CROP RESIDUES AND SOIL CARBON

Rattan Lal
Carbon Management and Sequestration Center
The Ohio State University, Columbus, OH 43210 USA
Lal.1@osu.edu

ABSTRACT

In addition to advancing food security and minimizing malnutrition, agriculture must also be an important solution to environmental issues including global warming, non-point source pollution, hypoxia, etc. In this regard, the impact of managing crop residues in conjunction with no-till (NT) farming and conservation agriculture (CA), cannot be over-emphasized. The amount of crop residues produced in 2001 was estimated at ~ 0.5 billion Mg in USA and ~ 4 billion Mg in the world. These residues contained ~ 11 x 10^6 Mg of NPK in USA and 81 x 10^6 Mg in the world. In addition to nutrient cycling, residue retention also enhances numerous ecosystem services including improvement in soil quality, increase in agronomic productivity and profitability and decrease in risks of soil erosion, water runoff and loss of fertilizers and other amendments. There are also numerous off-site benefits such as improvements in quality of water and air, and reduction in risks of non-point source pollution and damage to infrastructure and coastal ecosystems. The rate of soil organic carbon (SOC) sequestration is about 250 to 1000 kg/ha/yr in humid temperate climates and about 50 to 250 kg/ha/yr in arid tropical regions. Removal of crop residues as a source of biofuel (with energy value of 2 barrel of diesel equivalent and 1.86 x 10^9 J per Mg of residue) can have severe adverse impacts on the quality of soil and environments. Lack of adoption of NT/CA in developing countries is due to removal of crop residues for other competing uses. An important strategy is to compensate farmers through trading of C credits. To be effective, however, the societal value of C sequestered in soil must be fair and transparent and based on all ecosystem services.

INTRODUCTION

Atmospheric concentration of CO_2 has increased from ~ 280 ppm in pre-industrial era to ~ 385 ppm in 2008 (+ 37.5%) and is presently increasing at the rate of ~ 2 ppm/yr or 3.5 Pg/yr (1 Pg or pentagram = 1 Gt = 1 gigaton = 1 billion metric ton). The increase in CO_2 emission by human activity is attributed to fossil fuel combustion, deforestation and biomass burning, soil cultivation and drainage of wetlands or peat soils. Increase in fossil fuel combustion is caused by high global energy demand of 475 Quads (1 quad = 10^{15} BTU) and increasing at the rate of ~ 2.5 %/yr, especially in emerging economies including China, India, Mexico, Brazil, etc. There exists a strong positive correlation between population growth on the one hand and CO_2 emission or the energy demand on the other. The world population of 6.7 billion in 2008 is increasing at the rate of 1.3%/yr and is projected to be 9.5 billion by 2050 before stabilizing at ~ 10 billion towards the end of the 21st century.

Because of the anthropogenic perturbations of the global C cycle, there are serious concerns about the risks of global warming and the attendant sea level rise. Thus, identifying viable sinks for atmospheric CO_2 is a high priority with the objective of sequestering it into other C pools with long residence time. Several options of CO_2 sequestration being considered are geologic, oceanic, chemical transformations and terrestrial. In contrast to the engineering techniques (e.g., geologic), C sequestration in terrestrial ecosystems is a natural process. It is also cost-effective and has numerous ancillary benefits (Lal, 2008a).

Carbon sequestration in terrestrial ecosystems has two distinct but related components: sequestration in biomass (primarily trees comprising both the above ground and below ground components) and soil. A fraction of the biomass returned to the soil is converted into stable humic substances and related organo-mineral complexes with a long residence time. The effectiveness of soil C sequestration depends on the quantity and quality of biomass returned to the soil. In cropland soils, a principal source of biomass is the crop residues. Therefore, the objective of this manuscript is to discuss the impact o crop residues management on soil C dynamics, and the potential of residue management on off-setting industrial emissions, stabilizing atmospheric concentration of CO_2, and improving agronomic/food production.

STRATEGIES OF STABILIZING ATMOSPHERIC CO_2 BY MANAGING AGRICULTURAL ECOSYSTEMS

Agricultural activities have been a principal source of CO_2 emissions, along with those of CH_4 and N_2O. Yet, properly managed, agriculture can be a solution to numerous environmental problems such as global warming. The schematics in Fig. 1 show strategies of reducing net CO_2 emissions by implementing several mitigation and adaptation options. The mitigation options can be grouped under 2 categories: reducing emissions and sequestering emissions. Improving use efficiency of input, minimizing soil erosion, conserving energy and growing aerobic rice (rather than continuously flooded paddy) , integrated nutrient management (INM), and integrated pest management (IPM) are among some of the promising options of reducing emissions. Similarly, there are several opportunities of sequestering CO_2 including afforestation, restoration of degraded/desertified soils, and integrated no-till (NT) farming systems (CA). Agricultural activities can also be adapted to minimize adverse effects of global warming on agronomic productivity and the environment. Adaptation strategies can be grouped under two categories of crop management and soil management. Some examples of crop management are time of planting, soil water management comprising of drainage or irrigation as needed, choice of crops and cultivars through breeding for biotic and abiotic stresses, and improving pastures by changing species and using improved management. Similarly, examples of soil management to adapt to the projected climate change include conversion to NT or conservation agriculture (CA), precision warming, water harvesting and recycling to minimize the intensity and duration of drought, and providing a continuous soil cover either as plastic mulch or crop residue mulch (Fig. 1). Identification and implementation of mitigation and adaptation strategies over large areas in agricultural ecosystems can be an important step towards an attempt to stabilize atmospheric concentration of CO_2 and other greenhouse gases (GHGs).

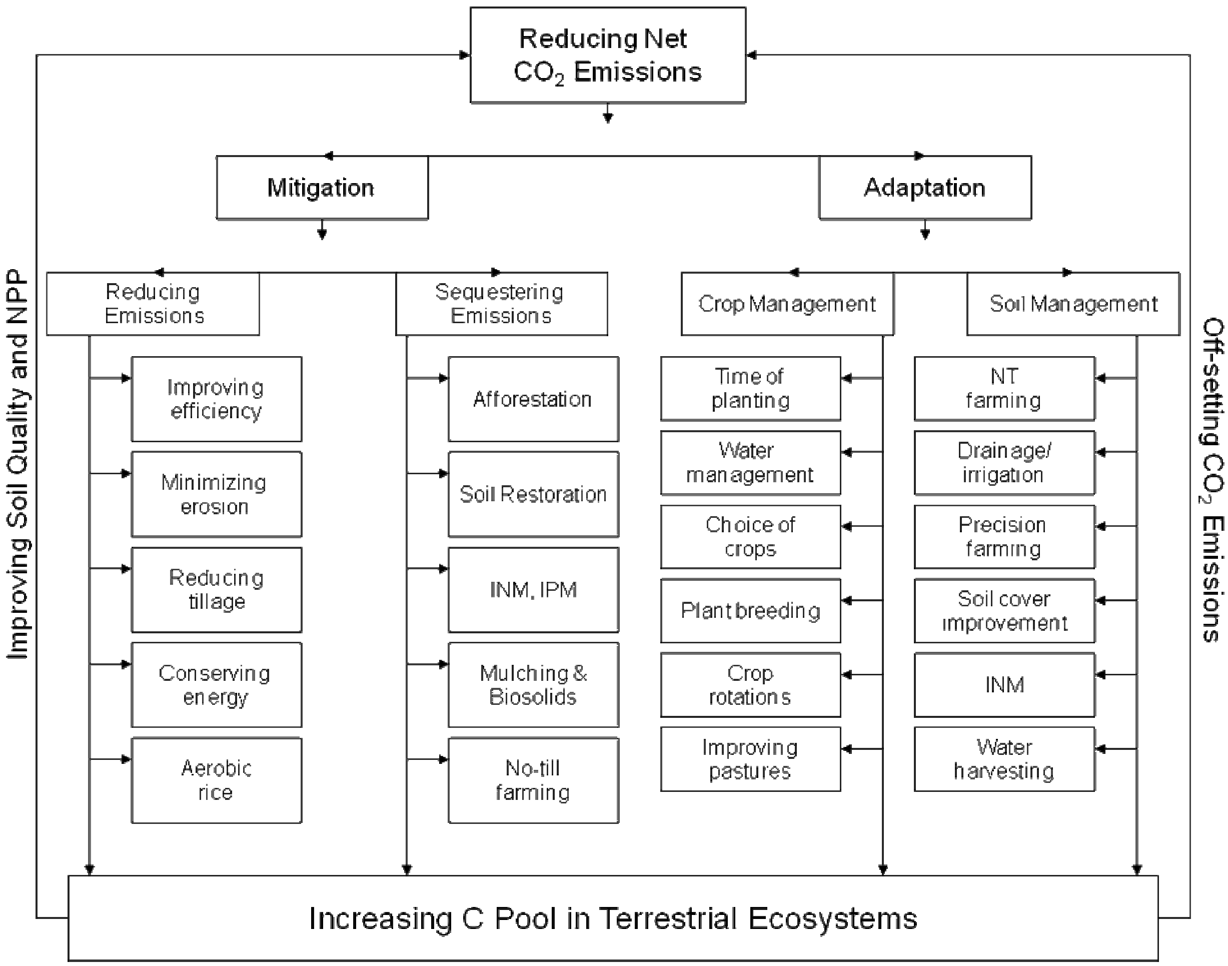

Fig. 1 Strategies of reducing net CO2 emission by sustainable management of agricultural and forestry ecosystems.

SOIL CARBON SEQUESTRATION

World soils constitute the third largest global C pool, comprising of two distinct components: (i) soil organic C (SOC) estimated at 1550 Pg, and (ii) soil inorganic C (SIC) pool estimated at 950 Pg, both to 1-m depth. Other pools include the oceanic (38,400 Pg), geologic/fossil fuel (4500 Pg), biotic (620 Pg), and atmospheric (750 Pg) (Lal, 2004a). Thus, the soil C pool of 2500 Pg is 3.3 times the atmospheric pool and 4.0 times the biotic pool. However, soils of the managed ecosystems have lost 50 to 75% of the original SOC pool. Conversion of natural to managed ecosystems depletes SOC pool because C input into the agricultural ecosystems is lower, and losses due to erosion, mineralization and leaching are higher than those in the natural ecosystems. The magnitude of SOC depletion is high in soils prone to erosion and those managed by low-input or extractive farming practices. The loss of SOC pool is also high in soils of coarse texture and those with a high initial pool. Most agricultural soils have lost 20 to 40 Mg C/ha due to historic land use and management.

The maximum soil C sink capacity, amount of C that can be stored in it, approximately equals the historic C loss. In other words, most agricultural soils now contain lower SOC pool than their capacity because of the historic loss. The maximum soil C pool is determined by the climate, parent material, physiography, drainage, and soil properties including clay content, clay minerals, and nutrient reserves. Soil drainage and moisture regime, along with soil aspect and landscape position, are important controls of soil C pool.

The SOC pool is at a dynamic equilibrium under a specific land use and management system. At equilibrium, the C_{input} into a system equals C_{output}. Upon conversion to another land use and management, depletion of SOC pool occurs if $C_{input} < C_{output}$, and sequestration if $C_{input} > C_{output}$ (Eq. 1 to Eq. 3).

Steady state . . . . $C_{input} = C_{output}$ . . . . Eq. 1

Depletion . . . . $C_{input} < C_{output}$ . . . . Eq. 2

Sequestration . . . . $C_{input} > C_{output}$ . . . . Eq. 3

Land use and soil management techniques which lead to C sequestration are retention of crop residues, NT farming and incorporation of cover crops in a diversified rotation cycle (together also referred to as CA), INM techniques of using compost and other biosolids, erosion control, water conservation, contour hedges with perennials, controlled grazing, etc. An average long-term rate of SOC sequestration with these techniques is 200 to 1000 kg/ha/yr for humid temperate regions and 50 to 250 kg/ha/yr for dry tropical regions. In addition, the rate of SIC sequestration as secondary carbonates is about 5 to 25 kg/ha/yr in arid and semi-arid regions. In contrast, depletion of SOC pool occurs with the use of excessive plowing, residue removal and biomass burning, and extractive farming practices where nutrient balance is often negative.

CROP RESIDUES MANAGEMENT

Crop residues include any biomass left in the field after grains and other economic components have been harvested. The aboveground components of crop residues include shoot, leaves, cobs, husk, etc. The amount of crop residues produced in 2001 was estimated at ~0.5 x 10^9 Mg/yr in the USA (Table 1) and ~ 4 x 10^9 Mg/yr in the world (Lal, 2005; Table 2). About 75% of the residues produced, both in the USA and world and elsewhere, is that from cereals (e.g., corn, rice, wheat, sorghum, millet, barley, rye). For example, the data in Table 3 show that rice and rice-based cropping systems produce ~ 0.6 x 10^9 Mg/yr of crop residues in the tropics.

Table 1 Estimates of the amount of crop residues produced in the U.S. in 1991 and 2001 (Adapted from Lal, 2005).

Crop	Estimates of Residues (10^6 Mg/yr)	
	1991	2001
Cereals	325	367
Legumes	58	82
Oil crops	17	20
Sugar crops	25	14
Tubers	5	5
Total	430	488

Table 2 Estimates of the amount of crop residues produced in the world in 1951 and 2001 (Adapted from Lal, 2005).

Crop	Estimates of Residues (10^6 Mg/yr)	
	1991	2001
Cereals	2563	2802
Legumes	238	305
Oil crops	162	108
Sugar crops	340	373
Tubers	145	170
Total	3448	3758

Table 3 Estimates of crop residues production in the rice and rice-based cropping systems in the tropics and the world (Adapted from Singh et al., 2005).

Region	Residue Produced (10^6 Mg/yr)
Asia	166
Africa	39
South America	55
Sub-Total Tropics	260
World Total	604

There are numerous ecosystem services of residue retention on cropland, especially if maintained as surface mulch (Fig. 2). On-site, residues retention improves soil physical (e.g., structure, infiltration rate, plant available water capacity), chemical (e.g., nutrient cycling, cation exchange capacity, soil reaction), and biological (e.g., SOC sequestration, microbial biomass C, activity and species diversity of soil biota) quality. Mulches are effective against soil erosion, and in decreasing losses of water by surface runoff and evaporation. Consequently, agronomic productivity and profitability are high with use of crop residues in conjunction with NT in CA. Off-site, mulch farming through residues retention and a NT system improve quality of water and air through reduction in erosion (water and wind), non-point source pollution, sedimentation, and transport of pollutants into the water bodies and aquatic ecosystems. Furthermore, reduction in frequency and intensity of floods causes minimal damages to infrastructure (e.g., highways, bridges, waterways) and tourism. Productivity of aquaculture and agricultural systems in the flood plains is improved because of less runoff of water, sediments and pollutants. In essence, retention of residues promotes sustainable land because of positive impacts on the environment and ecosystem services (Fig. 2).

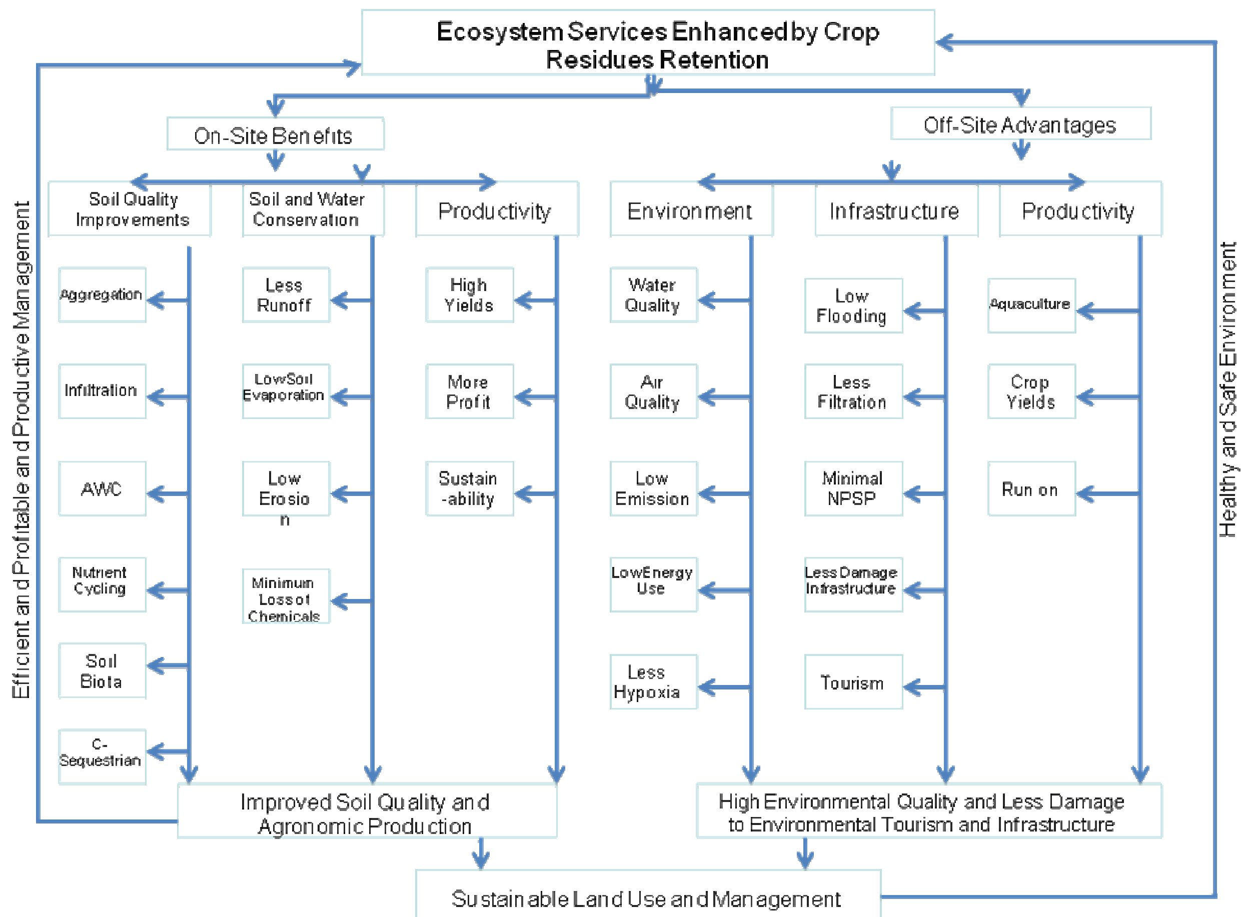

Fig. 2 Agronomic productivity and environmental quality impacts of crop residues retention (AWC = available water capacity, NPSP = non-point source pollution).

Positive impacts of crop residue retention on soil quality are partly due to nutrients recycled into the soil. On average, crop residues contain ~ 0.8 % N, 0.1 % P and 1.3% K (Table 4). Therefore, amount of NPK contained in crop residues produced is about 11 x 10^6 Mg in USA and 81 x 10^6 Mg in the world. (Table 5). Consequently, the long-term impacts of residues retention on soil quality are both due to elemental cycling and to providing food (energy source) and habitat for soil biota, especially micro-organisms and earthworms.

Table 4 Nutrient concentration in residues of some common crops (http://www.nres.usda.gov/TECHNICAL/ECS/nutrient/tbb1.html).

	Nutrient Concentration in residues (%)

Crop	N	P	K
Alfalfa (hay)	2.789	0.261	2.119
Barley	0.683	0.096	1.794
Canola	0.560	-	-
Corn	0.983	6.100	1.504
Cotton	0.986	-	-
Millet	0.678	-	1.600
Oats	0.708	0.085	2.389
Peanuts	1.643	0.143	0.138
Rice	0.704	0.091	1.477
Rye	0.503	0.094	0.970
Sorghum	0.768	0.115	1.010
Soybean	0.786	0.059	0.572
Wheat	0.611	0.064	1.174
Average (without alfalfa)	0.801	0.094	1.263

Table 5 Estimates of total amount of N,P, and K contained in the crop residues produced in the world and USA in 2001 (Estimated from Tables 1, 2 and 4).

Region	**Nutrients (10^6 Mg/yr)**			
	N	**P**	**K**	**Total**
USA	3.9	0.5	6.2	10.6
World	30.1	3.5	47.5	91.1

Crop residues are also a principal source of C, which constitutes about 40% of the total biomass on dry weight basis. Therefore, total amount of C assimulated in crop residues is about 0.2 Pg/yr in USA and 1.6 Pg/yr in the world. Increase in rate of application of biomass C increases the SOC pool (Fig. 3). The magnitude of increase in SOC pool, however, depends on other management input used in conjunction with crop residues mulch (e.g., depicted as Management 1,2 and 3 in Fig. 3). Components of the management packages may differ with increase in the rate of input of biomass C into the system. Because C is only one of the building blocks of stable humus and humic substances (which are enriched with N,P,S and other elements compared with crop residues), application of N and other elements can enhance the humification. Jacinthe et al. (2002) observed that fertilization of wheat residues with N increased humification of biomass and enhanced the C sequestration rate of the soil in central Ohio, USA.

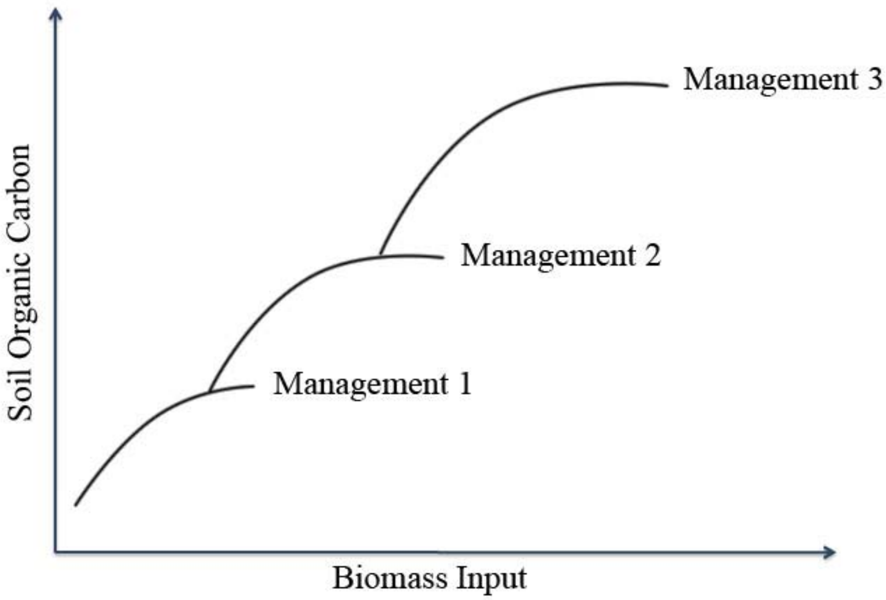

Fig. 3 Strategies of carbon sequestration in soil when marginal increase becomes low or negative, the management system must be replaced to create a positive C budget and increase humification.

COMPETING USES OF CROP RESIDUES

Crop residues are a precious commodity, and must never be considered as waste (Lal, 2004b). Residues have numerous competing uses including for feed, fodder, and fuel. Residues have been traditionally used as a household and industrial fuel (combustion with coal, wood, etc). Because of the high C content, residues have assimulated a large amount of solar energy. Energy equivalent of crop residues is estimated at about 2 barrels of diesel or 18.6 x 10^9 J per Mg of dry biomass (Weisz, 2004). Therefore, energy potential of crop residues for USA and world, respectively, is about 1 x 10^9 and 8 x 10^9 barrels of diesel, or 9 and 70 EJ (Table 6). It is because of its high energy value that crop residues as biofuels are considered an alternative to fossil fuel (Somerville, 2006; Lal, 2008b). However, environmental, agronomic and economic impacts of residue removal as biofuel feedstock must be critically and objectively assessed prior to installing numerous cellulosic ethanol production units.

Table 6 Estimates of total energy and C contained in crop residues produced in the world and USA.

Region	C pool (Tg C/yr)	Energy Content	
		10^9 Bbl of diesel/yr	EJ/yr
USA	200	1	9
World	1500	8	70

Assuming that crop residues contain 40% C, and the energy value per Mg of residue is 2 bbl of diesel or 18.6 x 10^9 J (Weisz, 2004).

ADVERSE IMPACTS OF RESIDUES REMOVAL FOR COMPETING USES

Agronomists and soil scientists, in view of numerous ecosystem services of residues retention, argue that there is no such thing as a free biofuel from crop residues (Lal, 2007a; Lal and Pimentel, 2007). There are numerous direct and indirect adverse impacts of residue removal on ecosystem services, including depletion of the SOC pool (Fig. 4). Important among direct impacts of residue removal are low input of biomass C, reduction in nutrient/elemental cycling, decrease in food/energy source and habitat for soil biota along with the attendant decline in soil quality. There are also numerous indirect impacts of residue removal. Notable among these are increase in risks of soil erosion and runoff because of decrease in aggregation and increase in soil's susceptibility to crusting and compaction. The loss of water and nutrients from the ecosystems also decreases crop growth and yields and reduces agronomic productivity. Several experiments on removal of crop residues have indicted the adverse impacts as outlined in Fig. 4 (Wilhelm et al., 2004; Blanco-Canqui et al., 2006; 2007; Blanco-Canqui and Lal, 2007). Mann et al.(2002) argued that more research information is needed on several topics to determine potential long-term effects of residue harvest, including (1) erosion and water quality, especially pesticides and nitrates,(2) rates of transformation of different forms of SOC, (3) effects on soil bioata, and (4) SOC dynamics in subsoil. Yet, biofuels are also important to minimizing the use of fossil fuels, and other sources of biofuel feedstock must be identified. Other sources include establishment of energy plantations (e.g., warm season grasses, short rotation woody perennials, algae, cynobacteria, halophytes grown with brackish water) in such a way that there is no competition for land and water needed for food production (Lal,2008c).

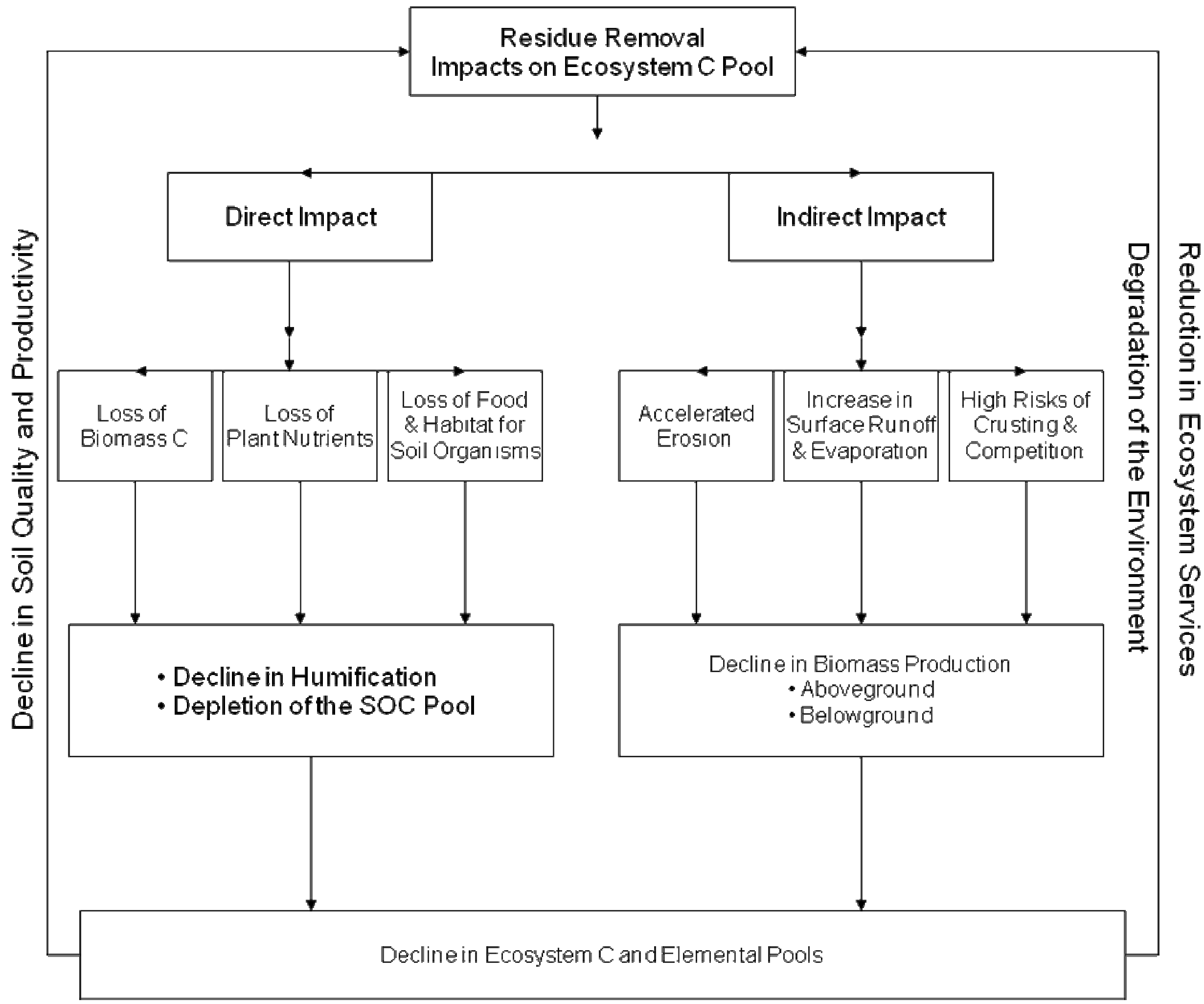

Fig. 4 Adverse impacts of crop residues removal on depletion of the ecosystem carbon pool, decline in ecosystem services, and degradation of the environment.

LINKING GLOBAL FOOD SECURITY AND CLIMATE CHANGE TO SOIL QUALITY IMPROVEMENT WITH CROP RESIDUE MANAGEMENT

There are about 850 million food-insecure people in the world (Borlaug, 2007), and an additional 3.7 billion are prone to hidden hunger and malnutrition due to deficiency of minerals (e.g., Zn, Cu, Se, I, B) and vitamins because food is grown on degraded soils. Most of the food-insecure people live in Sub-Saharan Africa (SSA) and Asia. The Green Revolution of the 1960s and 1970s that saved hundreds of millions from starvation in Asia and elsewhere by-passed SSA because soils of the region are severely degraded (Lal, 2008c). Resource-poor farmers and small land holders of SSA and Asia remove crop residues for use as fodder, fuel, construction material and other competing uses. Furthermore, most soils have extremely low levels of SOC concentration (< 0.5% in contrast to critical level of 1.1%). In addition, the negative nutrient budget of – 30 to – 40 kg/ha/yr of NPK on continental scale is exacerbated by residue removal and the attendant increase in soil erosion hazard. Adverse agronomic and environmental impacts are confounded by the use of animal dung as household fuel rather than as soil amendment. The data in Table 7 from a long-term experiment conducted on Alfisols in Western Nigeria, show that even the use of NT farming on a relatively flat terrain (< 1% slope gradient) caused severe decline in soil quality because of the residue removal. Despite the application of chemical fertilizers at recommended rates and use of improved crop varieties, soil quality deteriorated (e.g., decline in SOC concentration, soil pH, exchangeable cation, CEC). There was also a strong increase in bulk density and decrease in infiltration rate and AWC (Lal, unpublished data). Consequently, maize yields in the first growing season, after 13 consecutive years of growing 2 crops per year, was 2.7 Mg/ha with residue retention compared with 1.5 Mg/ha with residue removal (Table 7; Juo et al., 1995; 1996). It is apparent therefore, that the agronomic benefits of improved crop varieties and fertilizer input cannot be realized unless soil structure and hydrologic properties are improved with residue retention and application of other biosolids as amendments.

Table 7 Effects of residue removal for 13 consecutive years on soil properties and corn grain and stover on yields on an Alfisol in Western Nigeria (Adapted from Juo et al., 1995; 1996).

Soil Properties	With Residue Mulch	Residue Removal	LSD (.05)
Soil organic carbon (g/kg)	14.5	12.5	4.0
Soil pH	5.1	4.6	0.30
Exchangeable Ca^{+2} ($cmol_c$/kg)	3.6	1.2	1.4
Exchangeable Mg^{+2} ($cmol_c$/kg)	0.4	0.25	0.35
CEC ($cmol_c$/kg)	4.5	2.9	1.7
Grain yield (Mg/ha)	2.7	1.5	0.4
Stover yield (Mg/ha)	2.6	1.3	0.8

CONSTRAINTS TO ADOPTING NO-TILL FARMING AND CONSERVATION AGRICULTURE INDEVELOPING COUNTRIES

Beneficial impacts of converting plow tillage to NT farming and CA have been documented since the 1960s in North America and the 1970s in Africa and elsewhere. Yet, the cropland area under NT farming is ~ 100 x 10^6 ha or about 6 to 7 % of the global crop land area. Most of the NT is practiced by large scale commercial farms in USA, Brazil, Argentina, Australia, Canada, etc. It has been ignored by the small scale and resource-poor farmers of SSA and Asia, where it is needed the most. Indeed, there are numerous constraints to adopting NT and

CA in developing countries (Lal, 2007b). There are some biophysical constraints which indicates that NT is not a panacea, and cannot be adopted directly to all soils and edephic/physiographic environments. Initial crop yields with NT farming can be low in heavy-textured soils containing predominantly high activity clays and prone to waterlogging, in silty textured soils containing predominantly low activity clays and prone to crusting/compaction and hard setting, and in regions where spring time soil temperatures are sub-optimal and high wetness and anaerobiosis increase risks of mold, pests and pathogens, and slugs requiring other complementary measures. There are also social, economic and policy issues that inhibit adoption of NT and CA. The impact of land tenurial factors is confounded by infertile soils and removal of crop residues for quick economic gains by selling it as livestock fodder. Small land holders also do not have access to herbicides and NT seeders, and there is an increase in incidence of weeds (especially perennials) in the absence of mulch cover and chemical/biological weed control measures. Under these conditions, loosening soils by any tillage has short-term benefits on crop growth and yields. In the long-term, however, farmers and society pay a heavy price for use of crop residues and animal dung as fuels in terms of soil and environmental degradation.

TRADING CARBON CREDITS AS AN INCENTIVE TO ADOPTING NT FARMING AND CA

Giving handout as emergency aid, useful and humanitarian as it is over the short-term, is a symptomatic treatment of the problem and does not address the underlying causes of agrarian stagnation/decline and the perpetual food deficit in SSA and elsewhere in the developing countries. The long-term strategy is to establish biofuel plantations (e.g., warm season grasses, short rotation woody perennials, algae, cyanobacteria, halophytes), explore alternate sources of energy (e.g., wind, solar), incorporate forages in the rotation cycle so that animals/livestock and trees are closely integrated with the prevalent crop production systems.

In the meanwhile, desperate and resource-poor farmers need incentives to adopt, NT/CA and other recommended management practices (RMPs). Trading C credits is one possibility, either through the Kyoto Treaty (e.g., CDM), voluntary markets (e.g., Chicago Climate Exchange), or the World Bank (e.g., Bio Carbon Fund). The current price of C in the voluntary market of \$1.5 to \$2/ Mg of CO_2 or \$5.5 to \$7.3/Mg of C, provides farmer a gross income of only \$1.50 to \$3.5/ha/yr. With a farm size of 0.25 to 0.5 ha, an annual income of \$0.4 to \$1.5 is neither an incentive nor an economic source of income. There will be few takers, in developed and developing economies, who will convert to NT farming and CA for \$1.5 to \$3.5/ha/yr grains through trading of C credits.

It is important, therefore, that a fair and transparent value of soil C is determined through its societal benefits to the environment (e.g., climate change, water quality, biodiversity, sedimentation). Considering the inherent values of nutrients (N, P, K, Zn) and water contained in 1 kg of humus, the gross value of C in soil humus is about \$250/ Mg of C. Given that market forces have a strong impact on the price (especially in the absence of emission caps), the ecosystem services provided by SOC sequestration must never be ignored. Just as bailing out banks/ Wall Street and large corporations (e.g., GM) is important to lifting the sagging economy, so is providing a fair price to farmers for C sequestered in soil to advancing food security, mitigating climate change, and improving the environment.

CONCLUSIONS

Benefits of NT farming and CA to SOC sequestration, climate change mitigation, advancing food security and improving the environment depend on retention of crop residues as mulch. Using crop residues for competing uses (e.g., fuel, fodder, industrial and construction material) has adverse impacts on soil quality and agronomic productivity. Among numerous biophysical and socio-economic and political constraints to adopting NT/CA, removal of crop residues is an important non-tenurial factor. Beneficial impacts of residue retention are especially high to resource-poor and small size land holders of the developing countries who cannot afford the off-farm input of fertilizers, herbicides, etc. Carbon farming, treading C credits as another income stream, is an important strategy to provide incentives for promoting adoption of NT/CA and other RMPs. For C trading to be effective, it is important to establish the fair/transparent value of C based on the societal values and ecosystem services.

REFERENCES

Blanco-Canqui, H., and R. Lal. 2007. Soil and crop response to harvesting corn residues for biofuel production. Geoderma 141: 355-362.

Blanco-Canqui, H., R. Lal, W.M. Post, R.C. Izaurralde, and L.B. Owens. 2006. Corn stover impacts on near-surface soil properties of no-till corn in Ohio. Soil Tillage Res. 92: 144-155.

Borlaug, N.E. 2007. Feeding a hungry world. Science 318, 359.

Jacinthe, P.A., R. Lal, and J.M. Kimble. 2002. Effects of wheat residue fertilization on accumulation and biochemical attributes of organic carbon in a central Ohio Luvisol. Soil Sci. 167: 750-758.

Juo, A.S.R., K. Franzluebbers, A. Dabiri, and B. Ikhile. 1995. Changes in soil properties during long-term fallow and continuous cultivation after forest clearing in Nigeria. Agric. Ecosys. Env. 56: 9-18.

Juo, A.S.R., K. Franzluebbers, A. Dabiri, and B. Ikhile. 1996. Soil properties and crop performance on a kaolinitic Alfisol after 15 years of fallow and continuous cultivation. Plant Soil 180: 209-217.

Lal, R. 2004a. Soil carbon sequestrian impacts on global climate change and food security. Science 204: 1623-1627.

Lal, R. 2004b. Is crop residue a waste? J. Soil Water Consv. 59: 136-139.

Lal, R. 2005. World crop residues production and implication of its use as a biofuel. Env. Intl. 31: 575-586.

Lal, R. 2006. Enhancing crop yields in developing countries through restoration of soil organic carbon pool in agricultural lands. Land. Degrad. & Dev. 17: 197-209.

Lal, R. 2007a. There is no such thing as a free biofuel from crop residues. CSA News 52(5):12-13.

Lal, R. 2007b. Constraints to adopting no-till farming in developing countries. Soil Tillage Res. 94: 1-3.

Lal, R. 2008a. Carbon sequestrian. Phil. Trans. R. Soc. B. 363:815-830.

Lal, R. 2008b. Crop residues as soil amendments and feedstock for bioethanol production. Waste Manage. 28: 747-758.

Lal, R. 2008c. Food insecurity's dirty secret. Science 322: 673-674.

Lal, R. and D. Pimentel. 2007. Biofuels from crop residues. Soil Tillage Res. 93: 237-238.

Mann,L.,V.Tolbert and J.Cushman.2002.Potential environmental effects fo corn(Zea mays L.)stover removal on soil organic matter and erosion.Agric.Ecosyst.& Env.89:149-166.

Singh, Y., B. Singh, and J. Timsina. 2005. Crop residue management for nutrient cycling and improving soil productivity in rice-based cropping systems in the tropics. Adv. Agron. 85: 269-407.

Somerville, C. 2006. The billion-ton biofuel vision. Science 312: 1277.

Weisz, P.B. 2004. Basic choices and constraints in long-term energy supplies. Phys. Today 57: 47-52.

Wilhelm, W.W., J.M.F. Johnson, J.L. Hatfield, W.B. Vorhees, and D.R. Linden. 2004. Crop and soil productivity response to corn residue removal: a literature review. Agron. J. 78: 184-189.