Soil Science and the Carbon Civilization

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Soil science must play a crucial role in meeting present and emerging societal needs of the 21st century and beyond for a population expected to stabilize around 10 billion and having increased aspirations for a healthy diet and a rise in the standards of living. In addition to advancing food security by eliminating hunger and malnutrition, soil resources must be managed regarding numerous other global needs through interdisciplinary collaborations. Some of which are to mitigate global warming; to improve quantity and quality of freshwater resources; to enhance biodiversity; to minimize desertification; serve as a repository of waste; an archive of human and planetary history; meet growing energy demands; develop strategies of sustainable management of urban ecosystems; alleviate poverty of agricultural communities as an engine of economic development; and fulfill aspirations of rapidly urbanizing and industrializing societies. In addition to food and ecosystem services, bio-industries (e.g., plastics, solvents, paints, adhesives, pharmaceuticals and chemicals) through plant-based compounds (carbohydrates, proteins, and oils) and energy plantations (bioethanol and biodiesel) can revolutionize agriculture. These diverse and complex demands on soil resources necessitate a shift in strategic thinking and conceptualizing sustainable management of soil resources in agroecosystems to provide all ecosystem services while also meeting the needs for food, feed, fiber, and fuel by developing multifunctional production systems. There is a strong need to broaden the scope of soil science to effectively address ever changing societal needs. To do this, soil scientists must rally with allied sciences including hydrology, climatology, geology, ecology, biology, physical sciences (chemistry, physics), and engineering. Use of nanotechnology, biotechnology, and information technology can play an important role in addressing emerging global issues. Pursuit of sustainability, being a moral/ethical and political challenge, must be addressed in cooperation with economists and political scientists. Soil scientists must work in cooperation with industrial ecologists and urban planners toward sustainable development and management of soils in urban and industrial ecosystems. More than half of the world's population (3.3 billion) live in towns and cities, and the number of urban dwellers is expected to increase to 5 billion by 2030. Thus, the study of urban soils for industrial use, human habitation, recreation, infrastructure forestry, and urban agriculture is a high priority. Soil scientists must nurture symbiotic/synergistic relations with numerous stake holders including land managers, energy companies and carbon traders, urban planners, waste disposal organizations, and conservators of natural resources. Trading of C credits in a trillion-dollar market by 2020 must be made accessible to land managers, especially the resource-poor farmers in developing countries. Soil science curricula, at undergraduate and graduate levels, must be revisited to provide the needed background in all basic and applied sciences with focus on globalization and for preparing students in the competitive world of ever flattening Earth.

The strong link between soil and civilization (Howard, 1940, 1947; Hyams, 1952, Diamond, 2005) is likely to become stronger in the future through an increase in anthropogenic demands on world soils. Agriculture began with the recession of glaciers about 10, 000 BP when the world population was merely 3 million (McEvedy and Jones, 1979; Smil, 2000, 2001). It was 30 million about 2000 BP, 300 million at the onset of the Christian era, and 600 million by about 1600 CE. The world population doubled to 1.25 billion in 1850, 2.5 billion at the end of World War II in 1945, and 5 billion in 1987. It is 6.5 billion in 2007, and projected to stabilize at about 10 billion by 2100 (United Nations, 1998; Fischer and Heilig, 1997; Evans, 1998; Cohen, 2003). Ensuring food security has been a concern of humanity since the dawn of evolution, but especially so since Malthus expressed his apprehensions about the ability of humans to feed themselves (Malthus 1798, 1803). Thus far, those holding Malthusian views (Paddock and Paddock, 1967a, 1967b; Ehrlich and Ehrlich, 1987, 1991, 1992; Ehrlich et al., 1993) have been proven wrong (Boserup, 1965; McRae, 1994) primarily by the soil fertility management technology based on the "mineral nutrition theory" advanced by Justus Von Liebig (Waksman, 1942; Brock, 1997; Hopkins, 1914), and its application to input-responsive varieties of wheat, rice, corn, soybean etc. (Khush, 2001; Swaminathan, 2000). In this regard, the contributions of Haber-Bosch synthesis of ammonia to world's food production cannot be overemphasized. It is because of the use of nitrogenous fertilizers on well-watered fertile soils that global average yield of cereals increased from 1 Mg ha^{-1} in 1900 to 3 Mg ha^{-1} in 2000. Wheat yields in United Kingdom and Holland increased from 2 Mg ha^{-1} in 1900 to >8 Mg ha^{-1} in 2000 (Smil, 2000). However, soil science is facing new and more daunting challenges during the 21st century: of doubling the production by 2050 while improving the environment and mitigating the global warming (Cassman and Harwood,

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1995; Clay, 2004). It is, therefore, relevant to review past, present, and future paths of this relatively new but important discipline of natural sciences, specify the pivotal role that soil science can play, and develop modus operandi of creating such a research and graduate education program at the Land Grant Universities, USDA, and other research and teaching institutions.

Soil science, originated as a branch of geological/earth sciences, became an integral part of agronomy/crop sciences during mid 1930s when the need to grow more food was a high priority nationally and globally. Its close association with agronomic and crop sciences, as signified by the formation of Tri-societies (American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America), was important to ushering the so called "Green Revolution" in the 1970s. The basic principles underlying the success in bringing about a quantum jump in agronomic production during the second half of the 20th century was intensive management of soils, because the population carrying capacity of soil progressively increases with increase in use of external or off-farm input. For example, the population carrying capacity of different farming systems ranges from <1 person km^{-2} for foraging, 1 to 2.5 persons km^{-2} for pastoralism, 10 to 50 persons km^{-2} for shifting cultivation, 100 to 900 persons km^{-2} for traditional farming, to >2000 persons km^{-2} for modern specialized farming (Smil, 1998). Progressive decline in per capita availability of cultivated land area and fresh water resources necessitate use of modern innovations and the relevant land saving technologies. While the cultivated area remained about the same during the second half of the 20th century (Kainuma, 1999), it was the use of supplemental irrigation and fertilizers along with cultivation of input responsive varieties that brought about a quantum jump in food production (MEA, 2005).

With the increase in agricultural production and the attendant improvements in the standard of living, growing aspirations of the industrialized and industrializing societies have created more demands on soil resources. Until the end of the 20th century, principal function of soils was to produce food, feed, fiber, and traditional fuel (wood, biomass) for the growing human population (Fig. 1, the outer blue circles). However, the demands on world soils of the modern or carbon-based civilization have become more diverse and intense, and necessitate a paradigm shift in strategies for sustainable management of the limited and often fragile soil resources. Thus, future path of soil science is an important and a pertinent topic of debates and discussions (IUSS, 2006; McNeill and Winiwarter, 2006).

Therefore, the manuscript's objective is to describe the pivotal role that soil science can and must play during this crucial era when the anthropogenic demands on soil resources are diverse and more critical to human well-being than ever before. Deliberations are specifically focused on the need for creating and strengthening interdisciplinary alliances/synergisms between soil science and other disciplines to understand the interactive processes that underpin

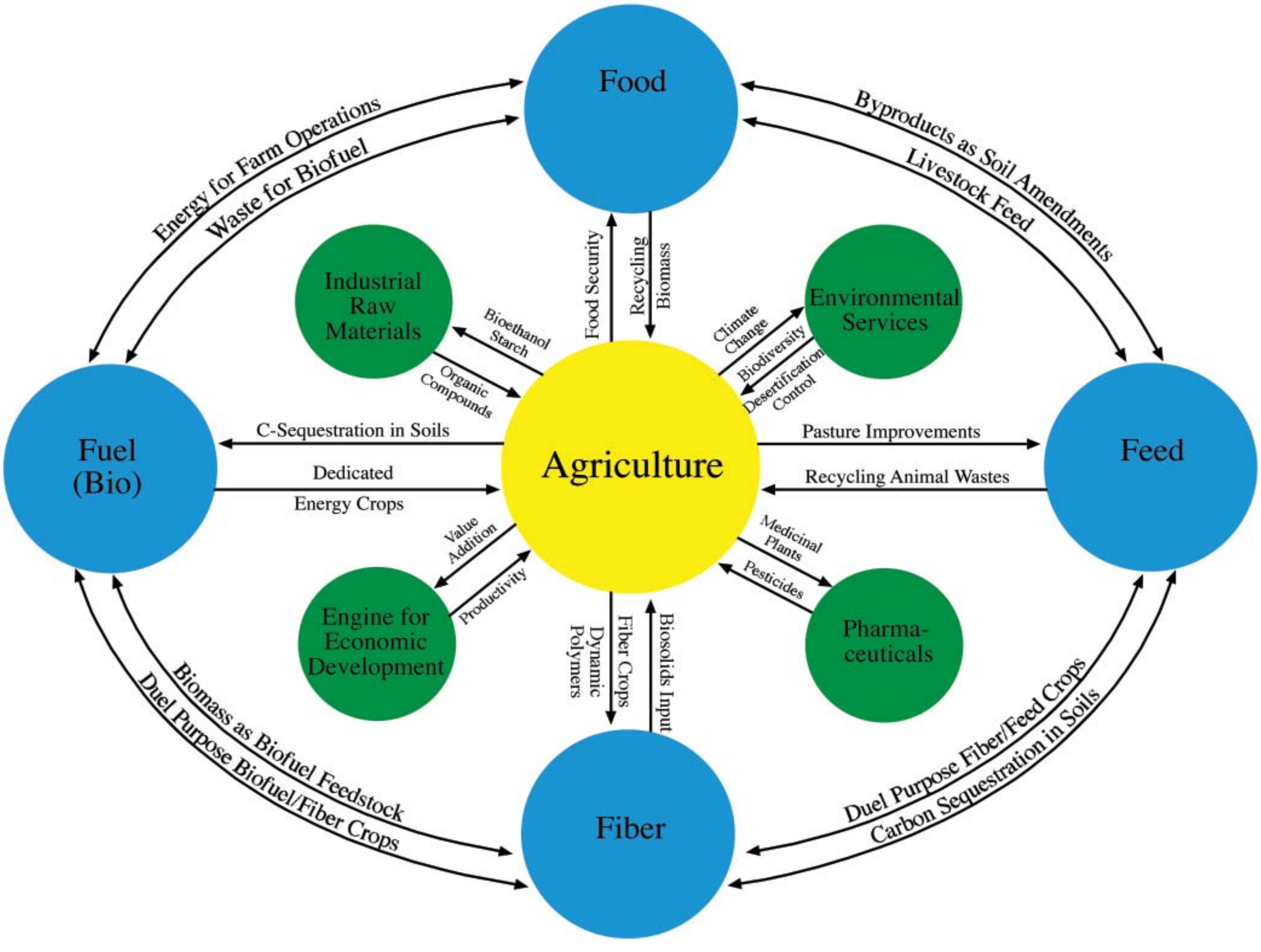

Fig. 1. Expanding role of agriculture in modern societies.

the essential ecosystem services generated through sustainable management of soil resources. The focus is on ideas that revitalize soil science at the Land Grant Universities, reverse the declining trends in faculty recruitment, strengthen student enrollment in graduate programs, and discuss ways to procure external funding and support from all stake holders.

EMERGENCE OF THE CARBON CIVILIZATION AND ITS ENVIRONMENTAL CONSEQUENCES

The industrial revolution, which started around 1750, driven by cheap and easy access to modern energy through fossil fuel combustion, led to mass production of modern amenities at low cost. Indeed all availed amenities by industrialized societies are based on fossil fuel derived energy. Thus, the modern civilization can be appropriately termed “the Carbon Civilization” or the C-Era (Lal, 2007), as compared with the historic hydric civilizations, which thrived in the valleys of Tigris, Euphrates, Nile, Indus, Huang etc. Indeed, the world energy consumption increased 40 times between 1850 and 2005. Ecological footprints (Wackernagel and Rees, 1996) of an increase in population and industrialization of concern to soil science are climate change, water pollution, water scarcity, loss of biodiversity, soil degradation, and desertification. Global emission of CO_2–C increased with increase in population-driven energy consumption. Fossil fuel combustion led to global CO_2–C emission (Tg equals million metric ton equals 10^{12}g) of 3 in 1750, 8 in 1800, 54 in 1850, 534 in 1900, 1630 in 1950, 6700 in 2000 (Marland et al., 2001; Marland and Andres, 2001), and 7300 in 2006. Of the global CO_2–C emissions, those from the USA are 1633 Tg (EPA, 2006). Additional CO_2–C equivalent emissions in the USA comprise 152 Tg from CH_4, 105 Tg from N_2O, and 39 Tg from CFCs. Thus, total emission of CO_2–C equivalent from the USA is 1929 Tg (EPA, 2006). Consequently, the atmospheric concentration of CO_2 has increased from 280 ppmv since the late 1700s to about 380 ppmv in 2006, is presently increasing at the rate of 1.8 ppmv yr^{-1} or 0.47% yr^{-1} (WMO, 2006.) Combustion of fossil fuel equivalent to 4 Pg of C increases CO_2 concentration in the atmosphere by about 1 ppmv (Broecker, 2007). With reference to the baseline of 1850, IPCC (2007) reported that the global average temperature has increased by 0.77°C (from 13.67°C to 14.44°C), snow cover in the northern hemisphere has decreased by 34.8 million km^2, and the mean global sea level has risen by 19.8 cm. In addition, the average coverage of arctic sea ice has shrunk at the rate of 2.7% per decade since 1978 with summertime ice reduction at the rate of 7.4% per decade. There is a strong evidence of an increase in hurricane intensity in the north Atlantic since 1970s. While severity and frequency of droughts have become more intense in lower latitudes (tropics), there has been an increase in precipitation in eastern Americas, northern Europe, and parts of Asia (IPCC, 2007).

In addition to climate change, industrialization has also impacted availability and quality of fresh water resources, a problem that will be more severe than the scarcity of cultivatable land area. There is a close link between water scarcity and food security (Rosegrant and Cai, 2001). While agriculture has been the principal consumer of water, there is a growing demand from urban and industrial sectors. Total and agricultural water use (10^9 m^3 yr^{-1}), respectively, is estimated at 430 and 350 in 1900, 1190 and 860 in 1950, 1990 and 1510 in 1960, 2630 and 1930 in 1970, 3080 and 2100 in 1975, 3970 and 2400 in 1985, 4750 and 2760 in 1995 and 6000 and 3400 in 2000 (Kondratyez et al., 2003). There has been a progressive decline in percentage of water use by agriculture from 81.4% in 1900 to 56.7% in 2000. In contrast, progressive increase in urban and industrial uses, respectively (10^9 m^3 yr^{-1}), is estimated at 20 and 30 in 1900, 60 and 190 in 1950, 80 and 310 in 1960, 120 and 510 in 1970, 150 and 630 in 1975, 250 and 1100 in 1985, 320 and 1560 in 1995, and 440 and 1900 in 2000. The problem of water scarcity is exacerbated by contamination and eutrophication, especially in rapidly industrializing and densely populated countries (e.g., China, India, and Mexico). In addition to industrial effluent, heavy use of pesticides and fertilizers is a serious concern (Tilman et al., 2001).

Increase in population, aided by mechanization of farm operations, led to increase in the global cultivated land area. The cropland area (million hectares) was 265 in 1700, 537 in 1850, 913 in 1920, 1170 in 1950, 1500 in 1980, and 1360 in 2000 (Lal, 2006). The land area under irrigated agriculture (million hectares) was 8 in 1800, 40 in 1900, 100 in 1950, 185 in 1975, 255 in 1995, and 270 in 2000 (Lal, 2006). Despite the progressive increase in total cultivated land area, the per capita arable land areas has and will continue to decline until the population stabilizes and there is no additional urban encroachment and land conversion for infrastructure. The per capita cultivated land area by 2025 (ha) is estimated at 0.05 in Bangladesh, 0.06 in China, 0.03 in Egypt, 0.11 in Ethopia, 0.12 in India, and 0.07 in Pakistan (Engelman and LeRoy, 1993). Similar to water, the problem of land scarcity is also exacerbated by the extent and severity of soil degradation (Oldeman, 1994).

EXPANDING ROLE OF AGRICULTURE

In accordance with the increasing aspirations of industrialized societies, the role of agriculture has to be broadened to meet diverse needs and provide numerous services and functions. Schematics in Fig. 1 (inner green circles) indicate additional demands on agriculture including those for producing industrial raw materials, pharmaceuticals, and chemicals. Basic molecules in plant biomass (e.g., carbohydrates, proteins, oils) can be processed to make plastics, solvents, paints, adhesive, drugs and other products (USDOE, 2006). The issue of sustainable agriculture is to be revisited (Pretty, 2005), and multifunctional production systems may be a necessity to advance agricultural bioeconomy (Jordan et al., 2007). Rather than being a cause, agriculture is increasingly being viewed as a solution to the numerous environmental problems such as mitigation of climate change, enhancement of biodiversity, and improvement in water quality. The strategy is to use technologies that save energy, land and water so that prime agricultural soils are used intensively and the land thus spared is used for nature conservancy, improvement of the quality and quantity of fresh/renewable water resources from protected/afforested watersheds, enhancement of biodiversity, and sequestration of atmospheric CO_2 in terrestrial ecosystems including restored wetlands. The need for expanding the role of agriculture to meeting material and aesthetic needs is equally dire in both industrialized and developing economies.

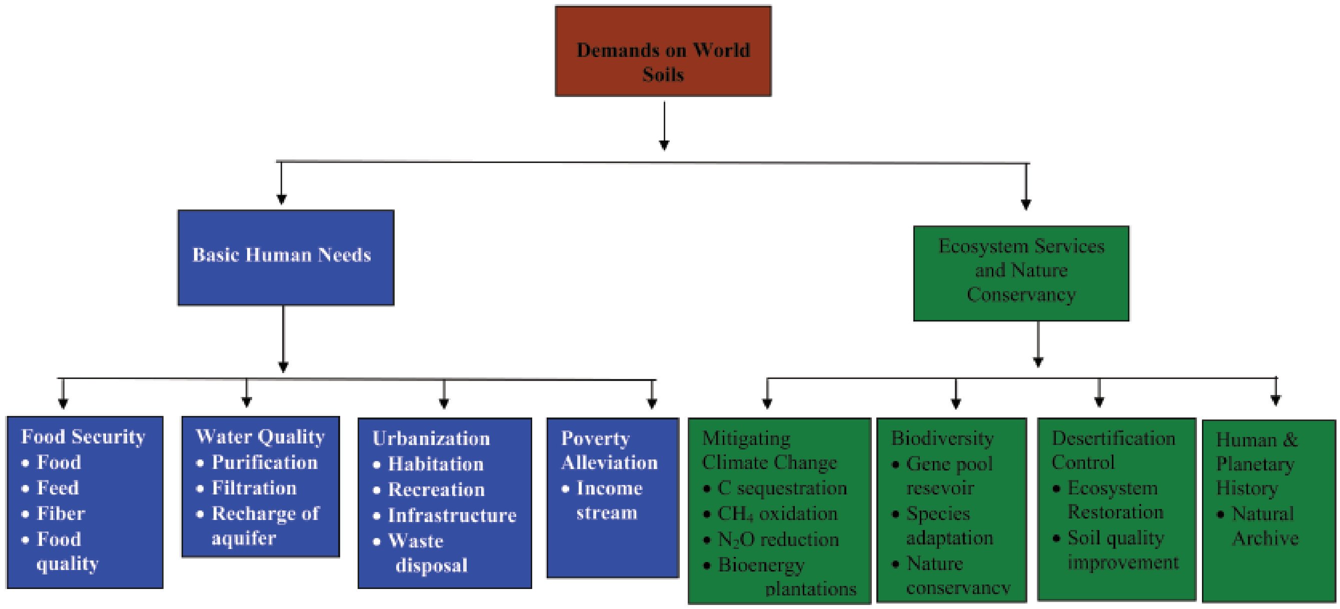

Fig. 2. Present and emerging demands on world soils.

DEMANDS ON SOIL RESOURCES

Rather than traditional functions of being a medium for food production and foundation for engineering structures, there are emerging soil functions (Fig. 2) that must also be recognized and addressed by the scientific community through cooperation with allied disciplines (Fig. 3).

1. Global Food Security

Despite impressive gains in agricultural production during the second half of the 21st century, food insecurity still haunts about 850 million inhabitants globally and the problem is being exacerbated in sub-Saharan Africa (SSA) (Smith et al., 2006) and South Asia (SA; Brown, 2004). It is widely recognized that the United Nation's Millenium Development Goals of cutting hunger by 50% by 2015 will not be met. To meet the food demand, agricultural production will have to be doubled between 2000 and 2050 (Tilman, 1999; Wild, 2003). Achieving the desired increase in production required by 2050, an additional 1 billion hectares of arable land (over and above 1.5 billion hectares presently cultivated) is needed (Tilman et al., 2001). Not only that there is no cause for complacency, the momentum in enhancing food production must also be sustained by identifying land saving technologies at the cutting edge of science (e.g., no-till farming with crop residue mulch and cover crops, soil-centric management to supply nutrients according to site-specific needs, and fertigation to deliver nutrients and water directly to plant roots at the rates required for the specific growth stages). It is important to enhance production from existing land rather than through horizontal expansion by conversion of natural to agricultural ecosystems. Balanced application of plant nutrients is also necessary to improve nutritional value of food grown in soils to minimize the risks of malnutrition and hidden hunger, which are severe problems in SSA and SA (Rosegrant and Cline, 2003; Sanchez, 2002). Soil degradation, especially by accelerated erosion, is also a threat to food security and the environment (Pimentel, 2000; Raloff, 1984; Brown, 1981). Micronutrient deficiency, due to intake of food deficit in essential elements (e.g., Zn, Fe, I, Vitamin A), is a major cause of malnutrition affecting billions of people (especially children) world wide (Underwood, 2003). "Indeed, the health of soil, plant, animal and human is an inter-connected chain. The impaired health of human population in developing countries and elsewhere is a consequence of failure in health of plants and animals due to poor soil health. Low soil quality is the root cause of all" (Howard, 1947). The problem of soil degradation and nutrient deficit is especially severe in SSA, where total nutrient mining is about 8 million Mg (metric ton = 10^6 g) of NPK per

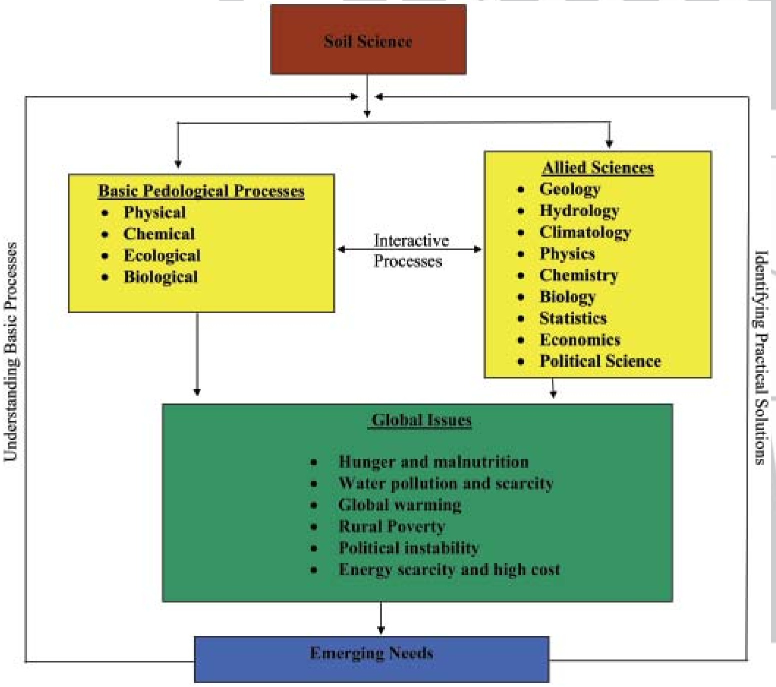

Fig. 3. Using knowledge of soil sciences to address global issues and emerging needs.

year (Henao and Baanante, 2006). Unless drastic changes occur in agricultural productivity, it is estimated that 60 million Mg of cereals will have to be imported to meet the food demands in SSA by 2020 (Henao and Baanante, 2006). That being the case, the presently used extractive farming practices must be replaced by highly productive, science-based and sustainable agricultural systems to ensure humanity's freedom from hunger. While the global average cereal yield is 3 Mg ha^{-1}, the highest yield recorded on research plots are 15 Mg ha^{-1} for rice and wheat, 20 Mg ha^{-1} for maize and 6 Mg ha^{-1} for soybeans (Smil, 2005). There is a large variation among national average yields, with a factor of 5 to 6 among industrialized and developing countries (Bruinsma, 2003). Thus, there is a tremendous scope of increasing production through soil management technologies. Yet, the question whether we need technology for obtaining higher farm yields or a better system of grain distribution remains an interesting intellectual debate (Smil, 2005). There is also a strong case for developing multifunctional production systems (Jordan et al., 2007), which is in agreement with the farming system concept of producing food staples along with achieving ecological services (e.g., C sequestration, biodiversity, water quality).

The issue of rapid urbanization is also closely linked with the food insecurity. Rapid urbanization, especially in land-scarce countries such as China and India, is encroaching on agricultural land that is shrinking rapidly (Chen, 2007). In some regions, topsoil to 1-m depth is removed annually for brick making from as much as 0.5 to 0.7% of the cropland area. Appropriate policy interventions to limit urban encroachment, find alternatives to brick making, and restore degraded/desertified/depleted soils are necessary to achieving global food security. How much land can be spared for nature conservancy and ecosystem services after meeting the basic needs of food, habitation and industrialized uses of 10 billion people? is a question that needs to be objectively addressed

2. Water Scarcity

Food security is also threatened by scarcity of fresh/renewable water resources (Brown, 2004). There are at least 30 densely populated countries (e.g., India,, Nigeria, Iran, Egypt, Tunisia) that will face severe water shortage by 2025 (Engelman and LeRoy, 1995; Gardner-Outlaw and Engelman, 1997). While agriculture is the largest user of fresh water (Gleick, 2003a, 2003b), there is a growing competition from industrial and urban uses (Kondratyev et al., 2003). Humans have greatly transformed Earth's water system (Vorosmarty et al., 2005). The problem of water scarcity is exacerbated by both point (industrial) and nonpoint source (agricultural) pollutions caused by anthropogenic activities (Vorosmarty et al., 2005). The water demand for food production will be greatly enhanced by the projected change in diet of the population from being predominantly vegetarian to animal-based. It is estimated that water requirement per kilogram of animal-based diet is three to four times more than that of the plant based diet. Thus, soil resources will have to be managed to enhance water-use efficiency, denature and filter pollutants, enhance aquifer recharge, and improve water quality and yield from protected watersheds. Water resources must be managed not only for people, but also for nature conservancy (Johnson et al., 2001). The projected climate change may also impact water availability, because there is a strong link between soil degradation, climate change, and water resources (Tao et al., 2005). Rice production, especially when grown in puddled soil and flooded water regime, has a large water requirement. Sustainability of the rice-wheat system in the Indo-Gangetic Plains covering about 13 Mha is threatened by the falling water table and rising temperatures at the flowering stage of wheat (mid March). Development of techniques to produce aerobic rice (direct seeding and grown under an unsaturated soil moisture regime) is a high priority. The objective is to enhance rice production per unit consumption of water. The importance of coupled cycling of H_2O with C (and N) can neither be ignored nor overemphasized.

Soil management practices strongly impact quality of surface and ground waters, because chemical and biochemical characteristics of soils affect quality of water passing over or though it (Kopacek et al., 2004). Application of P (Elrashidi et al., 2001), nitrates (Cambardella et al., 1999), manure (Pote et al., 2001), and other chemicals affect water quality. Transport of bioavailable P is a major cause of freshwater eutrophication (Sharpley et al., 1995), which must be addressed. Treated waste water disposal, a necessity in many megacities, also impacts quality of water and soil resources (Gale et al., 1994).

3. Waste Management

Waste is already choking arteries of the planet, and undermining soil's resilience. The importance of soil as a medium for waste/disposal will increase with increase in industrialization and population. In addition to disposal of livestock (e.g., manure) and urban (e.g., sludge) wastes, soils will be increasingly used for disposal of industrial wastes and low-level radioactive wastes (Katz et al., 1996). The study of soils in the vicinity of nuclear-reactor and waste water disposal ponds is another important topic, especially in view of the increase in production of nuclear energy (Blom and Johnson, 1991). Thus, environmental risk assessment and remediation of soils contaminated by application of industrial waste (Gowd et al., 2005) and from unlined waste-disposal pools are priority research issues that must be addressed. Study of gaseous fluxes through soils of waste-disposal sites (e.g., CH_4, N_2O, CO_2) is relevant to the issue of global warming. The subject of macropore flow and pollutant transport, a popular research topic during the 1980s, remains an important issue in terms of waste management and water pollution.

4. Soils and Biodiversity

Soils and their management play an important role in biodiversity and ecosystem functions (Hunt and Wall, 2002) and other environmental services. There is a strong relationship of biodiversity with soil structure and its functions (Davidson and Grieve, 2006); soil fertility (Mader et al., 2002), and tillage methods (Adl et al., 2006). Soil fauna and flora are key bioindicators of soil quality and its functions including earthworms (Shipitalo, 2002: Shipitalo and Le Bayon, 2004), ants (Lobry de Bruyn, 1999), invertebrates (Stork and Eggleton, 1992), and microbial diversity. Because soil biodiversity plays an important role in sustainable farming (Potter and Meyer, 1990) and strongly impacts economics of production systems (Huston, 1993), such studies must be integrated across disciplines. The hypothesis that biodiversity influences net primary productions (NPP) and ecosystem stability must be validated for diverse soils and ecosystems (Tilman, 1999).

5. Desertification Control

There is a close link between desertification, biodiversity and climate change, and desertification and soil degradation strongly impact food security (Shapouri and Rosen, 2006). Soil biodiversity and its impact on ecosystem functions can be strategically used to restore desertified/degraded soils. Understanding relationship between plant species (e.g., cover crops) and microbial processes (Garcia et al., 2005) can be important to identification of soil/ecosystem restoration techniques. The strategy of ecological restoration (Su et al., 2007) may have long lasting impact along with numerous ancillary benefits. Establishment of a vegetation cover can have a significant moderating impact on the climate and hydrology, especially in tropical ecosystems (Osborne et al., 2004). Therefore, studies to assess interactive effects of restorative measures on soil, climate, hydrology, and NPP are warranted. In addition to changes in climate and hydrology, improvement in soil quality also enhances crop yields (Raji et al., 2004) and advances the much needed food security in SSA.

6. Climate Change

Some argue that global warming has the potential to destroy the civilized societies (Fowles, 2007) or the “Carbon Civilization.” Even if the consequences of projected global warming are not nearly as drastic as reported by IPCC and other researchers, it is important that mitigation strategies are identified and implemented immediately to stabilize the climate. In this regard, principles of soil science must be used to adopt three strategies: (i) sequester C in terrestrial ecosystems notably soils (as humus and secondary carbonates), wetlands and trees, with an objective to maximize C offset per hectare of soil; (ii) enhance use efficiency of input needed in soil management (e.g., tillage, irrigation, fertilizer, pesticides), and (iii) produce ligno-cellulosic biomass and oil seed crops through establishment of biofuel plantations comprising dedicated species (e.g., switch grass, miscanthus, poplar, willow, halophytes, rape seed, jatropha, oil palm) so that crop residues are retained on the soil as mulch/amendment. The biomass produced on energy plantations can be used for producing energy (through either cocombustion with coal or conversion to ethanol) and also other products of industrial value. Numerous value added bio-based products, through appropriate enzymatic reactions and processing, include: chemicals, plastics, adhesive, lubricants, and natural fibers. Biochar fertilizer is another product being considered of relevance to C sequestration and producing fertilizer (Fowles, 2007). It is reported that black C can produce significant benefits when applied to agricultural soils in combination with some fertilizers (Fowles, 2007; Steiner et al., 2007)

Soil processes are strongly linked with climatic processes, which need to be quantified. There are several questions that need to be addressed: (i) Will soil amplify climate change (Powlson, 2005) through positive feedback such as temperature sensitivity of organic matter decomposition (Ruddiman, 2003, 2005; Argen and Wetterstedt, 2007; Davidson and Janssens, 2006), increase in sensitivity of non-labile C (Briones et al., 2007), and impact on Cryosols and changes in tundra snow thickness (Ling and Zhang, 2007; Potter, 2004) and C and N mineralization of peat lands (Keller et al., 2004)? (ii) Will soils have negative/mitigative impact through sequestration of atmospheric CO_2 as soil organic matter Machado, 2005; Grace et al., 2006), formation of secondary carbonates and leaching of dissolved organic C? (iii) Will soil erosion risks increase (Istanbulluoglu and Bras, 2006; O’Neal et al., 2005; Nearing et al., 2004; Zhang and Nearing, 2005; Lee et al., 1999; Vitafinzi, 1993; Phillips et al., 1993; Ohara et al., 1993) and drastically alter runoff chemistry (Mol-Dijkstra and Kros, 2001)? (iv) Will the burial of C in sea by sediments and phytoplankton important to the global C cycle (Middelburg and Meysman, 2007) and affect the oceanic sink (Le Quere et al., 2007)? (v) Will change in soil processes (Emmett et al., 2004), soil moisture regime (Chien et al., 1995), management practices (Rounsevell and Brignall, 1994) impact agronomic yields (Zhang and Nearing, 2005)? (vi) Will alterations in ecosystem C budget and its allocation to soil C pool (Gorissen et al., 2004), and distribution of NPP in aboveground and belowground components (Egli et al., 2004) affect soil C pool (Conen et al., 2003) and alter the global C cycle even more drastically? (vii) Can C input into soil decrease the SOC pool (Fontaine et al., 2004)? (viii) Will the land-based C sink increase with increase in atmospheric abundance of CO_2 (Baker, 2007; Stephens et al., 2007)? (ix) Will the CO_2 fertilization effect be negated by increase in plant/soil respiration and severely constrained by the lack of nutrients (e.g., N) and water? (x) Will alterations in soil quality at high temperatures undermine soil’s ability to produce food, feed, fiber and other ecosystem services? These questions must be addressed for principal soils in major biomes.

Closely linked with the climate change is the energy budget with the attendant impact on soil microclimate that needs to be understood to identify adaptive/mitigative practices. Understanding changes in soil temperature and moisture regimes due to management practices such as polyethylene mulch (Al-Karaghouli and Al-Kayssi, 2001) is important to urban agriculture. Change in energy budget on the soil surface can alter the evaporative demand and water-use efficiency thereby necessitating adaptive management practices. An interesting but relevant problem is the quantification of the re-emission process of tritiated water deposited on the soil surface in vicinity of the nuclear fusion facility (Yokoyama et al., 2004).

Carbon sequestration in soils and terrestrial ecosystem is an important strategy with global implications. Of the natural and anthropogenic strategies of C sequestration (Fig. 4), the biotic processes of terrestrial sequestration are cost-effective measures with numerous ancillary benefits. The option of enhancing soil C pool, both organic (SOC) and inorganic (SIC), has a special niche, and must fit within the overall strategy of geologic and oceanic sequestration and chemical mineralization (Fig. 4). Enhancing SOC pool, through judicious land use and soil management options, improves numerous ecosystem services through improvement of soil quality (Fig. 5) including mitigation of climate change. The soil C sink capacity, which depends on the historic C loss and inherent soil properties within the climatic control, depends on choice of restorative land use and the specific management options. The rate of soil C sequestration ($\Delta y/\Delta x$) is determined by the antecedent C pool, soil properties, drainage conditions, nutrient availability and the biomass C input (Fig. 6). Soil C management is an important issue and requires an interdisciplinary approach to manage it and commodify it through trading of C credits. While cost evaluation of CO_2 sequestration by different processes (Huijgen et al., 2007) is a priority issue, C sequestered in soil can be traded to generate another income stream for the farming community. In cooperation with economists, soil scientists must develop a protocol to trade C

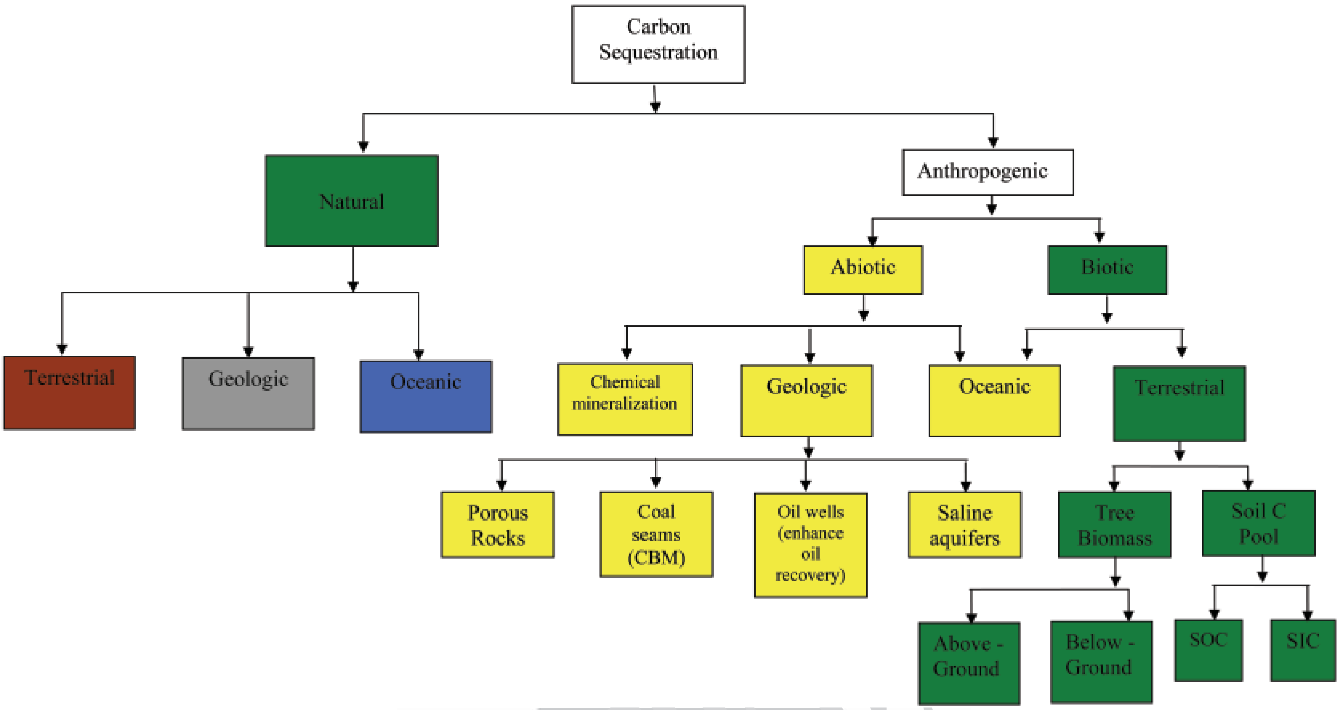

Fig. 4. Natural and anthropogenically driven processes of carbon sequestration (Redrawn from Lal, 2007).

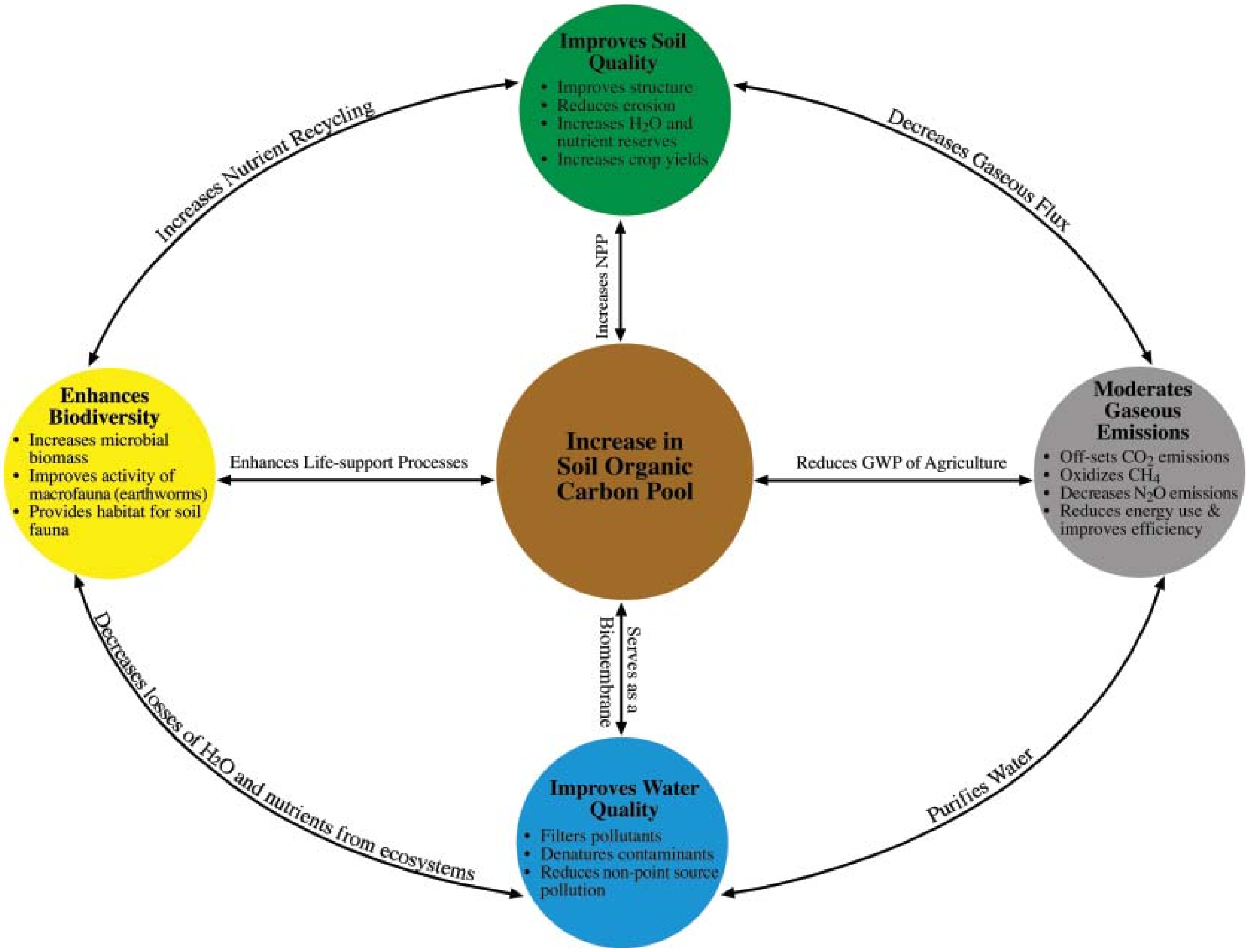

Fig. 5. Managing soil organic matter as the key to soil, air, and water quality (Redrawn from Andrews et al., 2006).

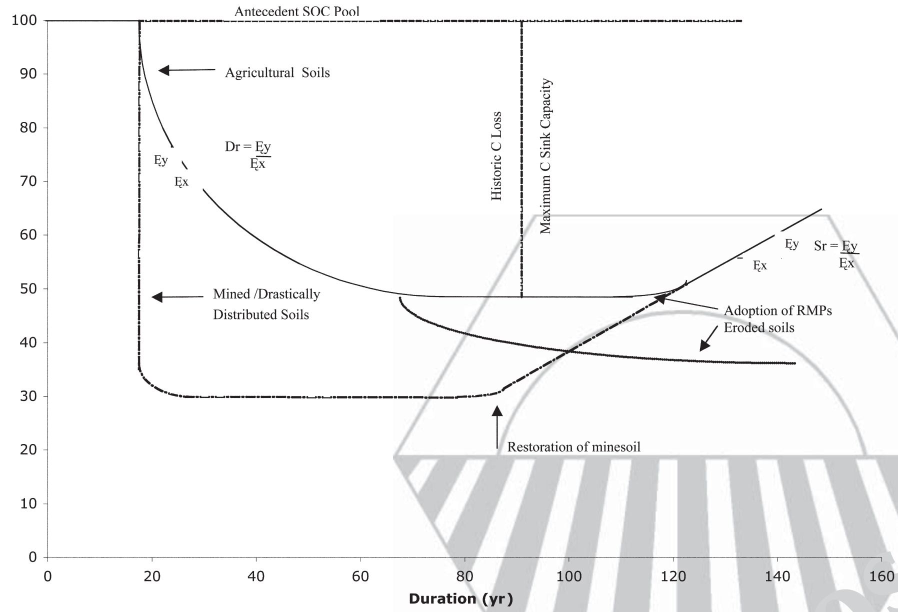

Fig. 6. Effect of land use change on soil organic C depletion and of adoption of best management practicess on soil organic C sequestration.

credits. It will require development of routinely usable techniques to measure change in soil C pool at landscape level over a time span of 1 to 2 yr. The process of "farming carbon" as a marketable commodity requires development of measurement, monitoring, and verification (MMV) techniques. The global C market in 2007 is about $30 billion, but it has a potential to grow to $1 trillion by 2020 or before. Soil scientists must position themselves to tap into this growing market by making soil C a tradeable commodity. In addition to CO_2, fluxes of CH_4 and N_2O from agroecosystems can also be converted to CO_2 equivalents and traded through domestic and international market.

7. Gene Pool

Soil is a major natural reservoir of gene pool. This natural resource must be studied in relation to its characteristics as impacted by land use, land use change and management practices. The biogeochemical signatures of this vast gene pool need to be studied in collaboration with molecular geneticists and biotechnologists. Soil warming may alter microbial communities in subarctic ecosystems (Rinnan et al., 2007) where changes in temperature due to climate change are likely to be the most drastic. Determining how will soil microbial community compositions and functions respond to climate change (Waldrop and Firestone, 2006) is important to understanding the magnitude of positive feedback. Study of the soil gene pool is even more relevant in view of the need to develop curative measures for energy and soil health issues under changing climate.

8. A Planetary and Human History

Soil is an archive of planetary and human history. Analyses of the lake sediment cores can indicate the past changes in climate (Filippelli et al., 2006). Measurement of ^{14}C activity (Genty et al., 1998) in soil provides insight into soil processes since the nuclear weapon testing began in early 1950s. Stable isotope composition of pedogenic/secondary carbonates and soil organic matter provides information about the pedogenic conditions thousands of years before present (Kovda et al., 2006). Presence of carbonaceous particles, concentration of P on the perimeter of these particles, and high quality of soil in the peri-urban regions may be indicative of the impact of past urban waste disposal on soil processes (Davidson et al., 2006). Basic studies on soil processes can provide insight into historic processes of soil formation on Earth (Guo et al., 2004; Kienast et al., 2001; Saettem et al., 1996; Tajika, 2003; Vallelonga et al., 2002; Von Blanckenburg, 2006; Yang et al., 2002; Ding et al., 2002; Adams and Post, 1999; Beltrami, 2001) and other planets (Horneck, 2000).

9. Energy Needs and Biofuel

Energy need is an important issue that soil scientists must address. The close link between energy, environment, and development (Goldemberg, 1996) cannot be ignored. Finding viable alternatives to fossil fuel energy is a topic of intense debate (Gunkel, 2006; Passero, 2006) because of the increasing global energy demands. The world consumption of energy for food production is about 25 Quads out of total energy use of 400 Quads yr^{-1}. In this regard, the importance of biofuel and the role of soils in producing the ligno-cellulosic feedstock for bio-ethanol and biodiesel are increasingly being considered (Vaitheeswaran, 2006; DeDanan, 2006; Glasgow and Hansen, 2006). Identifying appropriate sources of ligno-cellulosic materials (Tilman et al., 2006), and assessing the impact of residue removal on soil quality (Wilhelm et al., 2004; Blanco-Canqui et al., 2006a, 2006b, 2007) are important topics to be addressed. Identification of technology that enhances efficiency and reduce C emissions from farm operations (Lal, 2004) will always be a high priority. In addition to energy, the importance of biobased industrial products cannot be overemphasized (NRC, 1998). Choice of strategies for production of ligno-cellulosic materials must be linked to the objectives (e.g., off-setting CO_2 emissions, desertification control, soil restoration, ecosystem services). The need for production of ligno-cellulosic feed stock must be critically assessed in relation to competition of land (vis-a-vis food production), water (vis-a-vis industrial and agricultural needs), energy (input vis-a-vis output), and biodiversity (extinction of species by land conversion). There is no such things as a free biofuel from biomass. Complete life cycle analyses, considering all input and output, is needed to make objective decisions.

10. Urban Soils and Drastically Disturbed Lands

The amount of land converted to urban uses is rapidly increasing (Alig et al., 2004). More than half of the world population (3.3 billion) lives in cities and towns. The number of urban dwellers is expected to increase to 5 billion by 2030 (UNPF, 2007). Increase in urban population will be especially high in Africa and Asia, where food insecurity is a serious issue and soil/water resources are already under great stress. Developing countries are expected to have 80% of the world's urban population. Thus, there is a growing concern about the urban soil management issues (DeKimpe and Morel, 2000). Increasing urbanization, and rising interests in urban forestry,

Plate 1. Screenhouses must be used to produce specialty crops.

Plate 2. Vegetables can be produced in plastic houses in urban and peri-urban areas.

lawns, recreational land use and infrastructure development, necessitate study of soil processes under urban land uses. Urban soils, similar to mineland soils, are drastically disturbed lands. Management of urban lawns and recreational lands are energy-intensive activities with a large input of fertilizers, pesticides, irrigation and fossil fuel combustion because of mowing and maintenance operations (Qian and Follett, 2002; Golubiewski, 2006; Selhorst, 2007). There is a strong need to study fluxes of gases from urban landscape, especially that of CO_2 (Jo, 2002) and N_2O and CH_4 (Kaye et al., 2004). There is a distinct need to study soil C pool and fluxes in urban ecosystems (Pouyat et al., 2002; Pouyat et al., 2006).

Urban agriculture is a growing industry, and soil processes play a key role in its sustainability. It is important to systematically assess impacts of energy, water and waste management on soil processes in integrated plant and animal production technology within urban ecosystems. Horticultural crops (e.g., flower, vegetables) are intensively produced under plastic/screen houses within the urban centers (Plates 1, 2) and by using plastic mulch (Plate 3), especially in land-scarce countries (e.g., China, South Korea). Cycles of material flow in intensively managed soils must be studied in relation to food safety, water quality and soil pollution/contamination.

LINKING SOIL PROCESSES WITH NANOTECHNOLOGY, BIOTECHNOLOGY, AND INFORMATION TECHNOLOGY

Advances in nanotechnology, biotechnology and information technology are influencing human societies in all facets of life, and these advances need to be used to understand soil processes and identify innovative management options. For example, there is a strong need to develop technology for producing fertilizers that are C-neutral/C-efficient, and have a high use efficiency or recovery. Use of innovative technologies can greatly enhance understanding of key soil processes, and promote adoption of recommended practices. Nanotechnology, arranging matter atom-by-atom, has numerous applications in soil science. Some examples of such applications include: (i) using nanofertilizers that can transport nutrients to a rhizospheric site at the time needed and in amount and composition required thereby improving the use efficiency and enhancing quantity and quality of production, or nanoparticles locked onto the roots can enhance elemental uptake; (ii) improving water holding capacity of the soil through use of hydrogels or zeolites, which absorb excess water during rains but release later during the drought periods; (iii) maximizing productivity and value addition by creating some innovative by-products; (iv) improving use efficiency of water and energy and decreasing environmental foot prints of soil cultivation; (v) developing diagnostic systems that indicate abnormalities and stresses prior to plants being subjected to severe adverse effects; (vi) developing a film that can effectively discriminate between H_2O and CO_2 molecules and maintain photosynthesis even during the drought stress; and (vii) in remote areas dropping from a plane a sensor that can indicate soil moisture and temperature regimes, nutrient status, and soil reaction, etc.

There are also opportunities of using biotechnology in enhancing understanding of the rhizospheric processes. Soil Scientists can cooperate with biotechnologists in connecting molecules internally to the plant tissues to forewarn the deficiency or excess of an element, and other adverse biotic/abiotic environments. Such a system may be based on assessment of the quantity or quality of chlorophyll or production of other pigments (e.g., xanthophyll). Specific molecules produced by plants under stress can be detected during the initial stages to avoid severe adverse impacts. Biotechnology can also play a

Plate 3. Plastic mulch, extensively used in China and Korea, need to be widely used for weed control, moisture conservation and soil temperature management in Africa and South Asia.

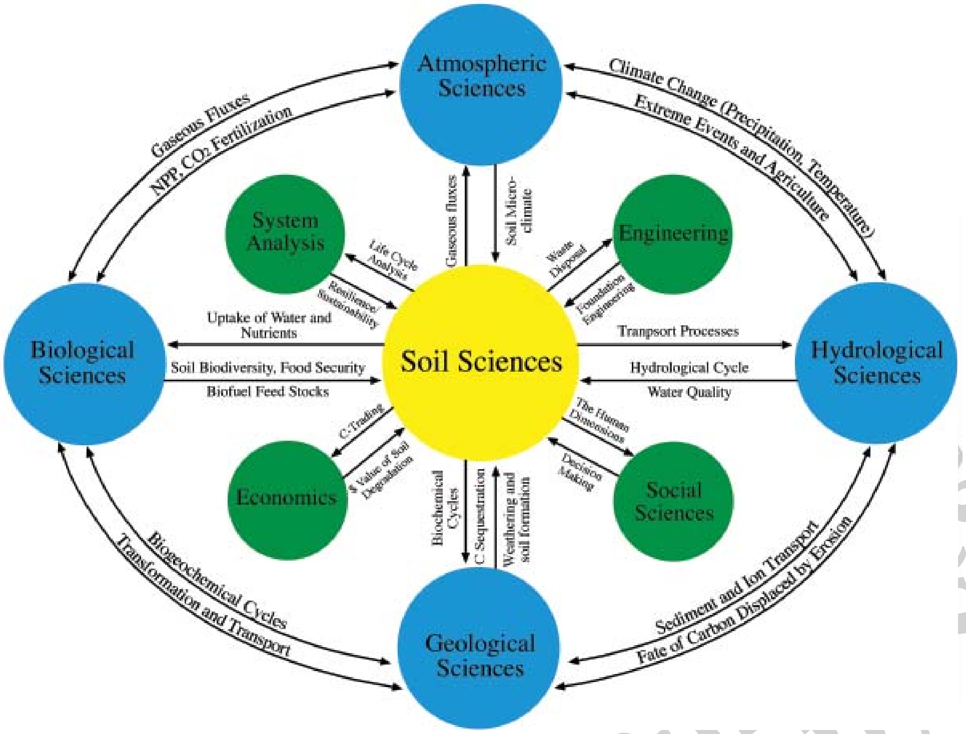

Fig. 7. Emerging demands on soil resources and strategies for achieving them through multidisciplinary approach.

crucial role in enhancing C sequestration in the biosphere. There is a strong need to develop cultivars that contain recalcitrant compounds (e.g., phenolics) with long residence time, and have a favorable root/shoot ratio. The long-term goal is to develop a plant that can indicate its needs through emission of stress signals that can be remotely transmitted. Information technology to transmit and process data, use of portable devices to enhance communication, and develop forecasting techniques prior to growing the next season crops can be extremely helpful. Development of automated decision support systems can revolutionize extension services and enhance adoption of recommended management practices.

POSITIONING SOIL SCIENCE TO EFFECTIVELY ADDRESS THE EMERGING ISSUES

Soil scientists must develop and strengthen interdisciplinary linkages to effectively address the emerging challenges of the Carbon Civilization outlined above. The soil science academy must formulate strong alliances with basic sciences (Fig. 7, blue circles). These alliances are needed to study: components of the hydrological cycle and transport processes in cooperation with hydrologists; gaseous fluxes and soil microclimate with atmospheric scientists; biogeochemical cycling of C and other elements and sediment transport with geologists; soil biodiversity/gene pool and food security along with production of ligno-cellulosic feed stock with biologists and plant physiologists (Fig. 7). In addition, there is a strong need to work in close cooperation with other disciplines (inner green circles in Fig. 7) to study: waste disposal and foundation for civil structure with engineers; life cycle analysis and resilience/sustainability with system analysts; C trading and economics of soil degradation with economists; and the human dimensions including policy imperatives and the decision making process with social scientists (Fig. 7). Marbut (1921) stated that "Probably more harm has been done to the science by the almost universal attempt to look on the soil as a producer of crops rather than a natural body worthy in and for itself of all the study that can be devoted to it, than most men realize. The science has undoubtedly been retarded in its development by this attitude." There is a strong need to broaden the scope of soil science discipline (Baveye et al., 2006). Basic scientific research is essential but not enough to combat world food insecurities and improve the environment. The human dimensions including economics, and policy issues are equally important (Underwood, 2003). Pursuit of sustainability is also a moral, educational and political challenge (Morgan and Peters, 2006), encompassing the concepts of planetary agrarianism proposed by Tom Berry (Berry, 1990a, 1990b) and Liberty Hyde Bailey (Bailey, 1905, 1915, 1927). In addition to continuation of the research on production agriculture to advance food security and eliminate malnutrition/hidden hunger, interdisciplinary programs need to be developed to study: the impact of climate change and extreme events on agriculture with climatologists and hydrologists; sediment transport and fate of C transported by erosional processes with hydrologists and geologists; biogeochemical cycles and transformation and transport with geologists and biologists; and gaseous flux and CO_2 fertilization/respiration impact on NPP and allocation/partitioning of photosynthesis into above and belowground components with climatologists and biologists (outer blue circles in Fig. 7).

To be effective and remain at the cutting edge of science, soil scientists must advance the basic knowledge underpinning interactive soil processes and ecosystem services by conducting research in cooperation with biologists, geologists, climatologists, and hydrologists (Fig. 8, lower half). Thus, the soil science faculty may either be an independent unit or housed in a department of Earth Sciences (geological sciences); Soil and Atmospheric Sciences; Soil, Water and Atmospheric Sciences; and Soil and Crop Sciences. Issues, such as structure, relating to emerging societal needs (Fig. 8, upper half) require practical/applied research. The latter will be strengthened by the basic process-oriented research described above.

CONCLUSIONS

Conservation, restoration, and enhancement of soil and water resources is essential to ensure humanity's freedom from hunger and malnutrition, mitigate climate change, improve quality and quantity of fresh water resources, enhance biodiversity, generate ligno-cellulosic feed stock for biofuel production and improve income and living standards of rural population dependent on agriculture. In addition to traditional functions, soil resources must be managed to offset emissions of greenhouse gases, produce ligno-cellulosic feed stock and oil seeds for biofuels, improve quality and quantity of water resources, dispose industrial/nuclear and urban wastes, enhance biodiversity, improve ecosystem services, etc. Study of soil processes under urban land uses (e.g., civil structures, lawns, recreational grounds, urban forestry and plastic house production of flowers and vegetables) is important. There is a strong need to revise and globalize soil science curricula, and develop close relations with allied sciences including geology, biology, climatology, ecology, hydrology, engineering, nanotechnology, biotechnology, information technology, and those dealing with the human dimensions. Soil scientists must develop channels of communication with these disciplines, land managers, industry entrepreneurs and policymakers, and also publish their findings in some mainstream journals (e.g., Science, BioScience, Nature). There is a strong need for advocacy with policymakers, land managers, and public at large to provide support to the soil science programs at the Land Grant Universities and research/development institutions. A citation from Sanskrit scriptures written around 1500 BP states that "Upon this handful of soil our survival depends. Husband it and it will grow our food, our fuel and our shelter and surround us with beauty. Abuse it, and soil will collapse and die, taking humanity with it." Soil scientists must take this responsibility very seriously.

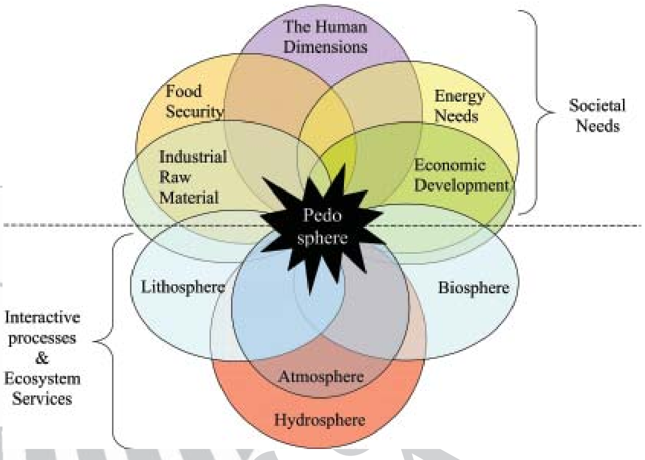

Fig. 8. Study of interactive processes of soils in relation to lithosphere, atmosphere, biosphere and the hydrosphere, to meet societal needs and enhance ecosystem service.

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