Platinum Jubilee Celebrations of the Indian Society of Soil Science
Souvenir, pp 39-46

Soil Carbon Sequestration for Climate Change Mitigation and Food Security

R. Lal

Carbon Management and Sequestration Center, Ohio State University, Columbus, OH 43210, USA

Introduction

Important among inter-related issues of global significance are: (i) climate disruption, (ii) food insecurity, (iii) environmental degradation including desertification, and (iv) energy crisis. These are among inter-twined global scale challenges driven by anthropogenic perturbances (Walker et al., 2009) (**Figs. 1 and 2**). All these four issues are driven by the increase in World's population, which is 6.7 billion in 2009 and may increase to 9.2 billion by 2050. It is the strong reliance on fossil fuel which is responsible for drastic increase in atmospheric concentration of CO_2 and other greenhouse gases (GHGs). Sources of all GHGs are fossil fuel combustion, cement manufacture, deforestation along with biomass burning and soil cultivation, nitrogenous fertilizer application, drainage of peatlands and extractive farming practices. Two principal sources of anthropogenic emissions are: (i) fossil fuel combustion and cement manufacture estimated at ~8 Pg C/yr, and (ii) change in land use, drainage of peat lands and soil cultivation estimated at 1.6 Pg C/yr (IPCC, 2007). Principal sinks of CO_2 include uptake by the atmosphere (3.3 Pg C/yr), ocean (2.2 Pg C/yr), vegetation (1.5 Pg C/yr) and land-based sinks (2.6 Pg C/yr) (Normile, 2009; IPCC, 2007). There are numerous uncertainties in these estimates, especially about the sinks. It is difficult to quantify how much C is going and where. Similarly, there are uncertainties about the magnitude of emissions through deforestation and land use conversion. These estimates could be off by as much as 100% (Normile, 2009).

Fig. 1. Emerging global issues of the 21st century driven by high demographic pressure and increasing demands on natural resources

Concentration of CO_2 in the atmosphere has increased from 280 ppm in the pre-industrial era (~1750) to 385 ppm in 2009 (Normile, 2009), and is presently increasing at the rate of about 2 ppm/yr (0.50 %/yr) (WMO, 2008). Atmospheric concentration of CH_4 has increased from the pre-industrial level of 700 ppb to 1789 ppb, at the rate of 13 ppb during the late 1980s, and 6 ppb from 2006 to 2007 (0.34%/yr). Similarly, the concentration of N_2O has increased from 270 ppb in pre-industrial era to 321 ppb in 2007, and is increasing at the rate of 0.8 ppb/yr (0.25%/yr) (WMO, 2008). Because of the increase in concentration of GHGs, mean earth's temperature has already increased by 0.6 ± 0.2 °C, and is projected to increase by 2 to 4 °C towards the end of the 21st

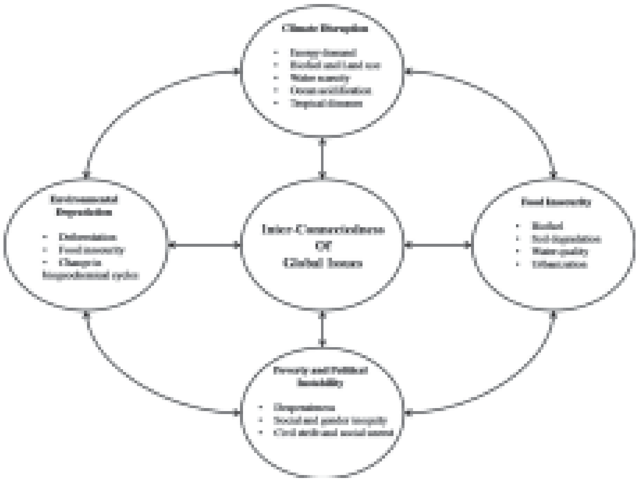

Fig. 2. Everything is connected to everything else

Fig. 3. Convergence of climate disruptions, increase in demand, emphasis on biofuels and decline in agricultural production on food security

century under the business as usual scenario (IPCC, 2007). With projected climate change, there are likely risks of increase in frequency and intensity of extreme events (e.g., drought), decrease in rainfall effectiveness, increase in incidence of pests and pathogens, reduction in net primary productivity (NPP), and decrease in crop yield and agronomic production.

The issue of food-insecurity is strongly intertwined with that of the climate disruption and other anthropogenic perturbations of natural ecosystems (**Fig. 3**). In broader terms, food insecurity involves low agronomic production, lack of access to food caused by poverty, nutritional inadequacy and low safety, and inability to utilize food because of poor health. Climate disruption affects agronomic production through adverse changes in temperature and precipitation which alter the growing season duration, affect intensity and frequency of drought and other extreme events, exacerbate incidence of pests and pathogens, and increase magnitude of biotic and abiotic stresses. Demand on biofuels, driven by an insatiable need for energy, is strongly impacting prices of food staples (e.g., corn, soybean). Indeed, agro-fuels may exacerbate food price instability and worsen food insecurity for poor people throughout the world (Koning and Mol, 2009).

The objective of this article is to review the food-insecurity hotspots of the world, discuss the impact of projected climate change, and outline the role of soil C sequestration (SCS) in advancing food security while mitigating the climate change.

Global Hot Spots of Food Insecurity

Number of food-insecure people in the world has increased to 1020 million (FAO, 2009), and the U.N. Millennium Development Goals of cutting hunger to half by 2015 will not be met. Increase in prices of food staples in 2007-08 has reduced the access to food and exacerbated food insecurity for poor people around the world. Over and above the problem of access to food, the supply of food is also limited by soil degradation, especially that caused by accelerated erosion, nutrient deficiency, and the depletion of soil organic carbon (SOC) pool. Regions with a severe problem of food insecurity include South Asia (or SA comprising of Afghanistan, Pakistan, India, Nepal, Bhutan, Bangladesh and Sri Lanka) (FAO, 1996; Banik, 2007; Agarwal et al., 2009), and Sub-Saharan Africa (SSA) (Anonymous, 2009). Farmers in SA and SSA are small landholders, resource-poor and highly vulnerable to climate-related and other natural and anthropogenic disruptions. The data in **Table 1** indicate per capita cereal production in several regions of SA and SSA in 2007 and the projected per capita cereal production in 2030, along with the per capita cropland area harvested in 2007. The subsistence level threshold of per capita availability of cereals is 190 kg ha^{-1} (Funk and Brown, 2009). With this criterion, those regions which will face a serious challenge of food-insecurity through 2030 and beyond, are SA and the entire continent of SSA (**Table 1**). Whereas the per capita food production will decline in all regions of SA, the production is below the threshold optimum in Western Asia (160 kg/person) and SA (193 kg/person). Assuming that access to food through better income can make a major impact in reducing regional and local food production gaps, food insecurity is not an issue in Western Asia because of the oil-based revenue. However, food-insecurity will remain a serious issue in SA. By 2050, the number of food-insecure people in SA may increase to 373 million, and the per capita production levels may reach similar to those of the 1960s and 1970s (Funk and Brown, 2009). The problem of food-insecurity is even more daunting in SSA where the per capita cereal production is below the threshold level (190 kg/person) in 2007 and is projected to decrease more drastically by 2030 (**Table 1**). The problem may be exacerbated by the projected climate change and the increase in drought stress (Verhagen et al., 2004), and the attendant increase in risks of soil degradation and land desertification.

Strategies of Advancing Food Security while Mitigating Climate Change

Improving agricultural production is the basic strategy for both advancing food security and mitigating climate change. Indeed, agriculture must be the engine of economic development in SA, SSA,

Table 1. Per capita cereal production in 2007 and 2030 in different regions of Asia and the World (Modified from Funk and Brown, 2009)

Region	Per Capital Cereal Production (kg ha^{-1})		Per Capita Cropland Area (ha)
	2007	2030	2007
World	354	306	0.11
North America	1374	1236	0.23
Asia			
Eastern Asia	314	276	0.06
Southern Asia	231	193	0.09
South-Eastern Asia	368	356	0.10
Western Asia	204	160	0.10
Central Asia	541	-	0.32
Sub-Saharan Africa			
Eastern Africa	131	84	0.09
Middle Africa	62	38	0.06
Northern Africa	190	180	0.11
Southern Africa	182	189	0.07
Western Africa	189	166	0.16

and elsewhere in the developing world. It is difficult to achieve poverty reduction without prior investment in agriculture (Lipton, 2005), especially in countries where majority of the population is rural and is dependent on agriculture. Developing countries in SA, SSA and elsewhere may not be able to advance economically and industrially without replacing extractive and subsistence farming (Katers, 2000; Funk and Brown, 2009) by science-based agriculture comprising of proven technologies and recommended management practices (RMPs). In addition to advancing food security and alleviating poverty, raising low crop yields, and breaking the agronomic barriers in SA and SSA (especially in rainfed/dry farming agroecosystems), SCS may also be the judicious strategy to adapt to climate change. The fact is that even the modest increase (20% to 30%) in production in rainfed agriculture in SA and SSA through SCS can have a drastic positive impact on the standard of living and wellbeing of hundreds of millions of people now living below the poverty line.

Adaptation to Climate Change

Strategies for adaptation to climate change, reducing risks to agriculture by adverse changes in growing season through alterations in precipitation and temperature regimes, are different at farm, national and global scales (**Fig. 4**). At the farm level, the goal is to improve soil quality and adjust farming operations to buffer against the adverse effects of climatic disruption. Improvements in soil quality can be brought about by RMPs of soil management such as mulch farming (Acharya and Sharma, 1994), conservation agriculture (Acharya et al., 1998), integrated nutrient management (INM), water harvesting and recycling through drip sub-irrigation (DSI) and judicious landscape management. Increasing fertilizer/N use efficiency, which in India decreased from 60 kg grain/kg of N applied in 1980 to 25 kg grain/kg of N applied in 2005 (IFA, 2007), is essential to increasing crop yields per unit consumption of energy-based inputs. Replacement of flooded rice by aerobic rice is important for saving water and sustaining crop yields (Kreye et al., 2009; Bouman et al., 2007; Ladha et al., 2009). Application of biosolids as soil amendments (e.g., compost, manure) is extremely important to improving productivity (Bejbaruha et al., 2009), and creating a positive C budget and enhancing the ecosystem C pool. Growing improved varieties (including GM crops) and selecting alternate crops which create diverse cropping/farming systems are essential to enhancing soil resilience. Climate change will create numerous opportunities of growing alternate crops, and availing such an opportunity can improve household income, enhance production, and increase access to food.

There are essential conditions of enhancing adaptation to climatic disruption at the national level. Important among these are political, economic and social stability, investments in agriculture, strengthening institutional support, and improving access to market and credit. At the global scale, the strategy is to restore degraded soils and desertified ecosystems, create opportunities for clean development mechanisms (CDM), formulate and implement World Soil Policy, and enhance ecosystem resilience (**Fig. 4**). It is important to commoditize soil C, so that it can be traded as any other farm commodity. It is better to reward farmers for delivering ecosystem services (e.g., C sequestration,

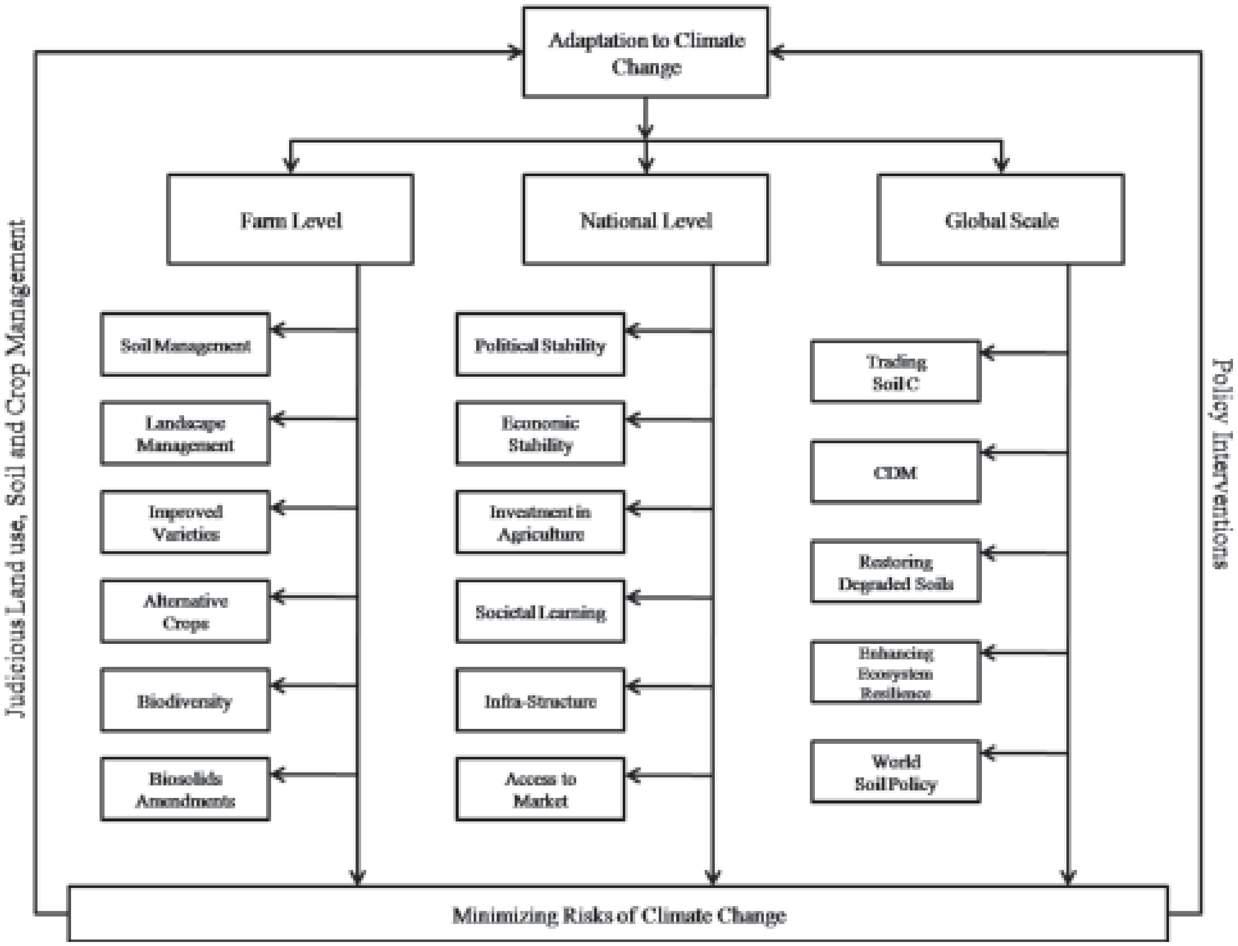

Fig. 4. Strategies for adaptation to climate change

water quality improvement, biodiversity enhancement) than to provide subsidies, and give emergence aid as handouts.

Soil Carbon Sequestration to Mitigate Climate Change

World soils comprise the third largest global pool after the oceanic pool of 38000 Pg, the geologic/fossil C pool of ~5000 Pg. The soil C pool is estimated at 2500 Pg, which has two distinct but related components: (i) the soil organic carbon (C) pool of about 1550 Pg, and (ii) the soil inorganic carbon (SIC) pool of about 950 Pg. Estimated to 1-m depth, the total soil C pool of about 2500 is about 3.2 times the atmospheric pool of 780 Pg, 40 times the biotic pool of 620 Pg, and about 1.8 times the terrestrial pool of 1400 Pg which is equal to combined atmospheric and biotic pools together. The atmospheric pool is increasing annually at the rate of 3.3 Pg C/yr (WMO, 2008; IPCC, 2007), while the terrestrial pool is decreasing because of deforestation, biomass burning, soil cultivation and drainage of wet/peat lands. There is a direct link between the soil and the atmospheric C pools, 1 Pg of soil C pool is equivalent to 0.47 ppm of CO_2 concentration in the atmosphere, and vice versa.

Conversion of natural and agricultural ecosystems leads to decline in the terrestrial (biotic and soil C) pools. The decline is caused by removal of the perennial vegetation cover (e.g., trees, shrubs, grasses) by seasonal/annuals which have low NPP. Thus, the amount of biomass-C returned to the soil is lower in agricultural than natural ecosystems. Furthermore, soils under agricultural ecosystems have higher decomposition rate than those under natural vegetation because of differences in soil temperature and moisture regimes. The rate of depletion of the SOC pool in agricultural ecosystems is exacerbated by soil degradation processes such as accelerated erosion by water and wind. Excessive tillage and drainage accentuate the rate of SOM decomposition. The rate and magnitude of depletion of SOC pool are also accentuated by removal of crop residues and uncontrolled grazing. Thus, most agricultural soils have lower SOC pool than their counterparts under natural ecosystems. The SOC pool in agricultural soils is lower than those under natural ecosystems by 25% to 50% in temperate climates and 50% - 75% in tropical regions (Lal, 2004). Most agricultural soils have lost 30 to 40 Mg C/ha, which can be restored.

Therefore, conversion of degraded and depleted agricultural soils to restorative land use(s) and adoption of RMPs can restore the SOC pool. The process of restoration of SOC pool, through conversion of atmospheric CO_2 into humus via photosynthesis, is called soil C sequestration. Similarly, the processes of increasing the terrestrial C pool (biota and soil) through photosynthesis and incremental addition of biomass C (above and below-ground) is called terrestrial C sequestration.

Assuming that the SOC pool to 1-m depth can be increased by 10% on a global scale over the next 50 to 100 years, difficult and challenging as the task may be, transfer of 250 Pg of atmospheric C 910% of 2500 Pg of soil C pool to 1-m depth) is equivalent to reducing atmospheric CO_2 concentration by 118 ppm (250 Pg x 0.47 ppm/Pg). If the process can be presumably accomplished today (which is not possible), increasing the soil C pool by 250 Pg would draw down the atmospheric CO_2 concentration from 383 ppm to 265 ppm, which is even lower than the pre-industrial concentration of 280 ppm. Indeed C sequestration in terrestrial ecosystems (soils and trees) is the only cost-efficient process of reducing the atmospheric abundance of CO_2 (McKinsey & Co., 2009). The best one can hope to achieve with the carbon capture and sequestration (CCS or geologic sequestration), is to stabilize the atmospheric concentration with 100% efficiency. In most cases, the efficiency of CCS with 15% additional cost of generating electricity is about 30%.

Ever since the dawn of settled agriculture about 10 millennia ago, the terrestrial ecosystems have lost as much as 478 Pg of C (Ruddiman, 2007; IPCC, 2007). Even if two-thirds of this can be restored (through afforestation, soil amelioration, and restoration of wetland/peat soils by inundation), this means increasing the terrestrial C pool by ~320 Pg or the equivalent to draw down the atmospheric CO_2 by 150 ppm.

These estimates of 120 to 150 ppm of draw down of atmospheric CO_2 are indicative of the technical potential of the strategy of C sequestration in terrestrial ecosystems. The attainable and economic potentials are much lower and depend on the site specific and regional conditions. The rate of C sequestration in terrestrial ecosystems is 3-4 Pg C/yr until 2050 (Pacala and Socolow, 2006) through adoption of no-till farming and conservation agriculture, afforestation, and establishment of energy plantations.

Co-benefits of Soil Carbon Sequestration

Sequestration of atmospheric CO_2 into the terrestrial ecosystems in general and soils in particular, is a win-win-win strategy. Among numerous co-benefits are: (i) advancing food security through improvements in soil quality, (ii) restoring degraded soils and desertified ecosystems, and (iii) mitigating climate change while improving the environment. It is extremely important to realize that enhancing SOC pool and maintaining it above the threshold (1.1% in the surface layer, Aune and Lal, 1998) is essential to advancing food security. For malnourished and resource-poor small landholders who are perpetually threatened by drought and crop failure, enhancing soil resilience and guaranteeing a minimum assured crop yield even during the worst seasons of below-normal rains is important to their survival. Thus, soil C sequestration is essential to their survival. Rather than being driven into the futile debate of who is responsible for gaseous emissions, food-insecure population would appreciate C-positive action towards elimination of hunger and malnutrition for which soil C sequestration is an important step and in the right direction. Commoditization of soil C can also create another income stream and provide the much-needed incentives for adoption of RMPs. Land managers can benefit by trading soil C in the emerging C-offset markets and by claiming the environmental benefits of the sustainable land management practices. Similar to C, the farmers can also be paid for water management. Downstream farmers may be required to pay upstream land managers for specific practices which ensure availability of good quality water. Payments for green water credits and charging users a fair price of the scarce water resource may be the only strategy to reverse the severe depletion of the ground water resources in northern India, as has been reported by Kerr (2009), Rodell et al. (2009). Both water credits and C credits are important to adoption of RMPs, and sustaining the resource use. Sustainable crop management is important to alleviating poverty (Lipton, 2005). Furthermore, this cost-effective option of mitigating climate change is also a bridge to the future until C-neutral or C-negative fuel sources take effect.

Diffusing the Population Bomb through Improvement in Agriculture

The world population has doubled numerous times since the primate started walking on two feet and descended from their habitat in trees. It was merely 5 million around 8,000 BC, 10 million in 3500 BC, 50 million by 1250, 800 million by 1750 and 1650 million by 1900. It has doubled twice during the 20th century to 6.7 billion in 2009. World population is expected to stabilize at ~10 billion around 2100, and will, thus, never double again. Evolution of agriculture about 10,000 years ago and its scientific advances especially during the 20th century have been responsible for increase in population. However, the future increases in population will also be moderated by improvements in agricultural production. Just as the quantum jump in agronomic production by The Green Revolution saved billions from hunger and malnutrition. Similarly, using improved agriculture as the engine of economic development in Africa and Asia would dampen the rate of population growth and stabilize world population lower than the 10 billion mark (6 or 7 billion by 2200 and beyond). Advancing food security, enhancing income, and improving standards of living are essential to reducing the rate of population growth. It is in this regard that the importance of improving soil quality and increasing agronomic production cannot be over-emphasized.

Managing Carbon-Climate Risks through Soil Sequestration

Two strategies of managing risks of climate change are: (i) reducing anthropogenic emissions, and (ii) sequestering emissions. Reducing anthropogenic emissions is the best strategy of which identifying low-C or no-C fuel sources and improving use efficiency of power are among numerous options. Sequestering emissions through the natural process of photosynthesis, and humification of biomass is the next best option and is a priority consideration. Carbon capture and storage (Chu, 2009; Schrag, 2009; Orr, Jr., 2009; Rochelle, 2009; Hazzeldine, 2009; Normile, 2009) is of a lesser importance, especially when the first two options are judiciously and prudently implemented. While soil C sequestration is not a silver bullet for mitigating climate change, it is essential for numerous co-benefits which are important to human wellbeing and other ecosystem services. These co-benefits are illustrated in **Figure 5**. It is these co-benefits of soil C sequestration which are important consideration in choosing it as a strategy for managing carbon-related climate risks. Resource-poor farmers and food-insecure people care more about increase in agronomic production and minimum assured crop yields through improvements in soil quality than the potential of mitigating climate change. Improvements in the quantity and quality of renewable fresh water resources are another important co-benefit of C sequestration in soils and terrestrial ecosystems. Establishment of energy plantations, especially on degraded croplands and other lands of marginal soil quality can also enhance ecosystem services from land of otherwise low utility.

Tenets of Soil Management

Soils must never be taken for granted. Soils must be used, improved and restored for generations to come. Sustainable management of soils is essential through observing 10 tenets of soil management (Lal, 2009a; b; **Fig. 5**). Ten tenets of soil management, constituting as spokes of a wheel representing the ecosystem services, include the following: (i) soil degradation by biophysical processes is driven by social, economic and political forces, (ii) desperate and helpless people do not care for the stewardship, (iii) to be sustainable, all outputs must be balanced by equivalent inputs in terms of nutrients and carbon, (iv) poor soils make people poor, and poor people make soils worst, (v) plants cannot differentiate between organic and inorganic sources of nutrients, and it is a matter of logistics and access to supply nutrients to crop at the most critical stages and for the amount required, (vi) soils can be a source or sink of atmospheric CO_2 depending on land use and management, (vii) a perpetual and widespread use of extractive farming practices can degrade the soils and the environment, (viii) benefits of improved varieties and GM crops can only be realized when grown under optimal soils and agronomic conditions, (ix) improved agriculture is a solution (rather than a cause) of the environmental problem, and (x) adoption of modern innovations of soil management, built upon the traditional knowledge, is essential to addressing the global issues.

Fig. 5. Co-benefits of carbon sequestration in soils and terrestrial ecosystems

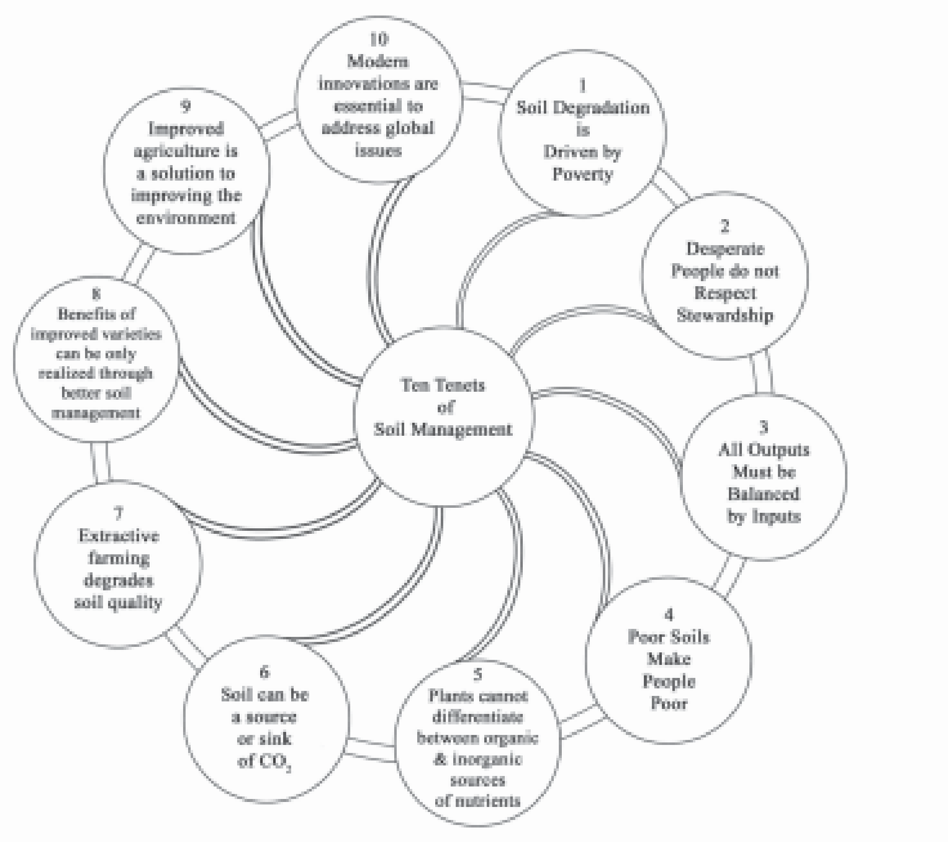

Fig. 6. Ten tenets of soil management (Adapted from Lal, 2009b).

Conclusions

Soils provide numerous ecosystem services essential to well being of all planetary life. Important among these are: producing biomass, cycling elements, denaturing and transforming of pollutants, purifying and filtering of water, storing and creating habitat for a vast gene pool, providing foundations for civil structures, generating raw materials, and serving as an archive of planetary and human history. Soil's capacity to provide these services depends on its quality (physical, chemical and biological) as moderated by the total and reactive carbon (C) pools. Most agricultural soils contain lower organic C (SOC) pool than their counterparts under natural ecosystems by about 25% to 50% in temperate and 50% to 75% in tropical ecosystems. The magnitude and severity of the depletion of SOC pool are exacerbated through decline in soil quality by accelerated erosion and other degradation processes. Perpetual use of extractive farming practices and mining of soil fertility also deplete the SOC pool. Conversion to a restorative land use and adoption of recommended management practices (RMPs), which create positive C and nutrient (N, P, K, S) budgets, can enhance SOC pool while restoring soil quality. The rate of SOC sequestration in soils of the terrestrial ecosystems is 2-3 Pg C/yr. Increasing SOC pool is also essential to advancing food security and improving ecosystem services. Adoption of RMPs by the resource-poor farmers can be promoted by payments for soil C credits, green water credits, and biodiversity credits. In addition to mitigation of climate change, soil C sequestration is also important for adaptation to climate disruption by buffering agricultural ecosystems against adverse changes in temperature, precipitation and other extreme events.

Soil carbon sequestration is a win-win-win strategy. Through its numerous co-benefits, it mitigates climate disruption, adapts agroecosystems to climate change, advances food security, and improves the environment. Rather than subsidies and emergency aids, payments to land managers for C credits, green water credits, and biodiversity credits can promote adoption of recommended management practices. This is a cost-effective strategy of moderating climate change, and is the only natural and viable option of reducing the atmospheric abundance of CO_2. The drawdown potential of soil C sequestration will help reducing atmospheric CO_2 concentration by 120 to 150 ppm over the next 50-100 years, while ensuring the food security for 10 billion people and improving the environment.

References

Acharya, C.L. and Sharma, P.D. (1994) Tillage and mulch effects on soil physical environment, root growth, nutrient uptake and yield of maize and wheat on an Alfisol in northwest India. *Soil and Tillage Research* **32**, 291-302.

Acharya, C.L., Kapur, O.C. and Dixit, S.P. (1998) Moisture conservation for rainfed wheat production with alternative mulches and conservation tillage in the hills of northwest India. *Soil and Tillage Research* **46**, 153-163.

Agarwal, S., Sethi, V., Gupta, P., Jha, M., Agnihotri, A. and Nerd, M. (2009) Experiential household food insecurity in an urban underserved slum of North India. *Food Security* **1**, 239-250.

Anonymous (2009) "L'Aquile" joint statement on global food security: L'Aquile Food Security Initiative (AFSI). *Food Security* **1**, 235-237.

Aune, J. and Lal, R. (1998) Agricultural productivity in the tropics and critical limits of properties of Oxisols, Ultisols and Alfisols. *Tropical Agriculture (Trinidad)* **74**, 96-103.

Banik, D. (2007) *Starvation and India's Democracy*. Routledge, London.

Bejbaruha, R., Sharma, R.C. and Banik, P. (2009) Direct and residual effect of organic and inorganic sources of nutrients on rice-based cropping systems in the sub-humid tropics of India. *Journal of Sustainable Agriculture* **33**, 674-689.

Bouman, B.A.M., Lampayan, R.M. and Toung, T.P. (2007) *Water Management in Irrigated Rice: Coping with Water Scarcity*. IRRI, Los Banos, Philippines, pp. 54.

Brown, M.E. and Funk, C.C. (2008) Food security under climate change. *Science* **319**, 580-581.

Chu, S. (2009) Carbon capture and sequestration. *Science* **325**, 1599.

FAO (1996) *Rome Declaration on World Food Security*. World Food Summit. Rome, Italy.

FAO (2009) *1.02 Billion People Hungry*. FAO New Room, Rome, Italy.

Funk, C., Dettinger, M.D., Brown, M.E., Michaelson, J.C., Verdin, J.P., Barlow, M. and Hoell, A. (2008) Warming of Indian Ocean threatens eastern and southern Africa, but could be mitigated by agricultural development. *Proceedings of National Academy of Science* **105**, 11081-11086.

Funk, C.C. and M.E. Brown (2009) Declining per capita agricultural production and warming oceans threaten food security. *Food Security* **1**, 271-289.

Hazzeldine, R.S. (2009) Carbon capture and storage: How green can black be? *Science* **325**, 1647-1652.

IFA (2007) Nutrient use efficiency in Indian agriculture. India Fertilizer Assoc., New Delhi, India.

IPCC (2007) The Climate Change 2007: The Physical Science Basis. Cambridge Univ. Press, Cambridge, U.K.

ISRIC (2009) On Solid Ground. World Soil Information. Wageningen, The Netherlands, p. 26.

Katers, R.W. (2000) Cautionary tales: Adaptation and the global poor. *Climatic Change* **45**, 5-17.

Kerr, R.A. (2009) Northern India's ground water is going, going, going. *Science* **325**: 798.

Koning, N. and Mol, A.P.J. (2009) Wanted: Institutions for balancing global food and energy markets. *Food Security* **1**, 291-303.

Kreye, C., Bouman, B.A.M., Castañeda, A.R., Lampayan, R.M., Faronilo, J.E., Lactaoen, A.T. and Fernandez, L. (2009) Possible causes of yield failure in tropical aerobic rice. *Field Crops Research* **111**, 197-206.

Kumar, P., Pant, M. and Negi, G.C.S. (2009) Soil physic-chemical properties and crop yield improvement following *Lantana* mulching and reduced tillage in rainfed croplands in the Indian Himalayan mountains. *Journal of Sustainable Agriculture* **33**, 636-657.

Ladha, J.K., Yadvinder Singh, Erenstein, O. and Hardy, B. (Eds) (2009) Integrated Crop and Resource Management in the Rice-Wheat System of South Asia. IRRI/ADB/RWC, Los Banos, Philippines, p. 395.

Lal, R. (2004) Soil carbon sequestration impacts on global climate change and food security. *Science* **304**, 1623-1627.

Lal, R. (2009a) Laws of sustainable soil management. Agron. Sustainable Soil Management **29**, 7-9.

Lal, R. (2009b) Ten tenets of soil management. *Journal of Soil and Water Conservation* **64**, 20A-21A.

Lipton, M. (2005) The family farm in a globalizing world: the role of crop science in alleviating poverty. IFPRI, Washington, D.C.

McKinsey and Co. (2009) Pathways to a low-carbon economy. Version 2 of the global greenhouse gas abatement cost curve. McKinsey & Co., New York.

Normile, D. (2009) Round and round: a guide to the carbon cycle. *Science* **325**, 1642-1643.

Orr, Jr., F.M. (2009) Offshore geologic storage of CO_2. *Science* **325**, 1656-1658.

Pacala, S. and Socolow, R. (2006) Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies. *Science* **305**, 968-972.

Rochelle, G.T. (2009) Amine scrubbing for CO_2 capture. *Science* **325**, 1652-1654.

Rodelle, M., Velicogn, I. and Famiglietti, J.S. (2009) Satellite-based estimates of ground water depletion in India. *Nature* (doi: 10.138/nature 08238): 1-4.

Ruddiman, W.F. (2007) Plows, Plagues, and Petroleum: How Humans Took Control of Climate. New York, Princeton UP.

Schrag, D.P. (2009) Storage of carbon dioxide in offshore sediments. *Science* **325**, 1658-1659.

Verhagen, J., Put, M. and Van Keulen, H. (2004) Climate change and drought risks for agriculture. In: *The Impact of Climate Change on Drylands: With a Focus on West Africa* (A.J. Dietz, R. Ruben, A. Verhagen, Eds), Kluwer Academic Publishers, Dordrecht, p. 49-59.

Walker, B., Barrett, S., Polasky, S. et al. (2009) Looming global scale failures and missing institutions. *Science* **325**, 1345-1346.

WMO (2008) Greenhouse Gas Bulletin. The State of Greenhouse Gases in the Atmosphere Using Global Observations Through 2007. World Meteorological Organization, Geneva, Switzerland.