Soil and Water Management Options for Adaptation to Climate Change

Rattan Lal
The Ohio State University
Columbus, Ohio

Atmospheric concentrations of carbon dioxide (CO_2) and other greenhouse gasses (GHGs) have been drastically influenced by anthropogenic activities. Humans have perturbed the global carbon (C) cycle for about 10,000 years since the dawn of settled agriculture (Ruddiman, 2003, 2005; Brook, 2009). Agricultural activities that have caused emission of GHGs from terrestrial ecosystems (biota and soil) include deforestation, biomass burning, soil tillage, and drainage of wetlands. In addition, domestication of cattle and cultivation of rice paddies, around 5,000 years ago, caused emission of methane (CH_4). Use of animal manure and plowing under of leguminous green-manure crops, widely practiced in South and East Asia for millennia, also increased emissions of nitrous oxide (N_2O). The rate and magnitude of the emission of GHGs increased drastically with the onset of the industrial revolution because of reliance on fossil-fuel combustion for energy. Yet, until the 1940s, more CO_2 was emitted from land-use conversion and agricultural activities than from fossil-fuel combustion. The data in Table 1 show that globally averaged mixing ratios reached high values in 2007 with atmospheric concentrations of 383 ppmv for CO_2, 1,789 ppbv for CH_4 and 321 ppbv for N_2O (WMO, 2006, 2008). In comparison with pre-industrial (~1750) concentrations, these values have increased by 37% for CO_2, 156% for CH_4 and 19% for N_2O (Table 1).

Table 1. Atmospheric concentrations of major greenhouse gases in 2007 (WMO, 2008).

Parameter	CO_2	CH_4	N_2O
Concentration in 2007 (ppm)	383	1,790	321
% increase since ~1750	37	156	19
Absolute increase in 2006–2007 (ppm)	1.9	6.0	0.80
% increase in 2006–2007	0.50	0.34	0.25
Mean annual absolute increase since 1997 (ppm)	2.0	2.7	0.77

Emissions from fossil-fuel combustion and cement manufacture between 1750 and 2006 are estimated at 292 to 330 Gt (Canadell *et al.*, 2007; Holdren, 2008). Projected emissions from fossil-fuel combustion between 2004 and 2030 are estimated at an additional 200 Gt C (Holdren, 2008). In comparison, emissions from land-use change (*e.g.* deforestation, soil cultivation, drainage of peatland) between 1850 and 2006 are estimated at 158 Gt C. Ruddiman (2003, 2005) estimated that C emission from terrestrial ecosystems, because of agricultural activities from ~10,000 years ago to 1850, may be 320 Gt. If Ruddiman's estimates are nearly correct, terrestrial ecosystems may have contributed as much as 478 Gt of C since the dawn of settled agriculture.

Because of the direct link between atmospheric concentration of GHGs and abrupt climate change (ACC) (IPCC, 2007a), there is a strong interest in identifying strategies for mitigation of, or adaptation to, climate change. The ACC refers to rapid change in temperature (>0.1°C/decade) such that ecosystems cannot adjust, and biomes shift poleward. Mitigation of global warming and ACC will involve taking action to reduce GHG emissions and to enhance sinks aimed at reducing the extent of global warming (IPCC, 2007b). In comparison, adaptation to global warming will consist of initiatives and measures to reduce the vulnerability of natural and human systems against actual or expected ACC effects (IPCC, 2007b). This manuscript reviews potential and challenges related to soil- and water-management options for adaptation to ACC.

World Soils and the Global Carbon Cycle

There are five principal global C pools (Fig. 1). The largest pool is lithospheric and the vast amount of C stored as sediment carbonates and kerogens is mostly inactive (out of circulation) and interacts with the atmospheric pool mainly through volcanic eruptions. The second-largest pool is oceanic, estimated at 37,400 Gt of inorganic C (of which 670 Gt are in the surface layer and 36,730 Gt are in the deep layer) and ~1,000 Gt of organic C. The third-largest pool of fossil fuel is estimated at 4,130 Gt, comprising coal, oil, gas and peat. The fossil-fuel pool is being mined and combusted at the rate of 8.0 Gt C/year. The fourth-largest pool, soil C, is estimated at 2,500 Gt to a depth of 1 m and >4000 Gt to 2 m (Batjes, 1996). The soil-C pool is being depleted at a rate of 0.1 Gt C/year or more. The fifth-largest pool, atmospheric, presently contains 780 Gt C and is increasing at >4 Gt C/year. The sixth-largest pool is the biotic pool, comprising 620 Gt of terrestrial and 102 Gt of aquatic components. The atmospheric, biotic and soil pools are closely interlinked (Fig. 1).

The biotic pool photosynthesizes ~120 Gt C/year. Of this, 59 Gt C/year is returned to the atmosphere through decomposition of biomass (plant respiration) and 58 Gt C/year through soil respiration. The oceanic pool is absorbing 2.3 Gt C/year and its sink capacity may increase with progressive increases in its partial pressure along with atmospheric concentration of CO_2. The atmospheric pool is absorbing ~4 Gt C/year. Canadell *et al.* (2007) computed the relative efficiency of natural sinks by evaluating the airborne fractions (AFs), the ratio of atmospheric CO_2 increase in a given year to that year's total emission. The data in Table 2 show that AF was 49% in the 1980s, 40% in the 1990s and 44% in the 2000s. It seems that the natural sink capacity in 2008 is lower (by ~2%) than that in the 1990s, probably because of soil degradation or decline in quality of soil and water resources. The global-C budget (Table 2) shows that natural sinks (soil, biota, ocean) absorb ~56% of the anthropogenic emissions. The strategy is to enhance sink capacity of soil and biota through judicious and sustainable management of natural resources, and targeted interventions.

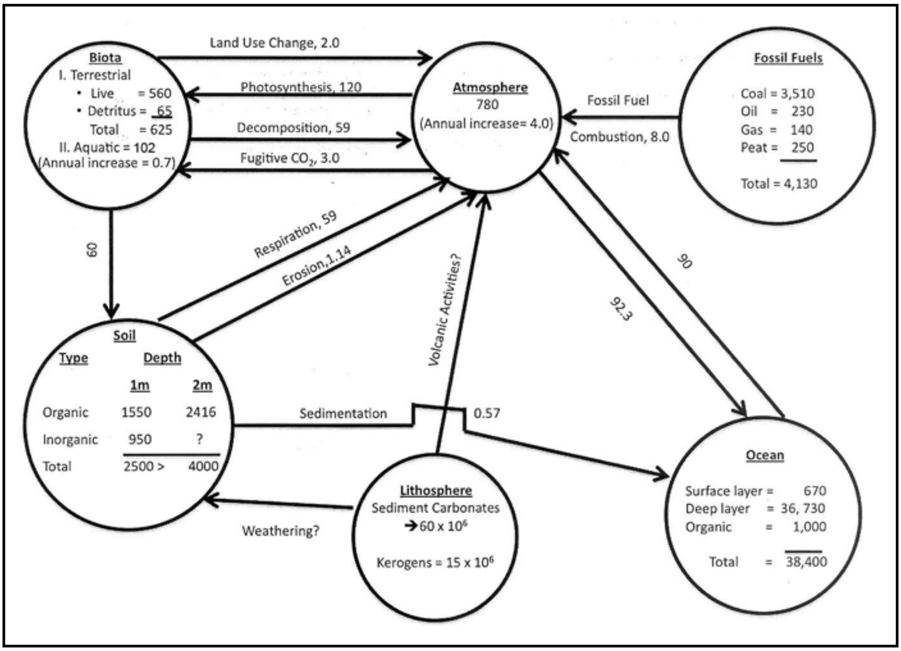

Figure 1. Principle global carbon pools and fluxes among them (Lal, 2004b; Houghton, 2001; Falkowski *et al.*, 2000; Canadell *et al.*, 2007; Koonin, 2008). All pools are in Gt and fluxes are in Gt/year.

Table 2. Contemporary global carbon budget (IPCC, 2007a; Houghton, 2001; Falkowski et al., 2000; Canadell et al., 2007).

Parameter	Flux (Gt/year)		
	1980s	1990s	2000s
Sources			
Fossil-fuel combustion	5.4	6.4	7.5
Land-use conversion	1.4	1.6	1.6
Total	6.8	8.0	9.1
Sinks			
Atmosphere	3.3	3.2	4.0
Ocean	1.8	2.2	2.3
Land	0.3	1.0	0.9
Total	5.4	6.4	7.2
Unknown land sink	1.4	1.4	1.9
Natural sinks (% of total source)	51	59	56

TABLE 3. ESTIMATES OF CHANGES IN AREA FOR DIFFERENT VEGETATION TYPES BETWEEN 1700 AND 1992 (RAMANKUTTY AND FOLEY, 1999).

Vegetation	Decrease in total area ($\times 10^6$ ha)
Forest and woodland	1,135
Savanna, grassland, and steppe	669
Tundra and polar deserts	26
Total	2,025

Land-Use Conversion, Soil Degradation and Desertification

The historic loss from terrestrial and aquatic C pools (wetlands) is estimated at 478 Gt C. These emissions are mainly from the biotic- (trees and biomass) and soil-C pools. Increases in population caused drastic alterations in vegetation cover between 1700 and 2000 through conversion of 2,025 million ha (Mha) of natural ecosystems (Table 3) and their conversion to an additional global cropland area by 1,135 Mha (Table 4), with attendant increases in global cropland area from merely 235 Mha in 1700 to 1,520 Mha by 2005 (Table 5). These alterations in land use resulted in expansion of areas under cropland, grazed pastures, forest plantations and urbanization (Table 6) with corresponding decline in areas under natural ecosystems (Tables 3, 4). Indiscriminate deforestation, land misuse, soil mismanagement and widespread use of extractive farming practices caused severe degradation of soil resources. Estimates of soil degradation—preliminary and tentative as these may be—are alarming (Table 7). Areas affected by a range of soil-degradation processes are estimated at a total of 1,965 Mha (Oldeman, 1994). In contrast, areas prone to land degradation (3,506 Mha, Bai *et al.*, 2008) and desertification (3,592 Mha, UNEP, 1991) are 1.8-fold higher (Table 7).

The extent and severity of soil degradation and desertification imply:

- loss of reserves of soil organic matter (SOM),
- depletion of plant nutrients,
- decline in cation-exchange capacity (CEC) because of reduction in soil colloids (clay and humus fractions) caused by accelerated erosion,
- change in soil reaction caused by acidification or alkalization,
- elemental imbalance caused by deficiency of some (N, P, K) and toxicity of others (Al, Fe, Mn),
- adverse shift in soil fauna and flora (build up of soil-borne pathogens),
- reduction in plant-available water retention capacity in soil, leading to increased intensity and duration of drought,
- loss of soil structure and tilth exacerbating problems of crusting, compaction, and anaerobiosis, and

- increase in emission of GHGs due to high rates of decomposition of biomass caused by changes in soil temperature and moisture regimes, and increases in methanogenesis and denitrification.

These degradative trends are vastly accentuated by observed and predicted ACC. Increases in air and soil temperatures will increase risks of soil degradation because of increases in:

- the rate of mineralization of SOM,
- soil erodibility and climatic erosivity,
- losses of water by surface runoff and evaporation, and
- losses of plant nutrients by leaching, erosion and volatilization.

The ACC may also reduce efficiency of use of inputs (*e.g.* fertilizer, nutrients).

TABLE 4. ESTIMATES OF CONVERSION OF FOREST VEGETATION TO CROPLAND BETWEEN 1700 AND 1992 (RAMANKUTTY AND FOLEY, 1999).

Forest	Land area converted to agriculture ($\times 10^6$ ha)
Forest and woodland	422
Temperate forests	451
Boreal forests	40
Evergreen deciduous forest and woodland	222
Total	1,135

TABLE 5. ESTIMATES OF INCREASES IN AREA UNDER CROPLAND AND PASTURES BETWEEN 1700 AND 1980 (FAO, 2008; RICHARDS, 1990).

Year	Cropland	Grazing land	Pasture
	($\times 10^6$ ha)		
1700	265	6,860	–
1850	537	6,837	–
1920	913	6,748	–
1950	1,170	6,780	–
1980	1,346	6,788	3,244
1990	1,396	–	3,368
2005	1,402	–	3,442

Table 6. Land use for the world and some countries in 2005 (FAO, 2008).

Land use	Area (x10^6 ha)				
	World	U.S.	China	India	Canada
Total land area	12,980	916	933	297	909
Arable land	1,402	176	137	160	46
Pastures	3,442	234	400	11	15
Forest land	3,952	303	197	68	310
Woodland	1,342	–	88	4	92
Productive plantations	0.34	0	0	0.10	0
Protected plantations	1.53	0	0	0.22	0
Urban land	351	19	24	21	13

Table 7. Estimates of degraded and desertified lands.

Type	Area (x10^6 ha)	Methodology	Reference
Soil degradation	1,965	Glasod	Oldeman (1994)
Land desertification	3,592	Dregne	UNEP (1991)
Soil desertification	1,137	Glasod	Oldeman & Van Lynden (1998)
Vulnerability to desertification	4,324	Land capability	Eswaran *et al.* (2001)
Land degradation	3,506	NPP loss	Bai *et al.* (2008)

Table 8. World total fertilizer consumption (Tilman et al., 2001; IFDC, 2004; Ponting, 2007).

Year	N	P	K	Total
	(x10^6 Mg/year)			
1900	0.41	0	0	0.41
1950	9	0	0	9
1960	12	11	9	32
1970	32	21	16	79
1980	61	32	24	117
1990	77	36	5	138
2000	81	33	22	136
2002	85	34	23	142
2020	135	–	–	–
2050	236	–	–	–

Agricultural Intensification and C-Based Input

Crop yields increased by a factor of 3 to 5 during the second half of the 20th century despite degradation of soil, desertification of land, and depletion/pollution of water resources. This quantum jump in crop yields and the overall increase in agronomic production was brought about by agricultural intensification through adoption of varieties that were responsive to inputs. For example, world fertilizer use increased from $<0.5\times10^6$ Mg/year in 1900 to 142×10^6 Mg/year in 2002, *i.e.* by a factor of 342 (Table 8). The use of nitrogenous fertilizer is expected to increase from 85×10^6 Mg/year in 2002 to 135×10^6 Mg/year in 2020 and to 236×10^6 in 2050 (Table 8). Similar to fertilizer use, the area under irrigation has increased by a factor of 20 since 1800 and of 6.7 since 1900 (Table 9). The irrigated land area increased from 16 Mha in 1800 and 41 Mha in 1900 to 277 Mha in 2003 (Table 9). Less than 20% of the irrigated cropland area produces more than 40% of the agronomic output. However, future increases in irrigation, most likely to occur in Africa and South America, will exacerbate competition for water resources from rapidly increasing demands from non-agricultural (*e.g.* urban, industrial) uses (Table 10). The non-agricultural use of water increased drastically between 1900 and 2000, from 20×10^9 m^3/year to 440×10^9 m^3/year (*i.e.* by a factor of 22) for urban land use and from 30×10^9 m^3/year to 1900×10^9 m^3/year (*i.e.* by a factor of 63) for industrial uses (Table 10). Consequently, agricultural use of water (as a % of total consumption) decreased from 81% in 1900 to 57% in 2000, and will continue to decrease during the 21st century

Increases in population and concomitant demands on soil and water resources drastically increased productivity and human exploitation of natural resources, often with adverse impacts on quality of soil, vegetation, water and air (Table 11). Demands for natural resources will increase even more drastically during the 21st century because of two factors: (i) increased need for food production, which may have to be doubled by 2050, and (ii) ACC which will further jeopardize the natural resources that are already under great stress (Table 11). Therefore, adaptation to climate change is essential for human survival and wellbeing.

Table 9. Global irrigation (Ponting, 2007; FAO, 2008).

Year	Irrigated land area ($\times10^6$ ha)
1800	14
1900	41
1950	120
1960	145
1970	169
1975	189
1980	210
1990	244
2000	275
2003	277

Table 10. Competition for water (Kondratyev et al., 2003; Gleick, 2003a, b).

Year	Water use (x10^9 m^2/year)				
	Total	Urban	Industrial	Agricultural	
				Net	% of total
1900	430	20	30	350	81
1940	870	40	120	660	76
1950	1,190	60	190	860	72
1960	1,990	80	310	1,510	76
1970	2,630	120	510	1,930	73
1975	3,080	150	630	2,100	68
1985	3,970	250	1,100	2,400	61
1995	4,750	320	1,560	2,760	58
2000	6,000	440	1,900	3,400	57

Table 11. Increased production and consumption of natural resources, 1900–2000 (Ponting, 2007).

Parameter	Increase factor
Population	3.8
Urban population	12.8
Industrial output	35
Energy use	12.5
Oil production	300
Water use	9
Irrigated area	6.8
Fertilizer use	342
Fish catch	65
Organic chemicals	1,000
Car ownership	7,750

Adaptation to Abrupt Climate Change

There are two strategies of addressing the issue of ACC: mitigation and adaptation (Fig. 2). Mitigation implies either reducing emissions (by enhancing energy-production efficiency, and identifying low-C or no-C fuel sources) or sequestering emissions in long-lived pools (*e.g.* soil, biotic). Adaptation implies changing lifestyle, and using technologies for management of resources in a manner that minimizes the adverse effects of ACC on soil and water resources. A wide range of soil- and water-management practices can be adopted to sequester atmospheric CO_2 in terrestrial ecosystems. The technical potential of C sequestration in terrestrial ecosystems is estimated at 5.7 to 10.1 Gt C/year (Table 12). The estimated economic (3 to 6 Gt C/year) and realizable (2 to 3 Gt C/year) potentials can be accomplished through adoption of innovative methods of soil and water management, along with other strategies.

Changing lifestyle is an important consideration in adaptation to ACC. This will involve creating awareness among the public and, especially, policymakers about the importance of reducing the C-footprint of modern civilization including food production, processing and transport, and dietary preferences. In this regard, the importance of heating and cooling, lighting, water use, and transportation cannot be over-emphasized.

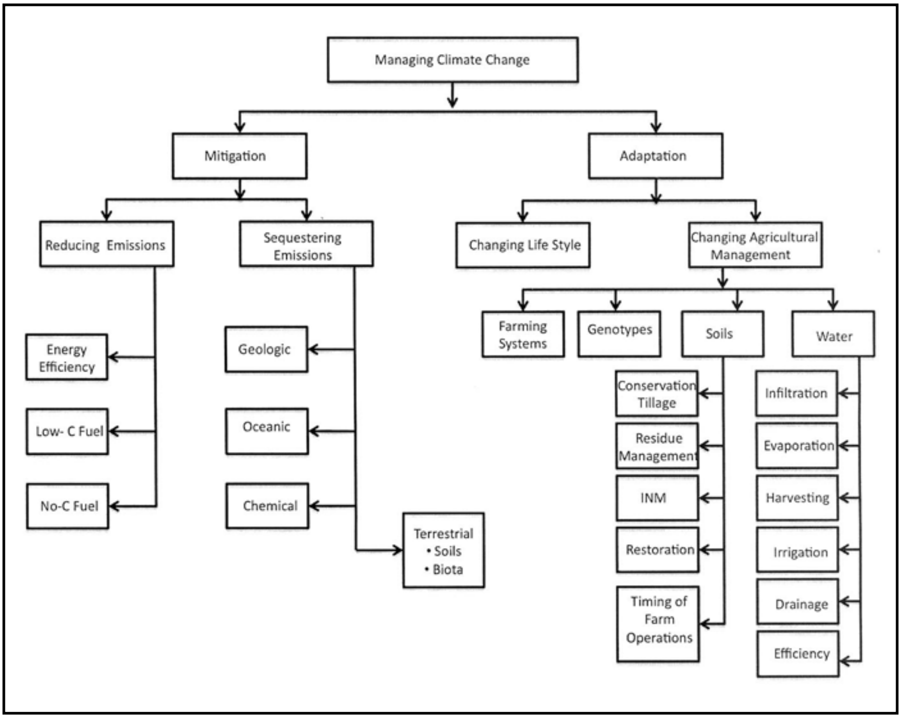

Figure 2. Strategies for mitigation and adaptation to climate change (INM=integrated nutrient management).

TABLE 12. TECHNICAL CARBON SEQUESTRATION POTENTIAL IN VARIOUS BIOMES (USDOE, 1999).

Biome	Technical potential (Gt C/year)
Agricultural soils	0.85–0.90
Biomass croplands	0.5–0.8
Grassland	0.5
Rangeland	1.2
Forests	1–3
Urban forests and grasslands	?
Deserts and degraded lands	0.8–1.3
Terrestrial sediments	0.7–1.7
Boreal peatlands and other wetlands	0.1–0.7

In terms of agricultural systems, there exists a wide range of strategic options. These options are different for mitigation (Fig. 3) versus adaptation to ACC (Fig. 4). Agricultural strategies for mitigation can be categorized as follows:

- reducing emissions,
- sequestering emissions,
- avoiding emissions, and
- minimizing emissions.

The overall goal is to minimize net emission from agricultural systems by efficient management of the biomass-C pool (and fluxes) and of inputs involving high hidden-C costs (*e.g.* fertilizers, pesticides, tillage). Anthropogenic emissions of CO_2 can be sequestered by increasing: (i) SOM pool, (ii) carbonate pool, and (iii) burial of unusable biomass under anaerobic conditions. Restoration of degraded and desertified soils is an important mitigation strategy because of its large technical potential for sequestering 1–2 Pg C/year. Important among several options of avoiding emissions are: (i) using biofuels, (ii) controlling erosion, (iii) intensifying agricultural production and using land-saving technologies, (iv) controlling and managing fire, and (v) managing grazing lands and stocking rate. Managing emission of other GHGs (CH_4, N_2O) is also important because of their high global-warming potential (GWP[1]) (21 for $CH_{4,}$ 310 for N_2O). There are several techniques for reducing emission of CH_4 from rice paddies (*e.g.* aerobic rice, midseason drainage, no-till and direct seeding, GM rice varieties). Restoring peatlands (by restoring drainage), and managing livestock are also important to CH_4 reduction. Efficient use of nitrogenous fertilizers is essential to reducing N_2O emission, including the use of slow-release formulations and nano-enhanced materials with zeolites.

[1]GWP for CO_2 is 1

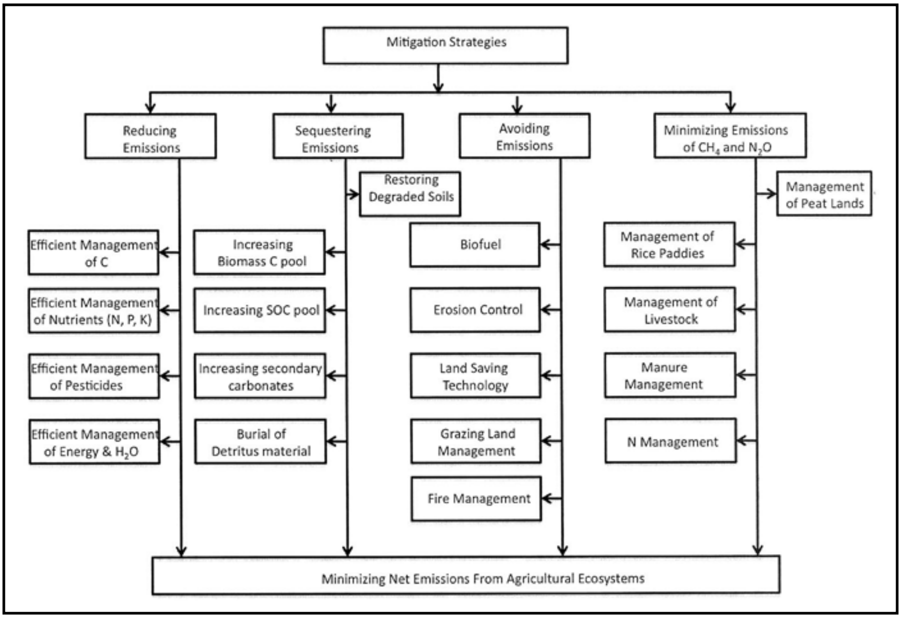

Figure 3. Agricultural strategies for mitigation of abrupt climate change (SOC=soil organic carbon)

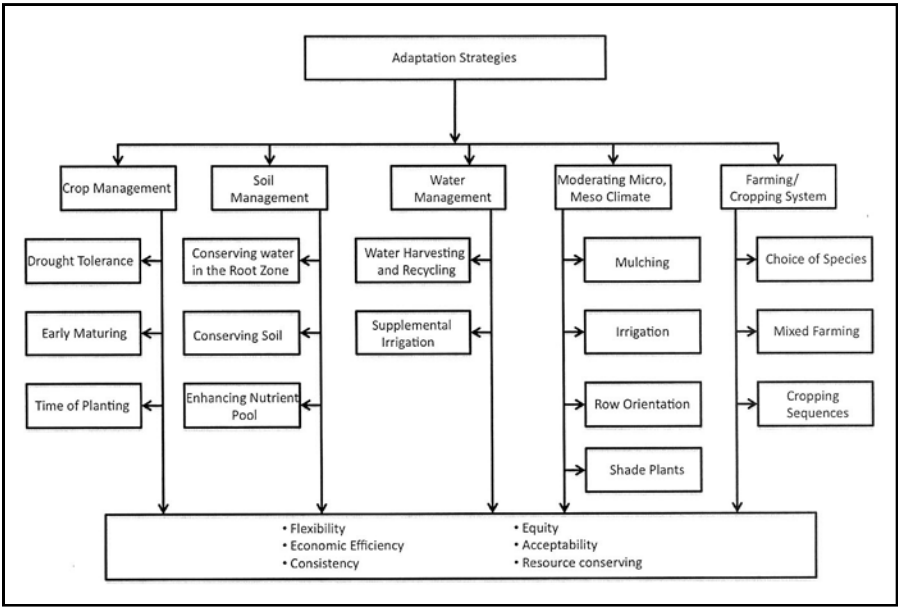

Figure 4. Agricultural strategies for adaptation to abrupt climate change.

Agricultural Adaptation

Important among several options for agricultural adaptation are (see also Fig. 4):

- choosing crop-management techniques including drought-tolerant (avoiding) and early-maturing varieties adopted in conjunction with adjustment in time of planting,
- converting to farming/cropping systems that reduce risks and produce minimum assured returns in bad years rather than maximum production in good years, with focus on choice of appropriate species and diversification (mixed farming),
- moderating micro- (soil) and meso-climates (canopy) to buffer against adverse impact of extreme events through mulch farming, using supplemental irrigation, row orientation, using shade-tolerant plants, *etc.*, and
- using appropriate fertilizers and soil amendments to minimize nutrient deficiencies at critical phenological stages.

Sustainable management of soil and water resources is among extremely important adaptation strategies. The goal of soil management is to conserve water, soil and nutrients in the root zone and minimize their losses from the ecosystem. The goal of water management is to conserve, harvest and recycle water while minimizing losses by runoff, evaporation, seepage and uptake by weeds.

Soil Management for Adaptation to Climate Change

Sustainable management of soil involves creating a positive C budget, a balanced nutrient/elemental budget, diverse soil faunal and floral activities including those of earthworms and microorganisms, and creating a favorable soil reaction (pH). Techniques to create a positive C budget are those that increase gains more than losses. Gain of C by soil ecosystems is mainly through input of biomass in the form of crop residues (above and below ground), compost, manure, mulch, cover crops, and alluvial or aeolian deposition. There may also be input of inorganic C as lime, and formation of secondary carbonates. Soil- and crop-management practices that increase the soil-C pool are outlined in Table 13. Important among nutrient-management options are slow-release formulations of fertilizer, and use of zeolites (Oren and Kaya, 2006). Biofertilization via rhizobia-legume symbioses (Lugtenberg *et al.*, 2002) is an important innovation. Increasing nitrogen fixation in legumes (Jones *et al.*, 2007) and even in non-leguminous plants (Cheng et al., 2005) can enhance N-use efficiency. The importance of root systems and especially of root exudates in improving soil structure and rhizospheric processes cannot be over-emphasized (Uren, 2000; Bertin *et al.*, 2003). Managing soils to make them disease-suppressive is an important innovation (Benitez *et al.*, 2007; Borneman and Becker, 2007, Gross *et al.*, 2007). Similar to N, there are several options for microbial enhancement of P uptake through inoculating with P-enhancing microorganisms (Legett *et al.*, 2001; Jakobsen *et al.*, 2005). There are also innovative remote-sensing technologies for improving nutrient use efficiency, such as those based on the Normalized Difference Vegetative Index (Raun *et al.*, 2001).

Adaptation Strategies for Water Management

There are two strategies of soil-water management: (i) conserving water in the root zone, and (ii) supplemental irrigation through surface-water management by water harvesting and recycling. Improving soil structure is essential to conserving water in the root zone and enhancing its use efficiency (Rockström *et al.*, 2007). Improvement of soil structure by application of nano-enhanced materials (*e.g.* zeolites) (Bhattacharyya *et al.*, 2006; Pal *et al.*, 2006) can enhance water-infiltration rate and decrease losses by surface runoff. Use in conjunction with crop residue or synthetic mulch (*e.g.* plastic) can minimize losses by evaporation. Growing crops in association with shrubs (*e.g. Piliostigma reticulatum* and *Guiera Senegalensis*) may enhance water use and nutrient recycling (Caldwell *et al.*, 1998; Dossa, 2007; Kizito *et al.*, 2007, 2009).

On-farm water management and supplementary irrigation are necessary to avoid drought. Micro-irrigation, especially sub-surface drip irrigation, is a modern innovation to enhance water-use efficiency (Visvanathan *et al.*, 2002; Aujla *et al.*, 2005; Molden, 2007).

Potential of Land Resources to Adapt to Climate Change

A wide range of recommended management practices, such as those listed in Table 13 and discussed in the previous section, has application on large areas under agricultural (Table 14) and forestry (Table 15) land uses. There also exists vast scope for expanding agriculture, especially in sub-Saharan Africa and South and Central America (Table 16). Although agricultural expansion must be undertaken only as a last resort, adoption of land-saving technologies on existing agricultural and forestry lands are important for both mitigation of and adaptation to ACC. For example, the technical potential of C sequestration is about 1 Gt/year in agricultural soils, 1 to 2 Gt/year through restoration

Table 13. Recommended soil-management practices for adaptation to climate change through C sequestration.

Objective	Practice	Potential (Pg C/year)
Crop-residue management	No-till, cover cropping, mulching	0.4–1.2 (Lal, 2004)
Nutrient management	Using compost, manure, balanced use of fertilizers, precision farming, nitrogen fixation, zeolites, mycorrhizae, elemental recycling, biofertilization	1 (Pacala & Socolow, 2006)
Terrain management	Strip cropping, contour hedgerow farming, contour buffers	0.85–0.9 (DOE, 1994)
Soil restoration	Afforestation, reforestation, conversion to perennial land use, agroforestry, transgenic plants	0.9–1.9 (Lal, 2001)

of degraded soils, and an additional 1 Gt/year through afforestration and establishment of biofuel plantations (Pacala and Socolow, 2004). The standing biomass is a large reservoir of C (Table 15), and management of terrestrial biomass C is important to managing atmospheric concentration of CO_2.

Table 14. Agricultural land use, 1961–2001 (IPCC, 2007b).

Land	Area (Mha)					Change	
	1961–70	1971–80	1981–90	1991–00	2001–02	(%)	(Mha)
World							
Arable land	1,297	1,331	1,376	1,393	1,405	+8	107
Permanent	82	92	104	123	130	+59	49
Permanent pasture	3,182	3,261	3,353	3,469	3,488	+10	306
Developed countries							
Arable land	648	649	352	633	613	–5	–35
Permanent	23	24	24	24	24	+4	1
Permanent pasture	1,209	1,210	1,201	1,209	1,202	–1	–7
Developing countries							
Arable land	650	682	724	760	792	+22	142
Permanent	59	68	80	99	106	+81	48
Permanent pasture	1,973	2,051	2,152	2,260	2,286	+16	313

Table 15. Regional and global area under forestland use (recalculated from IPCC, 2007b).

	Area (Mha)			C pool in live biomass (Pg C)		
	1990	2000	2005	1990	2000	2005
Africa	690	661	635	65.8	622	60.8
Asia	570	566	572	41.1	35.6	32.6
Europe	985	994	1,001	42.0	43.1	43.9
North & Central America	710	708	706	41.0	41.9	42.4
Oceania	208	207	206	11.6	11.4	11.4
South America	900	867	832	97.7	94.2	91.5
World	4,618	4,241	3,952	299	288	283

Co-Benefits of Soil- and Water-Management Options

Important global 21st-century issues include food insecurity affecting almost a billion people (Brown, 2004; Borlaug, 2007), urgency to intensify agricultural production on existing lands by raising crop yields per unit area and minimizing additional deforestation (Clay, 2004; FAO, 2004, 2005), scarcity of water resources and the need to increase and improve irrigation (Field 1990; Johnson *et al.*, 2001; Kondratyev *et al.*, 2003; Postel, 1999), and off-set fossil-fuel emissions in soils and terrestrial ecosystems for mitigating

TABLE 16. AVAILABILITY POTENTIAL OF RAINFED ARABLE LAND (READ, 2008).

Region	Potential land area (Gha)	Presently used (%)	Available land area (Gha)
Sub-Saharan Africa	1.05	15	0.893
North Africa and Near East	0.04	100	0.0
North Asia Urals Eastwards	0.28	64	0.101
Asia and Pacific	0.74	64	0.266
South and Central America	0.98	15	0.833
North America	0.43	54	0.158
Europe	0.32	63	0.118
World	3.82	38	2.38*

*1.99 Gha in tropical and 0.38 Gha in temperate regions.

ACC (Lal, 1999, 2001, 2004a, b, c; Marland *et al.*, 2001). Carbon sequestration in soils has potential to mitigate as well as adapt to ACC (Pacala and Socolow, 2004). The strategy is to create a positive C budget in soils and ecosystems through mulching with residues along with no-till farming and integrated nutrient management (West and Post, 2002; Lal, 2004a, c), and biochar application (Lehmann *et al.*, 2006). Soil-C sequestration has numerous ancillary benefits through improvement in soil quality and other ecosystem services. Restoration of degraded soils, through increases in SOC pools, improves agronomic production (Lal, 2006a) which advances food security (2006b) and improves human nutrition (Lal, 2009). Increasing the SOC pool is also important to enhancing efficacy of limited resources of N and P (Smil, 1990). There are also benefits to water quality from control of non-point source pollution. Important progress is also being made in measurement and monitoring of SOC concentration using field techniques (Ebinger *et al.*, 2003), remote-sensing devices (Shephard and Walsh, 2002) and other non-invasive and *in-situ* devices (Wielopolski, 2006; Wielopolski *et al.*, 2000).

CONCLUSIONS

Rapidly increasing atmospheric abundance of CO_2 and other GHGs leading to an increase in mean global temperature of 1 to 4°C by the end of the 21st century necessitates identification and use of relevant adaptation strategies. Depending on land use and management, sustainable agricultural ecosystems can be an important part of the solution to ACC and other environmental issues. While adjusting to time-of-farm operations and identification of appropriate species and rotation cycles, important soil- and water-management options must be carefully assessed. Sustainable soil-management options include conservation tillage with residue management, integrated nutrient management, and restoration of degraded soils. Water-management options include those that conserve water in the root zone and buffer crops against drought stress and other extreme events. These adaptation strategies are especially important to resource-poor and small landholders of the tropics. The goal of the adaptation strategies is to stabilize agronomic production against the adverse impact of biotic and abiotic stresses projected to be exacerbated by ACC.

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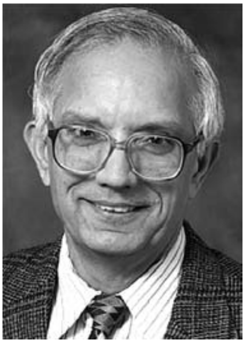

Rattan Lal is a professor of soil physics in the School of Environment and Natural Resources, and director of the Carbon Management and Sequestration Center at the Ohio State University (OSU). He has a BSc from Punjab Agricultural University, an MSc from the Indian Agricultural Research Institute, a PhD from OSU, and he worked at the University of Sydney, Australia, as a Senior Research Fellow. From 1969 to 1987 at the International Institute of Tropical Agriculture, Ibadan, Nigeria, he conducted long-term experiments on watershed management, water budgets in relation to land use, and land-use change, erosion control, water conservation in the root-zone, no-till farming, and agroforestry. Since joining OSU in 1987, he has worked on soils and climate change, drainage of agricultural lands, soil degradation and global food security.

Professor Lal is a fellow of the American Society of Agronomy (ASA), the Soil Science Society of America (SSA), Third World Academy of Sciences, American Association for the Advancement of Science, Soil and Water Conservation Society (SWCS), and the Indian Academy of Agricultural Sciences. Among many awards, he is the recipient of an honorary Doctor of Science degree from Punjab Agricultural University, India, and from the Norwegian University of Life Sciences, Aas, Norway.

He has (co)authored over 1,350 research publications and has (co)edited forty-three books and written thirteen.