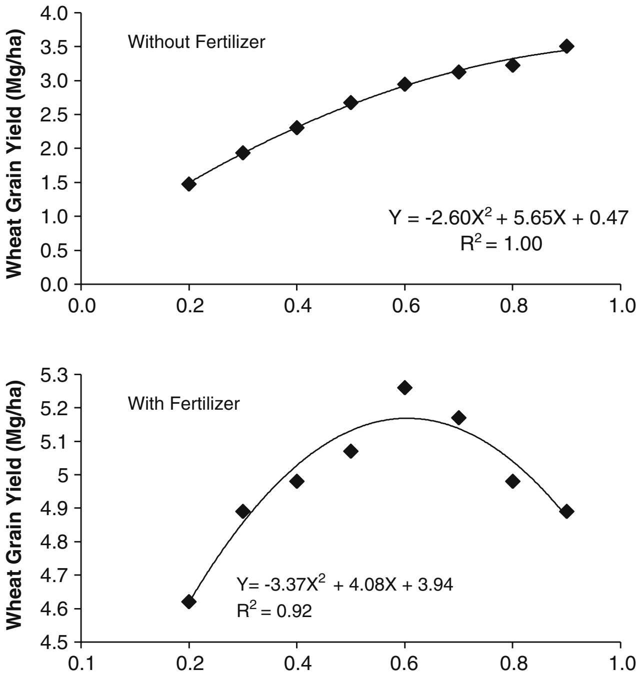
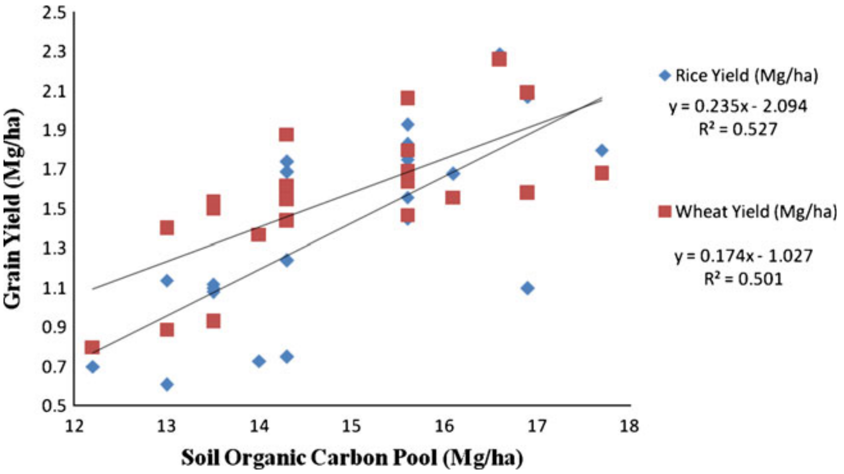


Fig. 2 Influence of soil organic carbon concentration on grain yield of wheat with and without fertilizer and on productivity (redrawn from Benbi and Chand 2007)

Fig. 3 Grain yields of rice and wheat on a Vertisol in Central India under low input and rainfed farming (Redrawn from the data of More 1994)



Germany (Beyer et al. 1999), and USA (Rasmussen and Parton 1994; Lucas et al. 1977, Bauer and Black 1994; and Barber 1979). Increasing the SOC pool in the root zone by 1 Mg C/ha could increase production of food grains (cereals and legumes) in developing countries by 32 million Mg/yr, and those of roots and tubers by 9 million Mg/yr (Lal 2006a, b). Such gains in agronomic production depend, as these may, on climate and other factors but could reduce the risk of hunger and food insecurity in these regions.

In general, contributions of the SOC concentration in the root zone to agronomic productivity are high for soils: (i) of coarse rather than heavy-texture, (ii) with lower than higher antecedent SOC concentrations, (iii) receiving lower rather than higher rates of chemical fertilizers, (iv) managed under rainfed rather than irrigated conditions, and (v) of poor rather than good quality.

Cost effectiveness and payments for ecosystem services

In comparison with geological sequestration (Chu 2009), C sequestration in soils and biota through adoption of RMPs is highly cost-effective. The cost of C capture and storage (CCS) technology is about US\$100/Mg of CO_2 or US\$367/Mg of C (McKinsey et al. 2009; Al-Juaied and Whitmore 2009), compared with low or negative cost of SOC sequestration because of increases in agronomic production and other co-benefits. If farmers and land managers were compensated for C sequestration in soils at the rate equivalent to the cost of carbon capture and storage (i.e. US\$367/Mg of C reported by McKinsey et al. 2009), the payment for ecosystem services even at the modest rate of soil C sequestration of 250 kg/ha/yr would be about

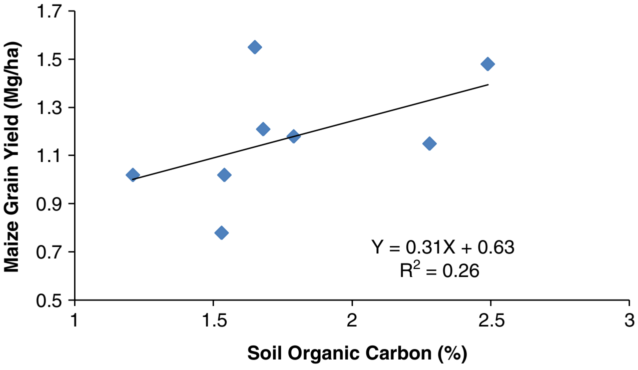


Fig. 4 Grain yield of upland rice as affected by soil organic carbon concentration across different ecoregions in West Africa (redrawn from Becker and Johnson 2001)

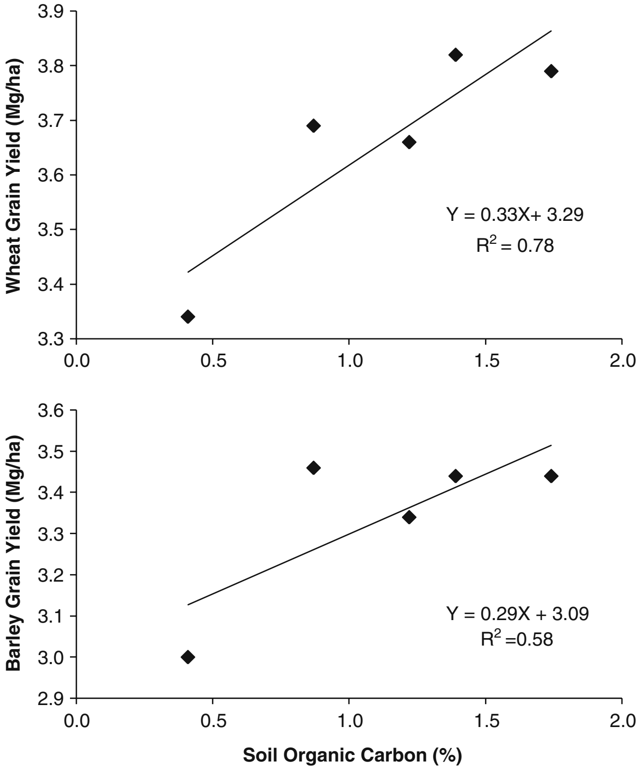


Fig. 5 Grain yield of wheat and barley grown on Sod-Podzolic loamy sand in Russia (Redrawn from Zhukov et al. 1993)

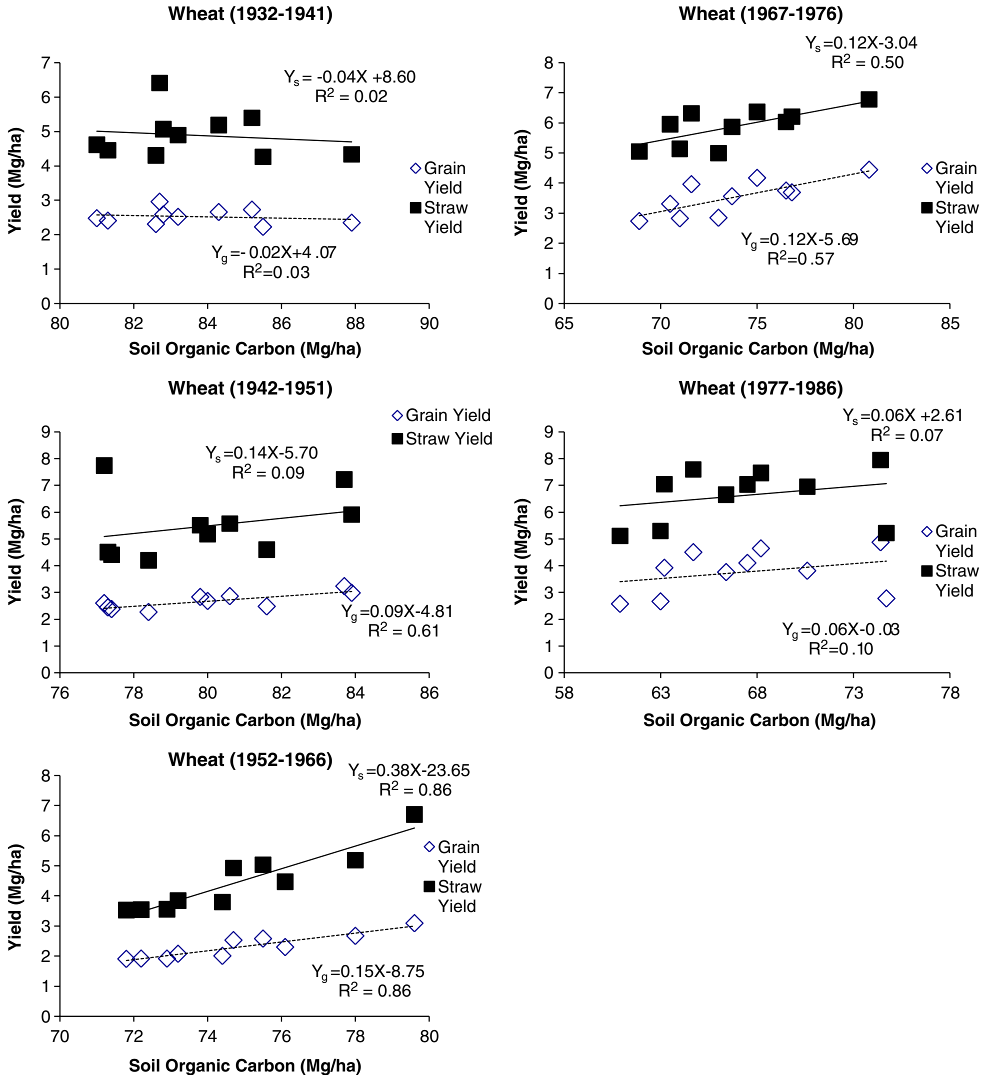


Fig. 6 Effects of soil organic carbon pool on grain and straw yields of wheat in Pendeton, Oregon (Redrawn from Rasmussen and Parton 1994). (*Y_s* straw yield, *Y_g* grain yield)

US$90/ha/yr. However, most farmers would be pleased to adopt RMPs at about one-quarter the cost of carbon capture and storage or about US$25/ha/yr (US$10/acre/yr). Thus, payments to land managers for sequestering C in agricultural soils and forestry projects, not only as sink projects under the Clean Development Mechanism (CDM) of the Kyoto Treaty (Zomer et al. 2008) but also for enhancing ecosystem services would be an important strategy to alleviate poverty and advance regional/global food security. Selling credits of soil carbon sequestered through restoration of salt-affected (Flugge and Abadi 2006; Lal 2010) and other degraded/desertified soils (Lal 2009) would promote the concept of "farming carbon", a step towards achieving the U.N. Millennium Development Goals of combating poverty and reducing hunger. The term "Farming Carbon" implies increasing the carbon pool (stock) in soils (and trees) with the purpose of trading carbon thus sequestered as a farm commodity similar to that of trading corn, soybeans, milk, meat, etc. With transparent and just prices of C sequestered in soils, based on the ecosystem services rendered, income generated through "farming carbon" would provide an important incentive for the resource-poor farmers to invest in soil restoration and adoption of RMPs.

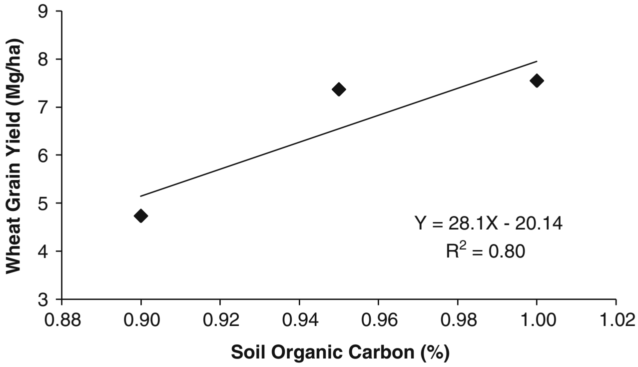


Fig. 7 Grain yield of wheat in Germany as influenced by soil organic carbon concentration in a Typic Haplumbrept or calcareous soils with a tendency towards podzolization (redrawn from Beyer et al. 1999)

Table 3 Synthesis of published reports indicating a strong positive correlation between agronomic yield of crops and concentration of soil organic carbon in the root zone

Crop	Country/Region	Reference
Wheat	Argentina, China, India, Russia	Quiroga et al. (2006); Fabrizzi et al. (2003); Pan et al. (2009); Dong et al. (2006); Kanchikerimath and Singh (2001); Benbi and Chand (2007); Sandhu et al. (1996); Zhukov et al. (1993)
Barley	Lithuania, Russia	Jankauskas et al. (2007); Zhukov et al. (1993)
Maize	China, India, Nigeria, Russia, Thialand	Kanchikerimath and Singh (2001); Lal (1981); Ganzhara (1998); Petchawee and Chaitep (1995)
Rice	China, India, West Africa	Majumdar et al. (2007); More (1994); Becker and Johnson (2001)
Cowpeas, Mustard, Pea, Soybeans	Nigeria, India, Russia	Lal (1981); Kanchikerimath and Singh (2001); Ganzhara (1998); Lal (2006a, b)

In this sense, the outcome of the 15th COP-15 meeting from 8 to 18 December 2009 in Copenhagen has been disappointing to scientists, policy makers, land managers and the general public because such strategies offering multiple benefits, particularly to the poorest members of society, were not fully discussed. Soils, essential to life on planet Earth and important to the mitigation of and adaptation to climate change (Gore 2009), were not given the emphasis that they deserve.

Conclusions

The trilemma of food insecurity, climate change, and soil/environmental degradation can be addressed by restoring the SOC pool in degraded/depleted cropland soils of the world. An SOC concentration above a critical concentration of about 1.1% in the root zone is essential for the creation of optimal edaphic/agronomic conditions. Principal benefits include favorable soil structure and aggregation, increase in plant available water capacity, improvement in nutrient retention and use efficiency, increase in microbial biomass C and activity of earthworms and other soil biota, etc. Thus, there is a strong correlation between concentration (pool) of SOC in the root zone and grain/straw yields of grain crops and other food staples (root crops). The technical potential of C sequestration is 0.6–1.2 Pg/yr in cropland soils, and about 3 Pg/yr in soils of all ecosystems (e.g., cropland, grazing land, forest lands, degraded lands, wetlands, etc.). This natural process of C sequestration in soils is also cost-effective and has numerous co-benefits. Important among these are increases in crop yields, improvement in use-efficiency of inputs (e.g., fertilizer, irrigation), decrease in erosion and sedimentation, reduction in non-point source pollution, decline in hypoxia/anoxia (dead zone) of coastal waters, increase in soil biodiversity, and mitigation of climate change through reduction in net CO_2 levels. Rewarding farmers/land managers for providing ecosystem services would be a strong incentive towards adoption of recommended management practices for sustainable management of soils and natural resources. Such a long-term strategy of addressing the issues of climate change and food security would also reduce the perpetual crises of aid, subsidies and ad hoc approaches to providing the basic necessities to resource-poor and small landholders dependent on low crop yields and uncertain rains in a changing climate. Farming soil C and trading C credits would potentially create another income stream for farmers. This is a truly win-win strategy, and a bridge to the future until low-C or no-C fuel sources take effect.

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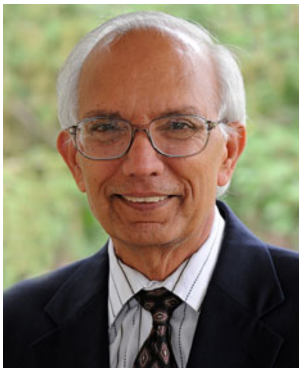

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