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Review article

Soils and sustainable agriculture. A review

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Abstract – Enhancing food production and supporting civil/engineering structures have been the principal foci of soil science research during most of the 19th and the first seven or eight decades of the 20th century. Demands on soil resources during the 21st century and beyond include: (i) increasing agronomic production to meet the food needs of additional 3.5 billion people that will reside in developing countries along with likely shift in food habits from plant-based to animal-based diet, (ii) producing ligno-cellulosic biomass through establishment of energy plantations on agriculturally surplus/marginal soils or other specifically identified lands, (iii) converting degraded/desertified soils to restorative land use for enhancing biodiversity and improving the environment, (iv) sequestering carbon in terrestrial (soil and trees) and aquatic ecosystems to off-set industrial emissions and stabilize the atmospheric abundance of CO_2 and other greenhouse gases, (v) developing farming/cropping systems which improve water use efficiency and minimize risks of water pollution, contamination and eutrophication, and (vi) creating reserves for species preservation, recreation and enhancing aesthetic value of soil resources. Realization of these multifarious soil functions necessitate establishment of inter-disciplinary approach with close linkages between soil scientists and chemists, physicists, geologists, hydrologists, climatologists, biologists, system engineers (nano technologists), computer scientists and information technologists, economists, social scientists and molecular geneticists dealing with human, animal and microbial processes. While advancing the study of basic principles and processes, soil scientists must also reach out to other disciplines to address the global issues of the 21st century and beyond.

sustainable agriculture / soil functions / food security / climate change / biofuels / water resources / waste management

1. INTRODUCTION

Goals of soil management during the 19th century and the first half of the 20th century, when world population was merely 38% of the 2006 level, was to maintain agronomic productivity to meet the food demands of 2 to 3 billion inhabitants. Demands on soil resources are different of a densely populated and rapidly industrializing world of the 21st century. In addition to food supply, modern societies have insatiable demands for energy, water, wood products, and land area for urbanization, infra-structure, and disposal of urban and industrial wastes. There is also a need to alleviate rural poverty and raise the standard of living of masses dependent on subsistence farming. In addition, there are several environmental issues which need to be addressed such as the climate change, eutrophication and contamination of natural waters, land degradation and desertification, and loss of biodiversity. To a great extent, solutions to these issues lie in sustainable management of world's soil resources (Fig. 1), through adoption of agronomic techniques which are at the cutting edge of science.

2. ADVANCING FOOD SECURITY

The world population of merely 0.2 billion during the biblical era increased by only 0.11 billion (to 0.31 billion) during the next one thousand years by 1000 AD. However, the population increased 20 times to 6 billion during the next 1000 years by 2000 AD. The world population is projected to reach 9.4 billion by 2050 and 10 billion by 2100 (Fischer and Heilig, 1997; Cohen, 2003). The most remarkable aspect of the future population dynamics is the fact that all of the projected increase by about 3.5 billion will occur in developing countries of Asia (mostly South Asia) and Africa (mostly sub-Saharan Africa). These are also the regions where soil resources are limited in extent (per capita), fragile to natural and anthropogenic perturbations, and prone to degradation by the projected climate change and the increase in demographic pressure. Thus, any future increase in agronomic/food production will have to occur through vertical increase in production per unit area, time and input (e.g., nutrients, water, energy) of the resources already committed to agriculture. It is in this context that developing and identification of some innovative methods of soil management are crucial to feeding the world population of 10 billion. These methods must minimize losses by delivering nutrients and water directly to the plant roots during the most critical stages of crop growth. Degraded and desertified soils must be reclaimed through enhancement of the soil organic matter (SOM) pool, creation of a positive elemental budget with balanced supply of all essential nutrients, effective control of soil erosion by water and wind, restoration of soil structure and tilth through bioturbation, and enhancement of activity and species diversity of soil fauna and flora. Soil management techniques must be chosen to ensure: (i) liberal use

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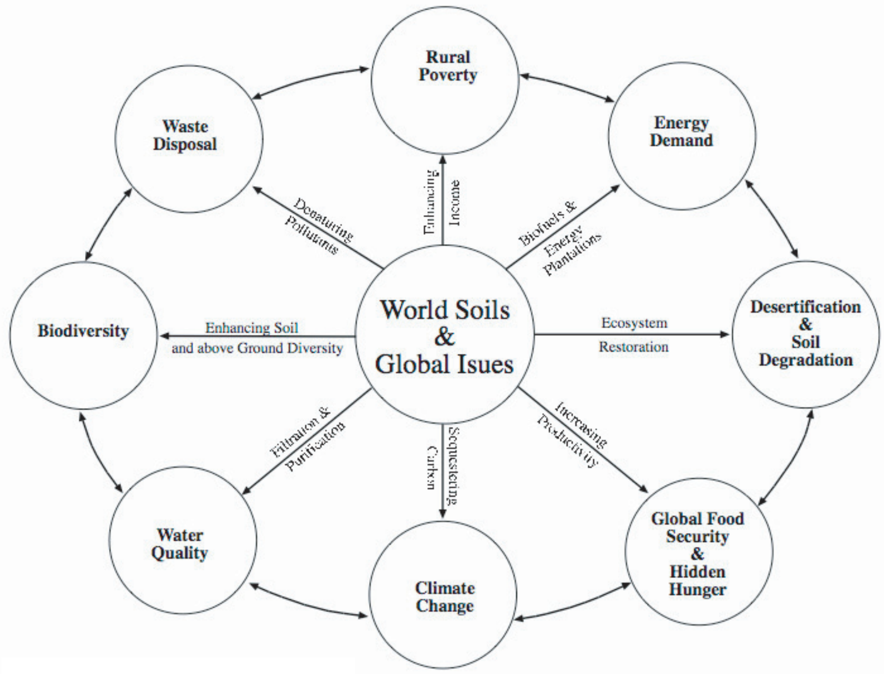

Figure 1. World soils and global issues of 21st century.

of crop residues, animal dung and other biosolids, (ii) minimal disturbance of soil surface to provide a continuous cover of a plant canopy or residue mulch, (iii) judicious use of sub-soil fertigation techniques to maintain adequate level of nutrient and water supply required for optimal growth, (iv) an adequate level of microbial activity in the rhizosphere for organic matter turnover and elemental cycling, and (v) use of complex cropping/farming systems which strengthen nutrient cycling and enhance use efficiency of input. Identification, development and validation of such innovations must be based on modern technologies such as GIS, remote sensing, genetic manipulations of crops and rhizospheric organisms, soil-specific management, and slow/time release formulations of fertilizers. Increase in crop yields must occur in rainfed/dry farming systems which account for more than 80% of world's croplands. Breaking the agrarian stagnation/deceleration in sub-Saharan Africa must be given the highest priority by soil scientists and agronomists from around the world. While expanding irrigated agriculture is important, crop yields have to be improved on rainfed agriculture in Asia and Africa, by conserving or recycling every drop of rain, and by not taking soils for granted.

3. BIOFUELS

In comparison with the stone age or bronze age, the industrial era (1750 to 2050) will be referred to the carbon (C) age or carbon civilization by future generations from 2100 AD and beyond. The use of fossil fuel, since the onset of industrial revolution ~1750, has drastically disturbed the global C cycle with the attendant impact on the climate change and the increase in earth's temperature along with change in rainfall amount and distribution. The present civilization is hooked on C, and is in need of a big time rehabilitation. Breaking the C-habit will require development of C-neutral or non-carbon fuel sources, and both soil science and agronomy have a major role to play in this endeavor. Not only the recommended agricultural input (fertilizers, pesticides, tillage methods, irrigation) must be efficiently used, the future energy demands will eventually be met by non-carbon fuel, most likely hydrogen. The latter can be generated from biomass produced through appropriate land uses and judicious cropping/farming systems. In the meanwhile, modern biofuels (ethanol, biodiesel) can play an important role in minimizing emissions of greenhouse gases and reducing the rate of increase of atmospheric concentration of CO_2 (Brown, 1999; Cassman et al., 2006). Converting grains (e.g., corn) to ethanol is rather an inefficient method of energy production, and grains are and will remain in high demands as food staple for humans and feed for livestock and poultry.

Crop residues are also being considered as a source of energy (Somerville, 2006; Service, 2007). Indeed, one Mg (1t) of lignocellulosic residues is equivalent to 250–300 L of ethanol, 15–18 GJ of energy, 16×10^6 kcal or 2 barrels of diesel (Lal, 2005; Weisz, 2004). The energy return on investment (EROI) for grain-based ethanol is low. Furthermore, crop residues (of

Table I. Species for establishing biofuel plantations.

English Name	Botanical Name
1. Warm Season Grasses	
• Switch grass	*Panicum virgutum* L.
• Big blue stem	*Andropogan gerardi*, Vitnam
• Indian grass	*Sorghastrum nuttans* L. Nas
• Blue giant grass	*Calanagrostis Canadensis* Michx Bean L.
• Guines grass	*Panicum Maximum* L.
• Elephant grass	*Pennisetum perpereum* schm.
• Kallar/Karnal grass	*Leptochloa frscha* L.
• Molasses grass	*Melinis minutiflona*
• Reed canary grass	*Phalaris arundinacae* L.
• Cord grass	*Spartina pectinata* Link.
2. Short Rotation Woody Crops	
• Popalar spp	*Populus* spp.
• Willow spp	*Salix* ssp.
• Mesquite (Velayti Babul)	*Prosopis juliflora*
• Miscanthus	*Miscanthus* spp.
• Black locus	*Robinia pseudoacacia* L.
• Birch	*Onopordum nervosum*
3. Halophytes	
• Pickle weed	*Salicornia bigelovii*
• Salt grass	*Distichlis palmeri*
• Salt brushes	*Atriplex* spp.
• Algae	*Spirulina geitleri*
4. Drought Tolerant Trees	
• Gum tree	*Eucalyptus* spp.
• Leucaena (Subabul)	*Leucaena leucocephala*
• Casurinas	*Casurina equisetifolia*
• Acacia	*Acacia* spp.
• Teak	*Tectona grandis*
• Cassia	*Casia siamea*

corn, wheat, barley, millet, rice) must be used as soil amendment/mulch to control erosion, conserve water and replenish the depleted SOM pool through soil C sequestration, and restore degraded soils and ecosystems (Wilhelm et al., 2004). Crop residues must not be considered a waste, because they have multifarious but competing uses including conservation of soil and water, cycling of nutrients, enhancement of the use efficiency of fertilizers and irrigation water, and above all, as a food of soil organisms which are essential to making soil a living entity. Using crop residues for production of biofuels is "robbing Peter to pay Paul" and all that glitters is not gold, not even the green gold. The price of harvesting crop residues (such as from the U.S. Corn Belt) will be severe soil and environmental degradation (dust bowl), because there is no such thing as a free lunch. It is, thus, important to identify dedicated crops which can be grown to establish biofuel plantations (Tab. I). Furthermore, new lands (agriculturally marginal/surplus soils; and degraded, disturbed and polluted soils) must be identified to establish appropriate biofuel plantations. In addition to providing the lignocellulosic biomass for conversion to ethanol, establishment of biofuel plantations on degraded soils would also lead to soil C sequestration and enhance soil quality and the ecosystem services that it would provide. The EORI of biofuel production system must be carefully assessed through a comprehensive life cycle analysis. In addition to establishing managed biofuel plantations, lignocellulosic biomass can also be harvested from natural vegetation growth on abandoned/set aside or fallowed land (Tilman et al., 2006). The issue of using crop residues for cellulosic ethanol production must not be resolved on the basis of short-term economic gains. The rational decision must be based on the long-term sustainable use of natural resources (Figs. 2, 3). Indeed, the immediate needs for fuel must not override the urgency to achieve global food security, especially for almost 1 billion food-insecure people in Africa and Asia. If the crop residues harvested for celunol production are not returned as compost (with enhanced plant nutrients such as N, P, K), the long-term adverse impacts on soil quality (such as has been the case

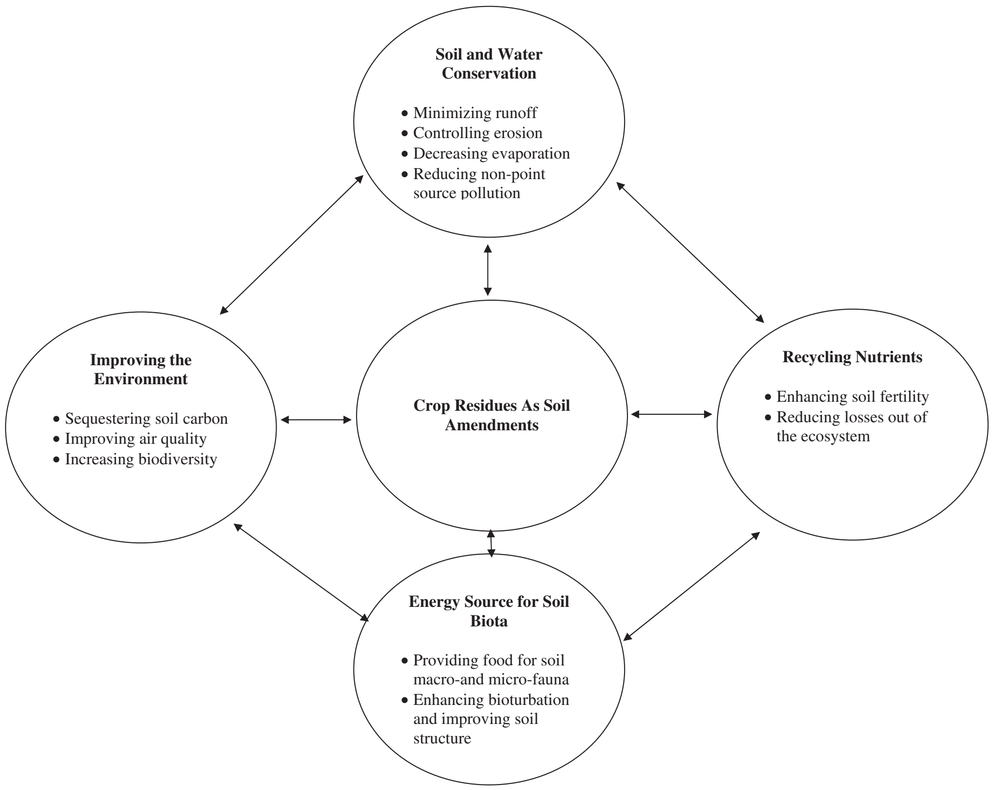

Figure 2. Site and eco-system specific effects of crop residue management on soil and environment quality must be assessed in relation to improvement in soil quality and sustainable use of natural resources.

in severely degraded soils of sub-Saharan Africa and South Asia due to perpetual removal of crop residues) will jeopardize global food security and set-in-motion the soil degradation spiral with the attendant impact on social unrest and political instability (Fig. 4).

4. WASTE DISPOSAL

The importance of soil for the safe disposal of ever-increasing industrial and urban wastes cannot be over-emphasized. The municipal solid wastes generated in the U.S. doubled between 1970 and 2003 (USEPA, 2006), as is also the case in western Europe and developing economies, In addition, there are wastes of animal and poultry industry, and food processing plants and restaurants. Theses wastes containing biosolids which can be used as energy source (either for direct combustion or conversion to methane or ethanol), and as soil amendment, or both. The by products of biosolids used for production of methane gas or ethanol must be composted and used as soil amendment.

Soils of appropriate characteristics (e.g., good drainage, absence of impermeable layer in the vadoze zone, high activity and species diversity of macro and micro-organisms in the surface layer, highly aggregated and stable structure) is also a natural biomembrane which must be used to filter and denature/biodegrade industrial pollutants. Carefully chosen soils and the underlying parent material/geologic strata are being used as a repository for nuclear wastes (e.g., Yucatan mountain range in the southwestern U.S.). Although questionable in terms of effectiveness and economic cost, geologic strata are also being used/considered for storage of industrial CO_2 emitted from point sources (Schrag, 2007). The importance of soil as a medium for waste disposal is bound to increase with increase in population and industrialization, and soil scientists must be pro-active in this emerging field of great significance. Similarly, agronomists must be very actively involved in phytoremediation of polluted soils by using plants to denature industrial pollutants.

5. FARMING CARBON

Carbon sequestration in terrestrial ecosystems (e.g., soils, trees, wetlands), and improving soil quality so that soils can be a net sink for CH_4 and release less N_2O, is an important issue which must be addressed by soil scientists, crop scientists, agronomists, foresters and wetland ecologists. While understanding the processes which impact the ecosystem carbon pool and fluxes is important, soil scientists and agronomists must liaise with economists and policy experts to develop a methodology for trading of carbon credits so that it can be traded like any farm commodity (e.g., corn, millet, poultry). Similar to C sequestered in trees, methodology must be

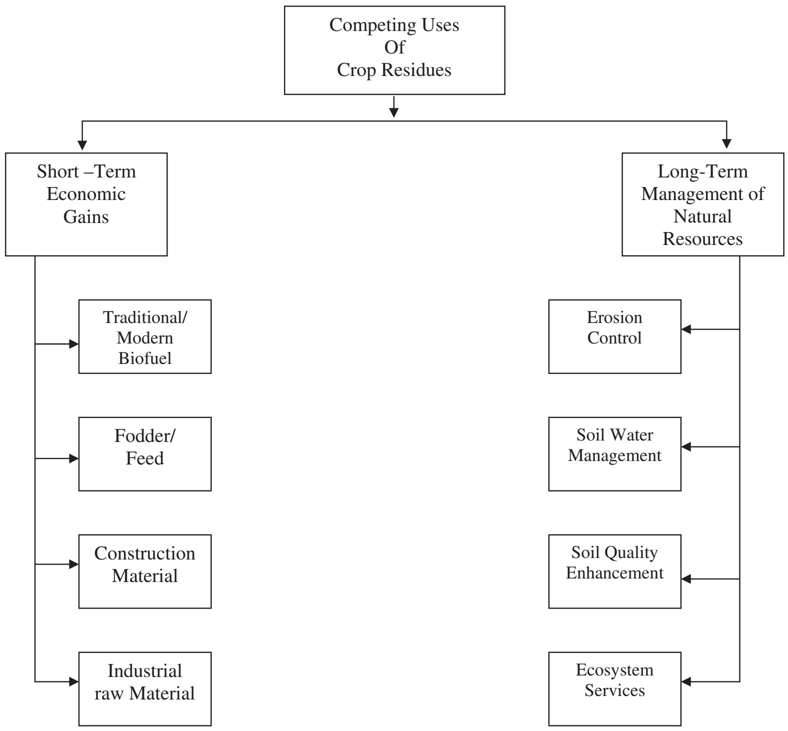

Figure 3. An objective assessment of short-term economic gains versus long-term and sustainable use of natural resources important to the decision-making process for competing uses of crop residues.

developed to trade C in soils (Breslau, 2006; Brahic, 2006). In addition, emissions of CH_4 and N_2O can be converted to CO_2 equivalent, and also traded. Trading C credits can provide another income stream for farmers, and provide the much needed incentives to invest in soil improvements (e.g., erosion control, fertility management, irrigation).

Restoration of degraded soils and ecosystems is an important facet intimately linked to soil C sequestration. Soil degradation and desertification, biophysical processes driven by socio-economic and political factors, are severe problems in developing countries of South Asia and sub-Saharan Africa (Oldeman, 1994). Restoration of eroded/degraded soils, through land use conversion via afforestation and conversion of degraded croplands to improved and well managed pastures, will lead to terrestrial C sequestration (in soils and trees) as an ancillary benefit. Soil degradation through land misuse, soil mismanagement, and excessive consumption of water through flood irrigation that leads to salinization and inundation are luxuries that the land-starved and the water-scarce world cannot afford, not anymore.

There is a strong link between soil restoration, carbon sequestration, food security (Lal, 2006) and biodiversity (Fig. 5). Improvement of soil quality, gradual and a slow process as it may be, is caused by an increase in the terrestrial C pool. The latter is also linked with biodiversity, water quality and micro and meso-climate, and emission of greenhouse gases into the atmosphere. Understanding interactive mechanisms, especially those which link processes in soil with those in atmosphere and hydrosphere through biosphere, are of a high priority for soil scientists and agronomists. In addition to quantifying these processes, soil scientists and agronomists must also communicate their findings to policy makers such as the US Congress, European Parliament, and the U. N. organizations. Through their interactive research outlined above, soil scientists must provide the basic information which is needed to bring together three U.N. Conventions (i.e., UNFCCC, UNFCBD, and UNFCDC). While providing crucial information on biodiversity, desertification control and climate change to strengthen cross linkages among three U.N. Conventions, soil scientists can also build bridges to link these organizations with the noble U.N. Millenium Development Goals of cutting poverty and hunger in half. In agricultural economy, which involves two-thirds to three-fourths of the rural population, increasing agronomic productivity and providing another income stream for farmers through trading of C credits are important strategies to advance food security while alleviating poverty and improving the environment. Generating income through trading of soil/terrestrial carbon credits may be the entry point or the handle to break the vicious cycle of soil degradation-low yields-poverty – hunger-severe soil degradation. It is a truly win-win-win strategy that deserves a serious attention of the world community.

6. WATER RESOURCES

In addition to fertility and nutrient supply, agricultural productivity will be constrained by lack of water resources, whose severity will be exacerbated by frequent and severe drought

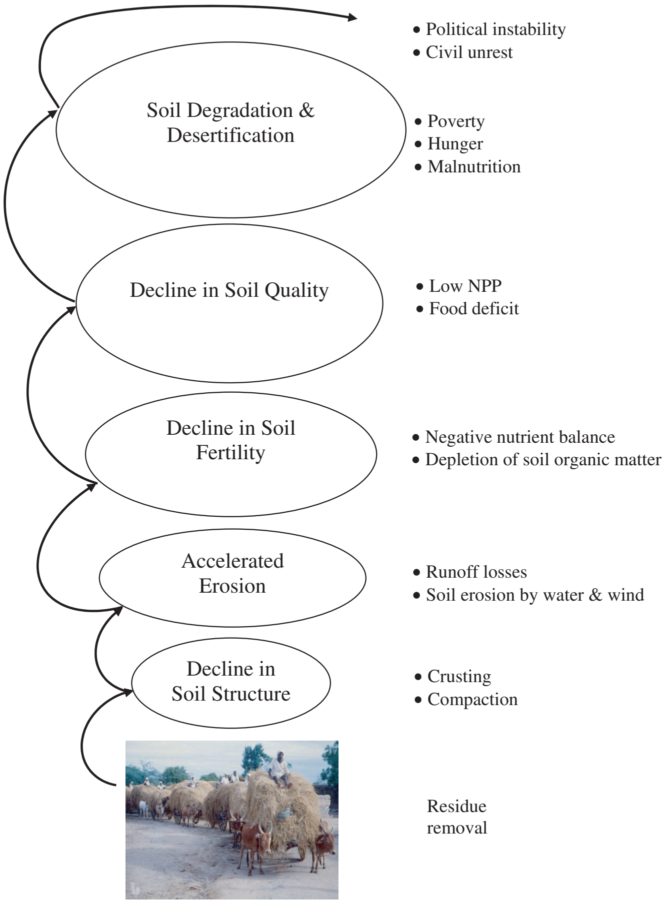

Figure 4. The Classic Collapse.

stress due to the projected climate change. Whereas agriculture is the largest consumer of water, the competition from industrial and urban uses is increasing with increase in demographic pressure and rapid industrialization (Gleick, 2003; Kondratyev, 2003; Johnson et al., 2001). The scarcity of fresh water is exacerbated by non-point and point source pollutions (Tilman et al., 2006), and will be further aggravated by likely shift in diet in developing economies (e.g., China, India) from plant-based to animal-based products (Clay, 2004). In this regard, improved understanding of soils and agronomic processes which enhance water use efficiencies is highly relevant and extremely critical. Soil scientists and agronomists need to work closely with plant breeders to develop genetically engineered plants which have high productivity per unit consumption of water, with irrigation engineers to reduce losses of water during conveyance and delivery, with micro-meteorologists to reduce losses from soil evaporation, with hydrologists to economically and effectively recycle water drained into the sub-soil or ground water, and with municipalities of large urban centers to develop techniques of recycling waste water for irrigation and aquifer recharge. Replacing flood irrigation with subirrigation or drip irrigation techniques is a high priority.

7. REACHING OUT

The traditional functions of soil have been: (i) the medium for plant growth, (ii) foundation for civil structures, and (iii) source of raw materials for industry. During the 21st century and beyond, functions of soil must be expanded to include the following: (i) mitigation of climate change through C sequestration in terrestrial and aquatic ecosystems, (ii) purification of water through filtration and denaturing of pollutants, (iii) disposal of urban and industrial wastes in a way that these do not contaminate water or pollute air, (iv) store germ plasm including that of microbes which can be used to combat diseases, (v) archive human and planetary history, (vi) support being a reactor of chemical and physical processes, and (vii) provide a strategic entity in national and international affairs to give peace a chance.

The concept of "sustainable agriculture" needs to be revisited in the context of the need for increasing productivity in developing countries which will entirely inherit the future increase in population of 3.5 billion by the end of the 21st century. With reference to the densely populated countries of Asia and Africa, sustainable agricultural practices are those which: (i) maximize productivity per unit area, time and input of fertilizers, water and energy, (ii) optimize the use of off-farm input, (iii) increase household income through increase in production, trading of carbon credits, off-farm employment, and value addition of farm produce, (iv) improve quality and quantity of fresh water resources at the farm level, (v) provide education opportunities especially for women, (vi) create clean household cooking fuel for the rural population to improve health of women and children and spare animal dung and crop residues for use as soil amendments, and (vii) address concerns of the farm family especially food security until the next harvest. It is a fact that indiscriminate use of chemicals, excessive tillage and luxury irrigation have degraded soils, polluted waters and contaminated air. The problem is not with the technology. It has been the over-fertilzation, overuse of pesticides, excessive application of irrigation because of free water, unnecessary plowing, complete removal of crop residues along with uncontrolled grazing, and the use of animal dung for household fuel rather than soil amendment that have caused the problems.

Access to adequate and balanced food and clean drinking water are the most basic human rights which must be respected. Political stability and ethnic conflicts are caused by hunger and the desperateness created by it. Thus, the concept of sustainable agriculture must be based on the simple fact that agricultural ecosystems are only sustainable in the long-term if the outputs of all components produced balance the inputs into the system. Whether the required amount of input (nutrients) to obtain the desired yield is supplied in organic rather than inorganic form is a matter of availability and logistics. Plants cannot differentiate the nutrients supplied through the organic or synthetic sources. The important question is of supplying nutrients in adequate quantity and when needed to produce enough food to meet the needs of 6.5 billion people now and 10 billion by the end of the century. In some cases, in vicinity of large livestock or poultary farms, organic manures may

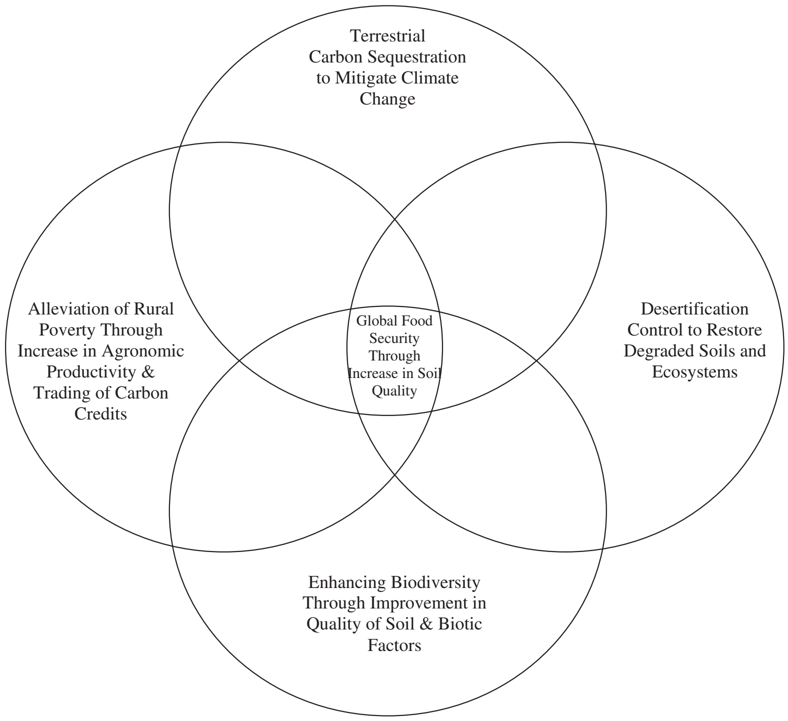

Figure 5. A positive and synergistic interaction between desertification control, biodiversity improvement, climate change mitigation, and food security. The latter is improved through improvement in soil quality, increase in availability of water resources, strengthening of elemental cycling, and enhancement of bioturbation in the rhizosphere. Soil scientists and agronomists must be actively pursuing quantification of these synergistic effects.

be available. In other cases, massive intervention through fertilizer use has no practical alternatives in a world of growing population. In some cases traditional breeding is acceptable, in others the natural process of gene manipulation may have to be accelerated through techniques of genetic engineering. The strategy is to use the technology prudently and with utmost objectivity and rationality. Transgenic plants can be grown on degraded and salt-affected soils to produce biomass for biofuels, and to alleviate biotic and abiotic stresses on dryland agriculture. If effective, why not?

While those holding the neo-Malthusian views will again be proven wrong through adoption of already proven and emerging technologies for sustainable management of soil resources, soil scientists and agronomists cannot undertake these serious issues all by themselves. These are far reaching and complex functions that soil scientists may take lead in but must develop close cooperation with other disciplines. While advancing and improving the knowledge of basic processes, soil scientists must also work with geologists, hydrologists, climatologists, biologists, chemists, physicists, computer scientists, nanto technologists, system engineers, economists and political scientists to address these emerging issues of the 21st century. The key strategy is to reach out to other disciplines while strengthening and advancing the science of soil and its dynamics in an ever changing physical, social, economic and political climate. Agriculture, implemented properly, is an important solution to the issue of achieving global food security but also of improving the environment. The agricultural history of 10 to 13 millenia has taught us that the motto of modern civilization must be "In Soil We Trust".

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