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Review Article

Managing soils for a warming earth in a food-insecure and energy-starved world§

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Abstract

World energy consumption increased from 11.5 EJ in 1860 to 463 EJ in 2005, and is projected to be 691 EJ in 2030 and 850 EJ in 2050. The principal driver of such a drastic surge in energy demand is the increase in world population which was merely 1 billion in 1800, 1.6 billion in 1900, 6.0 billion in 2000, and is projected to be 7.5 billion in 2030 and 9.2 billion in 2050 before stabilizing at ≈10 billion by 2100. Heavy reliance on fossil-fuel consumption has increased atmospheric CO_2 abundance from 280 ppm in 1750 to 383 ppm in 2008 and is increasing at ≈2 ppm (4.2 Pg) per year along with the attendant threat of climate disruption. Similar to the close link between energy use and atmospheric chemistry, there also exists a close link between food insecurity and climate change through degradation of soils and desertification of the ecosystems. Global annual per capita cereal consumption increased from 267 kg in 1950, peaked at 339 kg in 1985, and decreased to 303 kg by 2000. In the quest for identifying alternate sources of energy, world production of bioethanol (mostly from corn grains in USA and sugarcane in Brazil) was 65 billion L, and that of biodiesel was 13 million Mg (t) (55% in EU countries) in 2008. Conversion of lignocellulosic biomass, using crop residues or establishing energy plantations, has severe constraints of the additional requirements for land area, water, and plant nutrients. Removal of crop residues for energy and other uses has severe adverse impacts on soil quality and agronomic productivity. Yet, globally average crop yields must be increased by 60% to 120% between 2000 and 2050 for meeting the needs of increase in population and change in dietary habits. Meeting demands of the growing world population and rising aspirations necessitate serious and objective considerations of change in food habits (to a more vegan diet), improvement in energy-use efficiency, increase in crop yield per unit area and input, restoration of degraded soils and ecosystems, widespread adoption of recommended soil and crop practices, and identification of non-C fuel sources.

Key words: climate change / biofuels / renewable energy / soil management / crop residues / agricultural co-products

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1 Introduction

The world is faced with the trilemma of climate change, food insecurity, and the energy demand (Fig. 1). Sustainable management of the world's soil resources is essential to effectively addressing these issues. While scientific capacity to eradicate famines was achieved during the 20th century (*Devereux*, 2009) and elsewhere in developing countries, there still are more than 1 billion food-insecure people in the world (*FAO*, 2009a). Furthermore, the world food supply will have to be doubled between 2005 and 2050 (*Borlaug*, 2009) because of the increase in population and change in dietary preferences. The persistent problem of food deficit and famines in Sub-Saharan Africa (SSA) and South Asia (SA) is also exacerbated by the increase in food prices (*Pinstrup-Anderson*, 2009), soil degradation (*Lal*, 2009), and climate change (*IPCC*, 2007). Drought stress in India in 2009 and in Australia for 2006–2009 has exacerbated the problem of global food deficit. Similar to food, the world energy demand is also increasing rapidly and is projected to increase to 850 EJ (+84%) by 2050 compared with 2005. The emphasis on biofuels (*Fisher* and *Schrattenholzer*, 2001) is strongly impacting the availability of grains for food and soil resources for grain production (Yet, the world's hungry population cannot be deserted (*Anonymous*, 2008)).

The 20th century witnessed an unprecedented increase in the use of natural resources. *Ponting* (2007) estimated that during the 20th century, between 1900 and 2000, the factor of increase in global parameters was 3.8 for total population, 12.8 for urban population, 35 for industrial output, 12.5 for energy use, 300 for oil production, 9 for water use, 6.8 for irrigated cropland area, 342 for fertilizer use, 65 for fish catch, 1000 for production of organic chemicals, and 7750 for car

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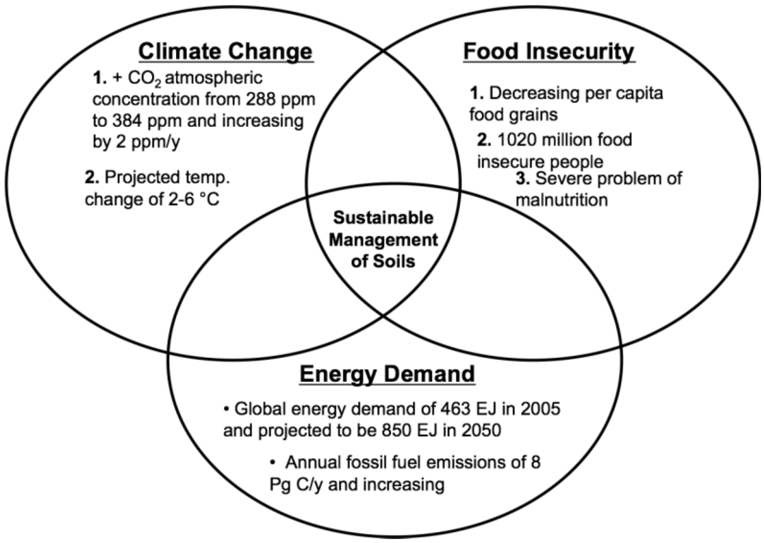

Figure 1: Addressing the trilemma of climate change, food insecurity, and increasing energy demand through sustainable management of world's soil resources.

ownership. Similar increase in use of natural resources during the 21st century is neither feasible nor desirable. The natural resources, especially soils and water, are already under great stress and must be improved and restored. Loss of ecosystem resilience, because of additional demands of the growing population with rising aspirations of the standards of living, would have severe impact on ecosystem services. Therefore, the objective of this article is to describe the importance of sustainable management of global soil resources to meet the just needs of the growing population for food, feed, fiber, and fuel, while also adapting to and mitigating the abrupt climate change (ACC). The answer lies in soils.

2 Global food demand

The green revolution of the 1960s, which brought about a quantum jump in agronomic production in SA and elsewhere, was based upon growing input-responsive varieties under irrigated conditions with use of chemical fertilizers and pest-control measures. Worldwide irrigated land area increased from 97 Mha in 1950 to 275 Mha in 2000 (Tab. 1). Irrigated cropland area of ≈18% produces >40% of total agronomic output. Similar to irrigation, global fertilizer use increased by a factor of 14 (Tab. 2), of which N use increased by a factor of 8. Global N use of 80.9 × 10^6 Mg y^{-1} in 2000 is projected to increase to 135 × 10^6 Mg y^{-1} by 2020 and 236 × 10^6 Mg y^{-1} by 2050. Consequently, the land area needed to feed one person decreased from ≈0.48 ha in 1950 to 0.25 ha in 2000 (*Ausubel*, 2001) and is projected to decrease with future advances in agronomic production. Global cereal yield increased from ≈1500 kg ha^{-1} in 1961 to ≈3000 kg ha^{-1} in 2005, and the global per capita harvested area decreased from 0.21 ha per person in 1961 to 0.10 ha per person in 2005 (*Funk* and *Brown*, 2009).

Despite the impressive gains, however, the Green Revolution has stalled in SA since mid 1980s, along with the threat of excessive water withdrawal in N India (*Kerr*, 2009). In 2008,

Table 1: World irrigated-land use (adapted from *Ponting*, 2007; *FAO*, 2008, 2009b; *Postel*, 1999).

Year	Irrigated land	
	Total / 10^6 ha	% of Cropland
1800	14	
1900	41	
1950	97	8.6
1960	135	11.3
1970	169	13.1
1975	189	
1980	210	
1990	244	16.1
2000	275	17.9
2003	277	18.0
2020	300	
2050	359	

Table 2: World total fertilizer consumption (*IFDC*, 2004; *Tilman* et al., 2001; *Ponting*, 2007).

Year	Fertilizer-Nutrient Use / 10^6 Mg y^{-1}			
	N	P	K	Total
1990	0.41	0	0	0.41
1950	9	0	0	9
1960	12	11	9	32
1970	2	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	–	–	–

Table 3: Trends in global average yield of stable food crops (adapted from *Clay*, 2004; *FAO*, 2008).

Crops	Global Average Yield / Mg ha^{-1}						% Increase (1960–2007)	
	1960	1970	1980	1990	2000	2007	Total	% y^{-1}
Corn	1.9	2.4	3.2	3.7	4.3	4.9	158	3.4
Rice	1.9	2.4	2.8	3.5	3.9	4.2	121	2.6
Sorghum	0.9	1.1	1.2	1.4	1.4	1.5	67	1.5
Soybean	1.1	1.5	1.6	1.9	2.2	2.3	109	2.3
Sugarcane	50	55	55	62	64	71	42	0.9
Wheat	1.1	1.5	1.9	2.6	2.7	2.8	155	3.4

the total food-grain production worldwide was less than the consumption. The world food stocks decreased by 50% since 1955 from a reserve of 116 d to only 57 d by the end of 2006 (*Brown*, 2009). Crop yields are practically stagnant since the 1990s. Global average increase in crop yield was 4% y^{-1} between 1960 and 1980, 2% y^{-1} during 1990s, and <1% during 2000s (Tab. 3). The projected ACC may have a negative impact on agronomic production, especially through warming of the ocean (*Funk* and *Brown*, 2009) and degradation of soils (*Lal*, 2009). It is estimated that increase in mean global temperature by 2°C may reduce agricultural output in the main grain-producing regions of the world by about a quarter. Chronically undernourished/food-insecure people in the world, estimated at 850 million around 2004 (*Borlaug*, 2007), has increased to 1020 million in 2009 (*FAO*, 2009a) with severe adverse impact on children in the poorest nations (*Dugger*, 2007a, b). The per capita grain consumption peaked in 1985 at 335 kg, which decreased to 302 kg in 2000 (Tab. 4). Grain production per person in SSA has decreased from 150 kg in 1960 to <120 kg in 2005 (*Brown*, 2004) and is projected to decrease drastically by 2030 (*Funk* and *Brown*, 2009).

Table 4a: Total global grain production and per capita grain consumption (*FAO*, 2009).

Year	Production / 10^6 Mg	Per Capita Consumption / kg
1950	631	267
1955	759	273
1960	824	271
1965	905	270
1970	1079	291
1975	1237	303
1980	1430	321
1985	1647	339
1990	1769	335
1995	1713	301
2000	1840	303

Among numerous causes of agrarian stagnation, the severe problem of soil degradation and desertification is an important factor which cannot be ignored. Globally, area prone to soil degradation by a range of processes is estimated at 1965 Mha comprising 1094 Mha prone to water erosion (8.4% of Earth's land area), 549 Mha by wind erosion (4.2%), 239 Mha by chemical degradation (1.8%), and 83 Mha by physical degradation (0.6%) (*Oldeman*, 1994). On the basis of decline in net primary productivity, *Bai* et al. (2008) estimated total area affected by land degradation at 3500 Mha (23.5% of Earth's area) with a total loss of NPP of 955 Mt C y^{-1} and adversely affecting 1.54 billion people (23.9% of world population). Secondary salinization of irrigated land, impacting about 73 Mha worldwide, has severe adverse impacts on agronomic productivity of croplands. The land area under

Table 4b: Global grain production and per capita consumption (*FAO*, 2009b).

Year	Total Production / 10^6 Mg y^{-1}				Per Capita Consumption / kg y^{-1}			
	World	China	India	SS Africa	World	China	India	SS Africa
1960	877	109	87	13 (1966)	135	118	143	115
1965	998	162	79	14	142	149	145	116
1970	1192	200	113	16	143	154	151	110
1975	1359	244	127	18	143	163	138	112
1980	1550	280	140	20	149	180	140	119
1985	1821	339	165	22	157	210	145	112
1990	1952	404	193	24	160	207	159	105
1995	1897	418	210	24	158	194	165	107
2000	2060	407	234	27	153	181	153	113
2005	2267	429	239	35	151	157	158	115

Table 5: Estimates of land area under crops and pastures (*FAO*, 2008; *Richards* et al., 1990).

Year	Area Under Different Land Uses / 10^6 ha		
	Cropland	**Grazing Land**	**Pastures**
1700	265	6860	–
1850	537	6837	–
1920	913	6748	–
1950	1170	6780	–
1980	1346	6788	3244
1990	1396	–	3368
2005	1402	–	3442

Table 6: Per capita cropland area (recalculated from *Rees*, 2004).

Country	**Cropland Eco Foot Print** / ha (Average Productivity)	**Domestic Cropland** / ha (Average Prod. Equiv.)
Canada	1.02	1.62
Australia	0.81	2.07
United States	0.71	0.83
Spain	0.50	0.43
Hungary	0.41	0.50
Netherlands	0.38	0.12
Mexico	0.36	0.21
United Kingdom	0.33	0.26
Germany	0.32	0.34
Brazil	0.31	0.35
Nigeria	0.26	0.36
Peru	0.21	0.17
China	0.14	0.14
Thailand	0.14	0.26
Indonesia	0.13	0.13
India	0.13	0.13
Pakistan	0.13	0.12
Ethiopia	0.10	0.10
Bangladesh	0.09	0.09
Mozambique	0.09	0.08

Table 7: Required cereal yield and production to meet future demands (adapted from *Wild*, 2003).

Year	**Cereal Yield** / Mg ha^{-1}	**Total Production** / 10^6 Mg
2005	3.27	2240
2025 a.	3.60	2780
b.	4.40	3629
2050 a.	4.30	3255
b.	6.00	4553

a = without dietary change
b = with change to preference for meat-based (animal-based) diet

crops (and pastures) has increased by a factor of 5.3 between 1700 and 2000 (Tab. 5), the per capita cropland area is progressively declining (Tab. 6; *Brown*, 2004; *Funk* and *Brown*, 2009). The challenge lies in increasing global yield of cereals from 3.27 Mg ha^{-1} in 2005 to 3.60 Mg ha^{-1} by 2025 and 4.30 Mg ha^{-1} by 2050 without any dietary change, and to 4.40 Mg ha^{-1} by 2025 and 6.0 Mg ha^{-1} by 2050 with possible dietary change in the developing countries (Tab. 7). The drought may affect crop yields because of climate change which will accentuate extremes (*Allan* and *Soden*, 2008; *Kerr*, 2007, 2009) and reduce water availability for agriculture because of the rising energy prices (*Zilberman* et al., 2008; *Collier*, 2008; *Levine*, 2009). In addition to crop improvement (*Stone*, 2008), conserving water to meet present and future water requirements (*Falkenmark* et al., 2009; *Rockström*, 2003) and making every drop count (*Finkel*, 2009) are important to advancing food security. While emphasizing the supply, there is also a need to address the demand side of food production. Stabilizing the world population at lower than the projected level of 9.5 or 10 billion and emphasizing the plant-based (vegan) diet are important strategies. Land, water, nutrients, and energy requirements are too high for the animal-based diet and for the rising population.

3 Global energy demand

Global energy demand increased 40 times from 11.5 EJ in 1860 to 463 EJ in 2005 and is increasing at the rate of 2% to 3% y^{-1} (*EIA*, 2008; Tab. 8). The global daily oil consumption of 18.9 billion L (86 billion barrels) is equivalent to 2.8 L d^{-1} per person for world population of 6.7 billion in 2008. Global energy demand, and the fossil-fuel consumption, are rapidly increasing (Tab. 8). Heavy reliance on fossil fuels has intensified per capita C emissions (Mg C $person^{-1}$ y^{-1}), which are estimated at 5.32 for USA, 4.95 for Australia, 4.54 for Canada, 3.11 for Norway, 2.63 for Japan, 2.60 for Germany, 2.47 for U.K., 1.69 for France, 1.16 for China, 0.48 for Brazil, 0.35 for India, 0.23 for Nigeria, 0.08 for Bangladesh, 0.03 for Ethiopia, and 0.01 for Burundi for 2005 (Tab. 9; *Marland* et al., 2005). Per capita energy use in China is only 20% of that of the USA and 50% of that of Japan. Similarly, per capita energy use in India is only 7% of that of the USA and 13% of that of Japan. The per capita energy use in Burundi and many other countries in SSA is <0.2% of that of the USA. One of the consequences of the heavy reliance on fossil-fuel consumption is the increase in atmospheric abundance of CO_2 and other greenhouse gasses (GHGs) (*WMO*, 2008), with attendant ACC and climate disruption. If energy use in populous emerging economies (*e.g.*, China, India) and countries with rapidly increasing population (SSA, SA) was to increase to the level enjoyed by those in N America and W Europe, the impact on ACC and the quality of natural resources would be dramatic (*IPCC*, 2007). There is a growing and strong emphasis on biofuels because of the threats of ACC and climate disruption.

4 Biofuels

Humans have used biomass as a source of energy (traditional biofuels) ever since the discovery of fire. Traditional

Table 8: Global energy demand between 2006 and 2030 (recalculated from *EIA*, 2008).

Year	Energy use / 10^9 t of oil equivalent						
	Oil + Gas	**Coal**	**Biomass & Waste**	**Nuclear**	**Hydro**	**Wind, Solar, & Other Renewables**	**Total**
2006	6.32	3.16	1.21	0.73	0.48	0.05	11.84
2015	7.54	4.14	1.60	0.50	0.24	0.10	14.1
2020	7.78	4.38	1.46	0.73	0.48	0.15	14.95
2025	8.27	4.86	1.46	0.73	0.68	0.18	16.20
2030	8.51	4.86	1.70	0.97	0.97	0.24	17.25
Growth / % y^{-1}	2.8	2.0	1.4	0.9	1.9	7.2	0.22

Table 9: Per capita CO_2 emissions in 2005 (adapted from *Marland* et al., 2005).

Country	**Per Capita Emission** / Mg C y^{-1}
USA	5.32
Australia	4.95
Canada	4.54
Norway	3.11
Japan	2.63
Germany	2.60
U.K.	2.47
France	1.69
China	1.16
Brazil	0.48
India	0.35
Nigeria	0.23
Bangladesh	0.08
Ethiopia	0.03
Burundi	0.01
World	**1.23**

biofuels comprise of a range of biomass including wood, crop residues, and animal dung. Wood is still considered a viable option to generate energy (*Dotty*, 2009), and other sources of biofuel feedstocks are being identified. Assessment of the global distribution of net primary productivity (*Huston* and *Wolverton*, 2009), increasing yields of biomass (*Abelson*, 2008), viability or lack of it of using crop residues (*Lal* and *Pimentel*, 2007) and the challenges of using croplands for biofuel are being addressed (*Searchinger* et al., 2008) to meet the booming ethanol demand (*Tyner*, 2008). Bioelectricity is considered by some as better option than bioethanol (*Campbell* et al., 2008). Modern biofuels involve either co-combustion of wood (*Richter* et al., 2009) with coal, conversion of animal manure and other plant/animal products into methane, fermentation of sugar (*e.g.*, from sugarcane, sugarbeet, or sweet sorghum) and starch (*e.g.*, corn, cassava) into bioethanol, and extraction of vegoil from grains (*e.g.*, soybean, rapeseed, peanut) or tree seeds (*e.g.*, palm oil, jatropha). Because of growing demand for food for the rapidly increasing world population, there is a strong interest in developing the second-generation biofuels. These include conversion of lignocellulosic materials into ethanol. Estimates of the crop residues produced in the US are available (*Graham* et al., 2007). As of 2009, there is not a single commercial-scale production unit converting plant biomass into ethanol. However, one such plant is planned to be commissioned in Georgia, USA in 2010.

Estimates of traditional and industrial uses of biofuels include ≈2.5 Pg of biomass, including 1.35 Pg of wood, 0.49 Pg of crop residues, 0.075 Pg of animal dung (mostly in SA), 0.039 Pg of charcoal, and ≈0.5 Pg of industrial products (*Fernandes* et al., 2007). Energy produced in 2000 through traditional biofuels worldwide is estimated at 36–53 EJ (7.7%–11.5% of the world's total energy use) and 6–7 EJ through modern biofuels (13%–15%) (*Hoogwijk* et al., 2009). In 2008, liquid-biofuel production worldwide included 65 billion L of ethanol (80% of which was produced in Brazil from sugarcane and in USA from corn grains), 13 million Mg (t) of biodiesel (55% in EU countries) (*Popp*, 2009). Worldwide, 6% of grains produced in 2008 were used for ethanol production and 9% of vegoil for biodiesel. Ethanol production (primarily from corn grains) is increasing rapidly in USA, which was 9 billion gallons in 2008, 10.5 billion gallons in 2009, and is projected to be 15 billion gallons in 2015.

Commonly used crops for production of bioethanol and biodiesel are listed in Tab. 10. In terms of ethanol, energy-production capacity is estimated at 120 GJ ha^{-1} for sugarcane, 140 GJ ha^{-1} for sugarbeet, 80 GJ ha^{-1} for cassava, and 70 GJ ha^{-1} for corn grains. In terms of biodiesel, energy-production capacity is 193 GJ for oil palm, 42 GJ for rapeseed, and 14 GJ for soybean.

Crop residues are widely considered as a source of lignocellulosic biomass. 1 Mg of lignocellulosic material is equivalent to 280 L of ethanol, 15–18 GJ or 3×10^6 kcal of energy (16×10^6 BTU) or two barrels of diesel (*Lal*, 1995b, 2008a, b). Global production of crop residues is estimated at ≈4 Pg compared with ≈0.5 Pg in the USA (*Lal*, 2005). Removal of crop residues, however, is not an option (*Lal*, 2007b) because of the negative impacts of removal on soil quality, and increase in soil erosion (*Lal*, 1995a), and positive impacts of its retention on numerous ecosystem services. Therefore, production of biofuel feedstock by growing dedicated species as energy plantations is widely being considered. Examples

Table 10: Crops suitable for biofuel production (adapted from *FAO*, 2006; *Marris*, 2006).

Crop	Biofuel Product	Biofuel yield / L ha^{-1}	Energy yield / GJ ha^{-1}
Sugarcane	Ethanol	6000	120
Sugarbeet	Ethanol	7000	140
Cassava	Ethanol	4000	80
Maize	Ethanol	3500	70
Palm Oil	Biodiesel	5500	193
Rapeseed	Biodiesel	1200	42
Soybean	Biodiesel	400	14

of species for biofuel plantations include warm-season grasses (*e.g.*, switch grass, *Miscanthus*, big blue stem, guinea grass, elephant grass, kallar/karnal grass) and short-rotation woody perennials (*e.g.*, poplar, willow, black locust, mesquite, birch, eucalyptus). Establishing energy plantations would also eliminate some of the underlying causes of tropical deforestation (*Geist* and *Lambin*, 2002).

Degraded soils are often considered as possible land for establishing energy plantations. With a low biomass-production capacity of ≈4 Mg ha^{-1} y^{-1}, biomass production on 358–472 Mha of globally abandoned agricultural land can meet <10% of the energy demand in countries in N America, Europe, and Asia (*Campbell* et al., 2009). With current yield and technology and to meet the current energy demands, additional land area required to establish energy plantations is ≈850 Mha compared with currently used cropland area of 1540 Mha in the world and 904 Mha in the developing countries. Deforestation of tropical rainforest, especially peatlands, for establishing energy plantations can create a large soil C debt which can take decades and centuries to repay (Tab. 11).

In addition to land, successful establishment of energy plantations also needs plant nutrients (especially N and P), and water. Adequate supply of water, needed at 1000–3500 L per L of biofuels is an important factor. While corn-based ethanol has several limitations (*Charles*, 2009), driving on biomass (*Ohlrogge* et al., 2009), cellulosic biofuels (*Regalbuto*, 2009), or using crop residues as sources of biomass (*Tilman* et al., 2009) are not viable options either (*Lal*, 2007b). Furthermore, biomass is hard to transport and can potentially hinder the integration of manufacturing-scale processes (*Williems* et al., 2009). Such a strategy may increase competition of limited land and water resources thereby increasing food crop and livestock prices (*Wise* et al., 2009). Harvesting the sun through biofuels (*Kramer*, 2009) has a hidden cost which must be considered. Low-temperature pyrolysis of biomass to generate energy and use of biochar as a soil amendment are possible options (*Chan* et al., 2007; *Fowles*, 2007; *Lehmann* et al., 2006; *Lima* et al., 2002; *Maoris*, 2006; *Rumpel* et al., 2006; *Seifritz*, 1993; *Schmidt*, 2004; *Sombroek* et al., 2003; *Steiner* et al., 2007). Charcoal is relatively stable and not rapidly decomposed (*Shneour*, 1966), but may accentuate the decomposition of soil organic matter in soil/site-specific situations (*Wardle* et al., 2008).

5 Soil and climate change

Since 1750, anthropogenic perturbations have resulted in gross global temperature increase equivalent to 1.95°C comprising of 1.6% caused by emissions of greenhouse gases (CO_2, CH_4, N_2O), 0.3% caused by soot particles, and 0.05°C caused by the urban heat-island effect. There is also a cooling effect caused by aerosols (*e.g.*, SO_4^{2-}, Cl^-, NO_3^-, NH_4^+) equivalent to 1.2°C. Biomass burning causes short-term cooling but long-term warming (*Jacobson*, 2004). Thus, the net increase in global temperature since 1750 is ≈0.75°C. The projected increase in global temperature, under business-as-usual (BAU) scenario, is 2°C–6°C by 2100 (*IPCC*, 2007). An appropriate and prudent response to the warming world (*Penuelas* and *Filella*, 2001) because of the irreversible climate change due to CO_2 emissions (*Solomon* et al., 2009) require a critical appraisal of all options. The CO_2 arithmetic in relation to emissions (*Broecker*, 2007) and a fair and just consideration for poorest nations (*Revkin*, 2007) are critical issues. It is thus important to identify management systems for adapting to ACC through improvement of soil quality, changing to appropriate farming/cropping systems, altering timing and type of farming operations, and enhancing farm income through payments for ecosystem services (Fig. 2). The terrestrial sequestration is a natural fix involving ecosystems in climate mitigation (*UNEP*, 2009). The goal is to enhance soil/ecosystem/social resilience (*Walker* and *Salt*, 2006) by identifying new opportunities, and enhancing eco-

Table 11: Effect of land clearing for biofuel production on ecosystem carbon debt (recalculated from *Fargione* et al., 2008).

Crop	Biofuel Product	Former Land Use	Site	C Debt / Mg C ha^{-1}	Time to Repay Biofuel C Dept/y
Oil Palm	Biodiesel	Tropical forest	Indonesia/Malaysia	191 (48)	86
Oil Palm	Biodiesel	Peatland forest	Indonesia/Malaysia	941 (805)	423
Soybean	Biodiesel	Tropical forest	Brazil	201 (55)	319
Sugarcane	Ethanol	Cerrados (woods)	Brazil	45 (27)	17
Soybean	Biodiesel	Brazil	Brazil	23 (23)	37
Corn	Ethanol	Grassland	USA	37 (3)	93
Corn	Ethanol	Abandoned cropland	USA	19 (1.4)	48
Prairie Biomass	Ethanol	Marginal cropland	USA	0	No Debt

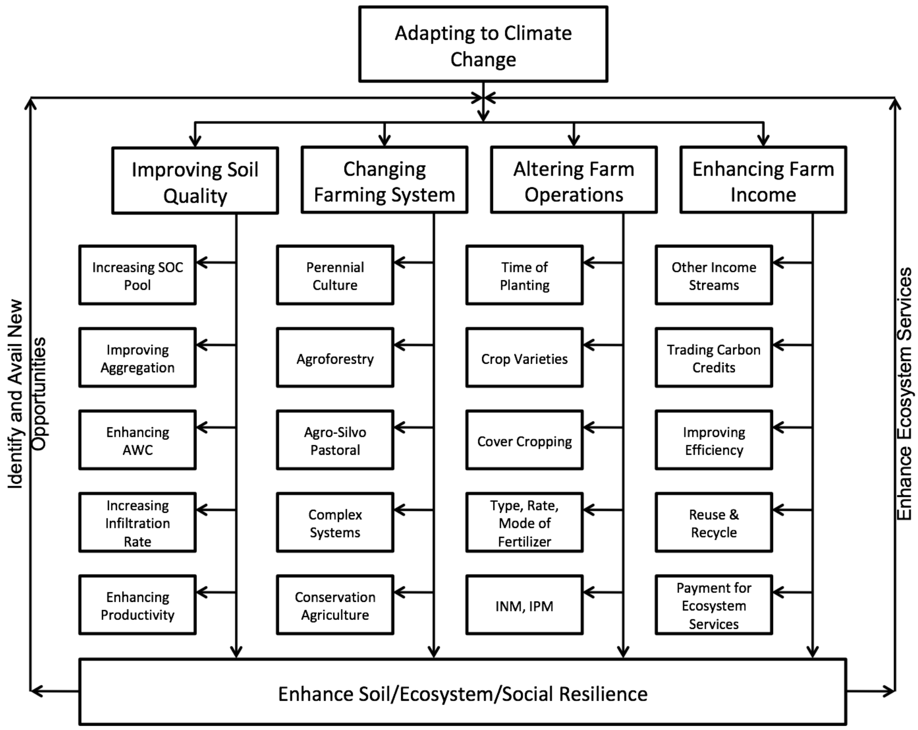

Figure 2: Soil management and farming systems for adapting to climate change (INM = integrated nutrient management, IPM = integrated pest management).

system services. Land-use change still contributes about 16% of the total anthropogenic emissions (Tab. 12). Therefore, identifying management systems which make agriculture an integral component of any solution to climate change is essential for advancing food security and harvesting numerous ecosystem services (*Lovejoy* et al., 2008) based on an integrated approach (*Rustad*, 2006). Sustainable management of soils is integral to the wellbeing of the so called carbon civilization (*Lal*, 2007a).

Global atmospheric concentration of CO_2 increased from 280 ppm in the pre-industrial era (≈1750) to 385 ppm in 2008, with annual rate of increase of ≈2 ppm or 4.2 Pg C y^{-1} during the 2000s (*Canadell* et al., 2007). The positive feedback, with the projected climate change leading to thawing of the permafrost (*Zimov* et al., 2006; *Schurr* et al., 2008), renders Tundra regions a major source of greenhouse gases. Therefore, mitigating climate change through adoption of improved agriculture is an appropriate and much preferred strategy. In this regards, soil management can play an important role in both sequestering emissions and also reducing emissions (Fig. 3).

Table 12: Contemporary global carbon budget (adapted from *IPCC*, 2000, 2007; *Canadell* et al., 2007).

Parameter	1980s	1990s	2000s
I. Sources			
1. Fossil fuel	5.4	6.5	7.6
2. Land-use change	**1.5**	**1.6**	**1.5**
Total source	6.9	8.1	9.1
II. Known Sinks			
1. Atmosphere	3.1	3.2	4.1
2. Ocean	2.0	2.2	2.3
3. Land	**0.2**	**0.7**	**0.7**
Total known sinks	5.3	6.1	7.1
III. Unknown Land Sink	1.6	2.0	2.0

Carbon sequestration implies transfer of atmospheric CO_2 into other long-lived C pools (*e.g.*, geologic, oceanic, terrestrial). The geoengineering strategies of capture and injection have a technical potential of 478 Pg, equivalent to reducing emissions by 120 ppm of atmospheric CO_2 (*IPCC*, 2007), even if only 50% of the technical potential is realized (1 Pg = 0.47 ppm of CO_2). While the technology is a work in progress, it is expensive and can merely reduce the magnitude of anthropogenic emissions. The cost of abatement per Mg of C is much lower in natural than in engineering systems (Tab. 13).

Carbon sequestration in the terrestrial biosphere is a natural process, based on photosynthesis of atmospheric CO_2. One hectare of actively growing vegetation (*e.g.*, corn) can photosynthesize 400 times the annual increment of CO_2 (≈2 ppm or ≈12.5 kg C) contained in the entire atmospheric column. Soils play an important role in the global C cycle (*Falkowski* et al., 2000). The rate of soil C sequestration is higher for increasing SOC pool than for improving the formation of secondary carbonates. Furthermore, rates of SOC sequestration are higher for cool and humid than warm and arid climates (*Lal*, 2008a, b, c). The technical potential of C sequestration in world's cropland soils is 0.6–1.2 Pg C y^{-1}. Soil- and crop-management options to enhance SOC pool include NT farming/CA, INM, complex crop rotations, use of biosolids (*e.g.*, manure) (*Lal*, 2004). Identification and implementation of

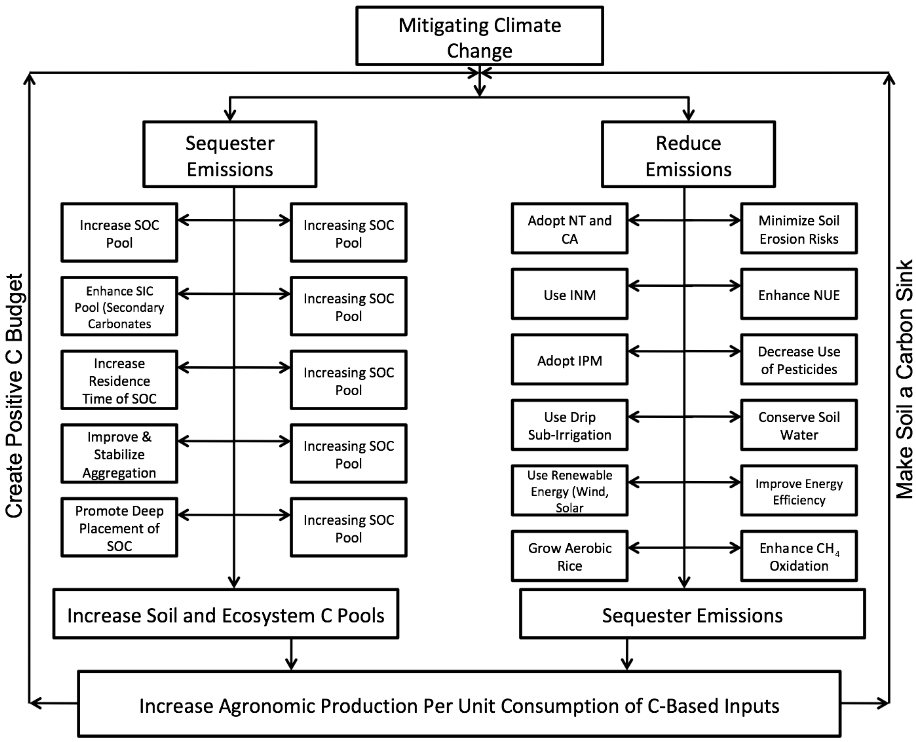

Figure 3: Soil-management options to mitigate climate change by sequestering CO_2, oxidizing CH_4, reducing methanogensis, and minimizing emissions of N_2O by moderating nitrification/denitrification.

strategies which emphasize the biological control of terrestrial C sinks (*Schulze*, 2006), C storage in forest soils and ecosystems (*Lorenz* and *Lal*, 2005), C storage in urban soils (*Pouyat* et al., 2006), and restoring degraded soils (*Muchena* et al., 2005) are among numerous options. Positive feedbacks due to temperature sensitivity of soil (*Davidson* and *Janssens*, 2006) must be duly considered. While geoengineering techniques, including reburial of fossil C in marine sediments, (*Dickens* et al., 2004) are being debated, the role of natural fix (*Trumper* et al., 2009) can never be over emphasized.

In addition to SOC sequestration, there are numerous practices which also lead to reducing emissions. The goal is to minimize the use of energy-intensive inputs (*e.g.*, fertilizers, chemical, irrigation, machinery), by reducing losses and enhancing efficiency (Tab. 14). Energy-intensive practices include seedbed preparation, pest management, soil-fertility improvement, and harvesting and grain drying. Improving use efficiency is essential to reducing emissions. Emissions can also be drastically reduced by increasing production from

Table 13: Cost of carbon sequestration by different techniques (adapted from *McKinsey & Company*, 2009).

Technique/strategy	Cost of abatement C / € (Mg C eq.)$^{-1}$
Tillage and residue management	–183.3
Waste recycling	–55.0
Degraded-land restoration	36.7
Second-generation biofuels	18.3
Pastureland afforestation	36.7
Degraded-forest restoration	44.0
Agriculture conversion	91.7
Biomass-co-firing power plant	110.0
Coal-C capture and sequestration	165.0
Gas plant capture and sequestration	220.0

Table 14: Fossil-fuel-based input in modern agriculture.

Agriculture Process	Specific Activity
1. Seed-bed preparation	Tillage methods (plowing, chiseling, harrowing)
2. Weed/pestcontrol	Intercultivation, herbicides, spraying
3. Soil-fertility management	Fertilizers, applying fertilizers
4. Harvesting	Combine, silage, hay bailing, transport
5. Grain drying	Heating, transport, lifting, storage
6. Marketing	Loading, transport, storage
7. Value addition	Processing, packaging, storage, transport

Table 15: Cumulative avoided emissions from land-use conversion (calculated from *Righelato* and *Spracklen*, 2007).

Land-Use	Conversion to	Avoided Emissions / Mg C ha^{-1}(30 y)$^{-1}$
Tropical forest	Cropland	–200
Tropical cropland	Forest	171
Temperate cropland	Forest	97
Temperate cropland	Grassland	29

existing lands so that any additional deforestation can be avoided (Tab. 15). Converting tropical forest and peatlands to cropland (or energy plantations) creates a large C debt which may take decades or centuries to repay (*Fargione* et al., 2008).

6 Achieving global food security

The global cereal demand is expected to increase at the rate of 1.75% y^{-1} (Tab. 16). The UN Millennium Development Goals will not be met by 2015 (*Sastre*, 2008). The global average cereal yield must be increased accordingly, especially in developing countries. National average crop yields in SSA and SA are low compared with those in developed countries (Tab. 17). Crop yields are low and highly variable in dryland/rainfed cropping systems, due to drought stress caused by variable and uncertain rains. The problem of low yields is exacerbated by the severe problem of soil degradation by erosion, depletion of SOC pool and essential plant nutrients, and either nonavailability or lack of access to essential inputs to resource-poor and low-income farmers. The negative nutrient balance is a problem at the continental scale in SSA (*Anonymous*, 2006; *Henoa* and *Baanante*, 2006; *Sanchez*, 2002; *Vitousek* et al., 2009). While GM crops, organic farming (*Tester*, 2009), and bioengineered crops (*Skostad*, 2009) can be used to enhance crop yields, it is important to realize that there is no viable substitute for judicious soil management. The strategy is to use modern and innovative technologies (*NRC*, 2009a) which sequester C in soils (*NRC*, 2009b), enhance soil/ecosystem/social resilience (*Walker* and *Salt*, 2006), and make every drop of rain count towards minimizing the drought stress. In this regards, the importance of aerobic rice (especially in the rice–wheat system of S Asia) cannot be overemphasized (*Peng* et al., 2006, *Bouman* et al., 2007).

The innovative technology to meet the future demands must also meet the following criteria: (1) limit atmospheric CO_2 concentrations through agricultural ecosystems and land-use conversion (*Wise* et al., 2009), (2) enhance or maintain ecosystem services and minimize their vulnerability to global ACC (*Schröter* et al, 2005), (3) enhance stability and diversity of ecosystems (*Ives* and *Carpenter*, 2007), and (4) restore degraded soils and ecosystems (*Lal*, 2009a).

With reference to enhancing agronomic production of resource-poor and small landholders of developing countries, it is also important to follow the ten laws of sustainable soil management (*Lal*, 2009b):

(1) **Soil degradation and poverty**: The biophysical process of soil degradation is driven by economic, social, and political forces.

(2) **Stewardship and desperateness**: The stewardship concept is relevant only when the basic necessities are met. Desperate people do not care about the stewardship.

(3) **The soil bank**: The nutrient and C pools in soil bank can only be maintained if all outputs are balanced by the inputs.

(4) **The Law of marginality**: Marginal soils cultivated with marginal inputs produce marginal yields and support marginal living.

(5) **The organic dilemma**: Plants cannot differentiate the nutrients supplied through organic or inorganic sources. It is a question of logistics and availability.

(6) **Soil as a source or sink of greenhouse gases**: Agricultural soils can be a major sink for CO_2 and CH_4, depending on land use and management.

(7) **Extractive farming and the environment**: Extractive farming and mining soil fertility adversely impact soil quality, perpetuate hunger and poverty, exacerbate CO_2 emissions, and reduce ecosystem services.

(8) **Synergism between soil management and improved germplasm**: The yield potential of improved germplasm can be realized only if grown under optimal soils and agronomic conditions.

(9) **Agriculture as a solution to environmental issues**: Rather than a problem, agriculture must always be integral to any solution towards environmental development. Humans will always depend on agriculture, and it must be the engine of economic development.

(10) **Modern innovations**: Yesterday's technology cannot resolve today's problems.

Table 16: Global food demand by 2025 (recalculated from *Cassman* et al., 2003; *Wild*, 2003). Cereals include rice, wheat, and maize, which provide 60% of all human calories.

Parameter	1995	2025	2050	Annual rate of change / % y^{-1}
Population / 10^9	5.7	7.9	9.2	1.12
Cereal demand / 10^6 Mg	1657	2436	3255	1.75
Area under cereals / Mha	506	609	625	0.43
Cereal yield / Mg ha^{-1}	3.3	4.0	5.2	1.04

Table 17: Mean crop yield in 2005 in some developing vis-a-vis developed countries (adapted from *FAO*, 2006).

Crops	Average yield / kg ha^{-1}			
	Kenya	Ethiopia	India	Developed Countries
Maize	1640	2006	1907	8340
Sorghum	1230	1455	797	3910
Millet	580	1186	1000	2010
Rice (paddy)	3930	1872	3284	6810
Wheat	2310	1469	2601	3110
Beans, cowpeas	378	730	332	1790
Chickpeas	314	1026	814	7980

7 Conclusions

World soil resources have the capacity to meet basic needs of the present and the future population. For this to happen, the following requirements must be met: (1) observe ten tenets of soil management, (2) decrease human demands and reduce intake of animal-based diet, (3) restore degraded soils and ecosystems, and (4) do not take soils for granted. If soils are not restored, crops will fail even if rains do not; hunger will perpetuate even with emphasis on biotechnology and genetically modified crops; civil strife and political instability will plague the developing world even with sermons on human rights and democratic ideals; and humanity will suffer even with great scientific strides. Political stability and global peace are threatened because of soil degradation, food insecurity, and desperation. The time to act is now (*Lal*, 2008c).

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