SYMPOSIA

Enhancing Eco-efficiency in Agro-ecosystems through Soil Carbon Sequestration

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ABSTRACT

Global cereal production must be increased by ~50% by 2050. Crop yields in sub-Saharan Africa and South Asia have either stagnated or declined since the 1990s because of the widespread use of extractive farming practices and problems of soil and environmental degradation. Yield potential of improved varieties and elite germplasm is not realized because of soil degradation. The concept of eco-efficiency implies efficient and sustainable use of resources in agronomic production and soil management. However, it is not enough to merely minimize the environmental impact. It is also important to maximize agronomic production while enhancing ecosystem services. Most degraded and depleted soils of agro-ecosystems contain a lower soil organic carbon (SOC) pool than in those under natural ecosystems. Thus, restoring the SOC pool is essential to improving soil quality, increasing eco-efficiency, and enhancing numerous ecosystem services. Increasing the SOC pool in the root zone can enhance agronomic production (kg grains ha^{-1} Mg C^{-1}) at the rate of 200 to 300 for maize (*Zea mays* L.), 30 to 60 for bean (*Phaseolis vulgaris* L.), 20 to 40 for wheat (*Triticum aestivum* L.), 20 to 50 for soybean [*Glycine max* (L.) Merr.], and 20 to 50 for rice (*Oryza sativa* L.). Not all improved management practices are applicable to all soil and ecological conditions. However, no-till farming along with application of crop residue mulch, manuring, legume-based complex rotations, and integrated nutrient management should be applicable under most conditions. Global food insecurity, affecting 1.02 billion people in 2009, can only be alleviated by improving soil quality and eco-efficiency through restoration of degraded/depleted soils.

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Abbreviations: INM, integrated nutrient management; SOC, soil organic carbon; SA, South Asia; SSA, sub-Saharan Africa.

The 20th century witnessed a drastic change in global resource use. Between 1900 and 2000, there occurred an increase in world population by a factor of 3.8, urban population by 12.8, industrial output by 35, energy use by 12.5, oil production by 300, water use by 9, irrigated area by 6.8, fertilizer use by 342, fish catch by 65, organic chemical production by 1000, car ownership by 7750 times, and atmospheric CO_2 by 30% (Ponting, 2007). World population of 6.8 billion in 2009 is projected to increase to 8.1 billion by 2030 and to 9.2 billion by 2050 (United Nations, 2008; Table 1). Almost all the future increase in population will occur in developing countries where soil and water resources are already under great stress. In 2006, food-insecure population of 854 million comprised 300 million in South Asia (SA), 220 million in East Asia, 200 million in sub-Saharan Africa (SSA), 50 million in Latin America and the Caribbean (LAC), and 41 million in Near East and North Africa (FAO, 2005, 2008). By 2009, food-insecure population increased to 1020 million because of surge in prices of food staples since 2008 (FAO, 2009). Of this, 645 million food-insecure people are in the Asia/Pacific region, 265 million in SSA, 53 million in LAC, 43 million in Middle East/North Africa, and 16 million in the developed countries (FAO, 2009).

Cereal production will have to be increased from 2012 × 10^6 Mg in 2005 to 3009 × 10^6 Mg by 2050. The required increase

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Table 1. World population and per capita cropland and irrigated land area (calculated from Postel, 1999; FAO, 2002; Lal, 2007; Stewart, 2009; Falkenmark et al., 2009; Bruinsma, 2009).

Year	Population	Cropland area		Irrigated land area	
		Total	Per capita	Total	Per capita
	billions	Mha	ha	Mha	ha
1900	1.5	805	0.536	40	0.027
1950	2.5	1170	0.468	94	0.038
1970	3.9	1300	0.333	169	0.043
1980	4.5	1333	0.296	211	0.047
1990	5.2	1380	0.265	239	0.046
2000	6.3	1360	0.216	277	0.044
2030	8.1	1648	0.203	300	0.037
2050	9.2	1673	0.182	318	0.034

in global food production will have to be achieved despite the increasing temperatures, decreasing rainfall effectiveness, increasing frequency of extreme events, degrading soils, declining and polluting water resources, increasing demands on energy, and regressive change to more fragile and harsh environments. The Green Revolution technology, growing input-responsive varieties on favorable soils under irrigated conditions, progressively increased global average grain yields of cereals to 1.77 Mg ha^{-1} in 1970, 2.16 Mg ha^{-1} in 1980, 2.75 Mg ha^{-1} in 1990, and 3.06 Mg ha^{-1} in 2000. Even if dietary preferences do not change, meeting the food demands simply because of the increase in world population will necessitate increasing average cereal yield to 3.60 Mg ha^{-1} (+18% compared with 2000) by 2025 and 4.30 Mg ha^{-1} (+41%) by 2050. With change in dietary preferences, toward a more animal-based diet, the world average cereal yields must be increased to 4.40 Mg ha^{-1} (+44%) by 2025 and to 6.0 Mg ha^{-1} (+96%) by 2050 (Wild, 2003). The objective of this article is to describe the importance of using the eco-efficiency concept in enhancing agronomic production while restoring degraded soils and improving the environment.

DATA SOURCE AND METHODS

This article is based on collation, analyses, review, and synthesis of the data published in the literature. Relevant articles containing data on agronomic yields under a range of farming techniques in relation to rainfall and soil properties were selected as appropriate examples of eco-efficient production systems. Being from diverse sources, data were converted to metric units. For example, data on crop yields were changed to kg ha^{-1} or Mg ha^{-1}, and those on soil organic matter (SOM) were converted to soil organic carbon (SOC; 58% C in SOM) to % on mass basis, or to Mg ha^{-1} for specific depths if soil bulk density was known. All graphs included in this article are based on recalculations and redrawing of the secondary data thus generated. Regression equations were computed relating crop yields to SOC concentration or pool. Rather than a comprehensive review, this article specifically cites some examples from diverse ecoregions and for eco-efficient systems, and the impact of SOC concentration and pool on agronomic yield and productivity. Readers are referred to other review articles (e.g., Bindraban et al., 2008; Wilkins, 2008; Keating et al., 2009) for additional details.

Resource Constraints to Achieving Food Security

Agriculturally suitable soils are limited, unequally distributed among ecoregions/biomes, and most are already being used for agricultural production. The remaining soils are either located in ecologically sensitive ecoregions (e.g., tropical rainforest, peat lands) or are marginal (e.g., too shallow, stony, steep, dry, or wet) for agricultural land use. Consequently, per capita cropland area declined from 0.536 ha in 1900 to 0.216 ha in 2000, and is projected to decline to 0.182 ha by 2050. Similarly, per capita irrigated land area peaked at 0.046 ha in 1990, and is projected to decline to 0.034 ha by 2050 (Table 1). Approximately 7000 km^3 of water is used annually in crop production, corresponding to about 2750 L^{-1} person^{-1} d^{-1} for the world population of 7 billion in 2010 and increasing at the rate of 6 million mo^{-1}. Additional resources required by 2050 for medium-level population projection include 200 Mha of land and 1002 km^3 of water per year for expanding cropland area, and 80 Mha of land and 398 km^3 of water per year for expanding grazing land (Falkenmark et al., 2009). Water scarcity is also closely linked with the energy crisis (Kahrl and Roland-Holst, 2008). Change in dietary preference to meat-based diet may drastically increase the demand for already scarce water resources (Table 2). Production of 100 kg of protein equivalent from different food sources requires 0.6 ha of land for ruminant meat, 0.36 ha for pork, 0.25 ha for grain legumes (pulses), and 0.10 ha for milk (Stehfest et al., 2009). Similarly, kilograms of grains (and kcal of energy) required to produce 1 kcal of protein is 21 kg (57 kcal) for lamb, 13 (40) for beef cattle, 11 (39) for eggs, 5.9 (14) for swine, 3.8 (10) for turkey, 2.3 (4) for boilers, and 0.7 (14) for poultry (Pimentel and Pimentel, 2003).

Soil, water, and nutrients are also required for meeting the projected demands for biofuels. Conversion of tropical rainforest and peatlands for soybean [*Glycine max* (L.) Merr.] or oil palm (*Elaeis guineensis* Jacq.) production can drastically deplete the ecosystem C pool, and create a long-term ecosystem C debt (Farigone et al., 2008). Because corn (*Zea mays* L.)–based ethanol production has escalated food prices (Rosegrant, 2008), using biomass for producing cellulosic ethanol (second generation) is being widely considered. Biomass required to meet the projected demand for bioethanol in the United States is about 1 billion Mg yr^{-1} (Somerville, 2006). However, residue retention on croplands is essential to soil and water conservation, C sequestration, nutrient cycling, and other ecosystem services. Use of crop residues and other agricultural coproducts can exacerbate the already severe problems of soil degradation and desertification (Bai et al., 2008). Despite the increases in food demand, the rate of annual increase in crop yields has either been negative or declining, especially in rainfed agriculture in SA and SSA. Crop yields stagnated in the range of 750 kg ha^{-1} and 1000 kg ha^{-1} in SSA between 1960 and 2005 (Hazell and Wood, 2008). In India, the grain yield of pigeonpea [*Cajanus cajan* (L.) Millsp.] decreased by 0.5% yr^{-1} between 1986 and 2006. The yields of chickpea (*Cicer arietinum* L.) and groundnut (*Arachis hypogaea* L.) increased at the rate of 0.7 and 1.1% yr^{-1}, respectively (Singh et al., 2009). The yield of groundnut in India declined from 1030 kg ha^{-1} in 1992–1996 to 1020 kg ha^{-1} in 2002–2006 (Singh et al., 2009). The problem of yield stagnation or decline is even more severe in SSA (Table 3). Over the 30-yr period ending in 2005, yields of most crops in SSA hardly increased, at the rate of merely <1% yr^{-1} (Table 3).

In view of the increasing population and scarcity of natural resources, there are three options for meeting the growing demand for food, fuel, fodder, and other agricultural products. One, loosening or breaking the grip of agrarian stagnation on rural communities in SSA, SA, and elsewhere in developing countries by replacing extractive farming practices with scientifically proven technologies. It is important to recognize that agro-ecosystems are sustainable in the long term only if the outputs of all components harvested are balanced by inputs into the system (Lal, 2009a). The negative nutrients and carbon budgets of agro-ecosystems must be changed to positive balances to set in motion soil restoration trends. Productivity and ecosystem services of degraded/desertified soils must be restored. Soil restoration also increases C sink capacity which must be filled for increasing ability of ecosystems toward adaptation and mitigation of climate change. Furthermore, C sink capacity of terrestrial ecosystems is decreasing (Canadell et al., 2007), probably because of the increasing problem of land degradation and desertification. Two, soil and other natural resources must be managed to enhance their resilience (Walker and Salt, 2006). Three, production from agro-ecosystems must be increased on the basis of per unit area and input of external resources (fertilizers, irrigation, energy) by improving eco-efficiency of production systems. The term *eco-efficiency* was first proposed by the World Business Council for Sustainable Development (WBCSD) in 1992. It implies creating more goods and services while using fewer resources and creating less waste and pollution (WBCSD, 1997). The 1992 Earth Summit endorsed eco-efficiency to implement Agenda 21. The WBCSD defines eco-efficiency as a strategy to produce "competitively priced goods and services that satisfy human needs and bring quality of life while progressively reducing environmental impacts of goods and resource intensity throughout the entire life-cycle to a level at least in line with Earth's estimated carrying capacity" (WBCSD, 1997; Day, 1998). The strategy is to produce more food without using more land, water, and energy-based inputs. The key to enhancing and preserving ecosystem services of soil and natural resources lies in enhancing eco-efficiency and their resilience to both natural and anthropogenic perturbations. Soils must have the capacity to restore their physical, chemical, and biological quality through enhancing restorative processes.

Table 2. Water requirements per kilogram of different agricultural products (Clay, 2004).

Product	Water requirement by area	Water requirement by weight
	10^6 L ha^{-1}	10^3 L kg^{-1}
Potato (*Solanum tuberosum* L.)	3.50–6.25	0.5–1.5
Wheat	4.50–6.50	0.9–2.0
Rice	5.0–9.5	1.9–5.0
Sorghum	NA†	1.1–1.8
Soybeans	4.50–8.25	1.1–2.0
Sugarcane	10.0–15.0	1.5–3.0
Chicken	NA	3.5–5.7
Cotton (*Gossypium hirsutum* L.)	5.5–9.5	7.0–29.0
Beef	NA	15.0–70.0
Shrimp	10.0–100.0	1.0–300.0

†NA, not available.

Causes of Low Agronomic Production in Developing Countries

Long-term and widespread use of extractive farming practices, leading to negative nutrient (N, P, K, Ca, Mg, Zn, Cu) and C budgets in soil and ecosystems and the attendant decline in soil quality, are among important causes of low and declining agronomic production in SA and SSA. Decline in soil quality has numerous feedbacks which exacerbate the process of soil degradation, such as those caused by accelerated erosion, increase in intensity and frequency of drought, and high risks of desertification. Soil degradation is also a reason for inadequate human nutrition (Lal, 2009b). Consequently, there is a strong decline in the rainfall effectiveness (i.e., the percentage of rain utilized by plants as evapotranspiration; also called *green water*) and the use efficiency of inputs (e.g., fertilizer, irrigation, energy). The data in Fig. 1 from Machakos, Kenya, indicate the adverse impact of soil degradation on regressive decline in grain yield of maize. The grain yield of 1.3 Mg ha^{-1} in 1987 (Year 21) declined to <400 kg ha^{-1} after 1994 (Year 28) even with good rainfall of 816 mm (1994) and 1020 mm (1997). Decline in grain yield of maize even in seasons with high rainfall (Fig. 2) may be because of severe soil degradation and reduction in the rainfall effectiveness (kg ha^{-1} yr^{-1}). The yield potential of improved varieties and elite germplasm is not realized when soils are degraded and crops are grown under sub-agronomic/edaphic conditions.

Table 3. Grain yields at rainfed crops in Africa (recalculated from Singh et al., 2009).

Region	Crop	Grain yield 1971–1975	Grain yield 2001–2005	Increase over 30 yr
		kg ha^{-1}		% yr^{-1}
West Africa	Millet	600	770	0.9
	Sorghum	690	900	1.0
	Maize	860	1230	1.4
Central Africa	Millet	610	560	−0.3
	Sorghum	660	880	1.1
	Maize	790	930	0.6
East Africa	Millet	1170	1380	0.6
	Sorghum	800	1000	0.8
Southern Africa	Maize	1810	2840	1.9
	Sorghum	1270	1930	1.7

Heinrich and Rusike (2003) reported sorghum [*Sorghum bicolor* (L.) Moench] grain yield of 330 kg ha^{-1} with traditional crop varieties and no input, 440 kg ha^{-1} (+33%) with improved crop varieties and no input, and 740 kg ha^{-1} (+124%) with improved varieties and recommended agronomic management. Similar experiments at IITA in Nigeria (Lal, 1987) and CIMMYT in Mexico (Govaerts et al., 2009) have shown that optimal soil management (conservation agriculture with mulch cover, and integrated nutrient management [INM]) is essential to achieving the agronomic potential of improved varieties. Genetic engineering can also help in utilizing water (Somerville and Briscoe, 2001), but it is not a substitute for good soil quality.

There is a wide range of indicators that can be used to assess the impact of technological options on quality of soil and the environment (Bastida et al., 2008), and evaluating differences in sustainability efficiency (Van Passel et al., 2007). Metabolic quotient (qCO_2), defined as respiration to microbial biomass ratio, an indicator of the soil biological quality, is strongly influenced by the SOC concentration–pool and its quality. An optimal level of the SOC pool, which enhances soil biodiversity, is also sustained by eco-agriculture (Scherr and McNeely, 2008).

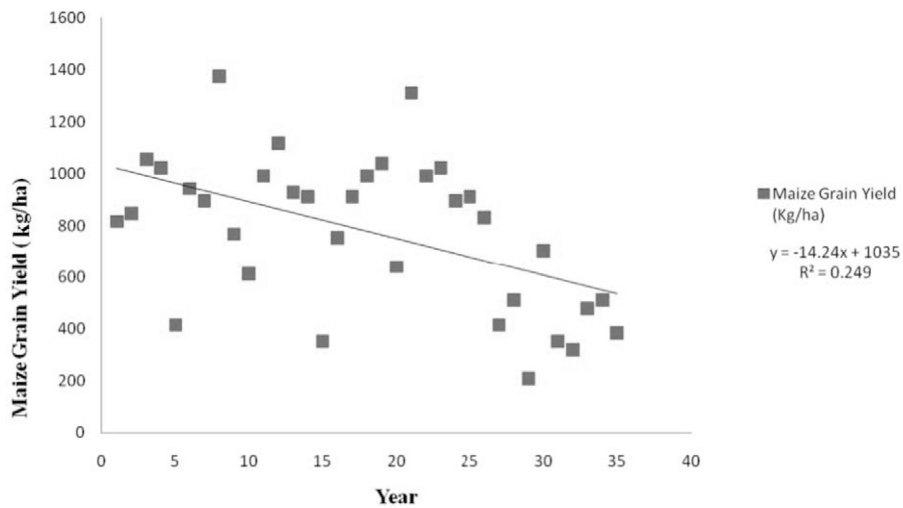

Figure 1. Decline in maize grain yield with continuous cultivation with subsistence farming in the Machakos and Makueni districts of Kenya (redrawn from Singh et al., 2009).

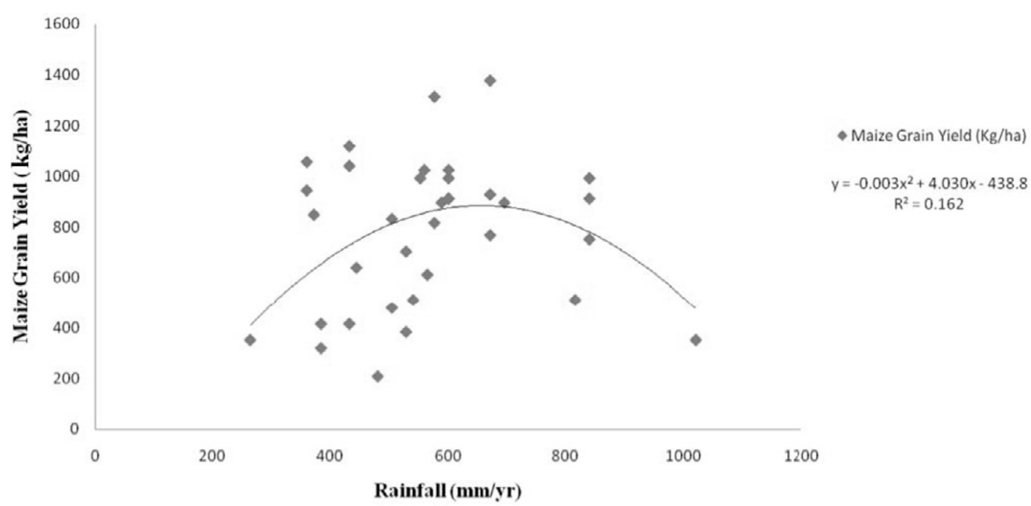

Figure 2. Effect of rainfall on maize grain yield under subsistence farming in the Machakos and Makueni districts of Kenya (redrawn from Singh et al., 2009).

The threshold level of SOC concentrations in the root zone for most upland soils in the tropics (e.g., Oxisols, Ultisols, Alfisols) is ~1.1% (Aune and Lal, 1997).

Eco-efficiency of Agro-ecosystems

Soil resources of good agronomic quality are limited, yet essential for the production of food, feed, fiber, and fuel. There is also a scarcity of water and energy needed for producing the required amount of biomass. Thus, the concept of eco-efficiency is important to producing more and more from less and less. Eco-efficiency is related to both "ecology" and "economy," and denotes both efficient and sustainable use of resources in farm production and land management (Wilkins, 2008). Eco-efficiency is increased by those farming systems that increase agronomic production by using less resources through reduction in losses of input, and sustaining and enhancing the production potential of land. Yet it is not enough to develop agricultural practices that merely minimize the adverse environmental impact. Because of the increasing population and rising standards of living, it is essential to develop those agricultural practices that maximize agricultural production while also enhancing ecosystem services (Firbank, 2009). Considering the vast amount of capital required for improving agronomic production in developing countries (Schmidhuber et al., 2009) in a changing climate (Schmidhuber and Tubiello, 2007), feeding of 9.2 billion people by 2050 (Evans, 2009) necessitates identification, development, validation, and use of eco-efficient agro-ecosystems.

There exists a strong relationship between agronomic production and the SOC pool, especially in low-input agriculture (none or low rate of fertilizer input). An optimal level of the SOC pool is an essential determinant of soil quality because of its positive impact on (i) soil structure and aggregation, (ii) water retention, (iii) nutrient retention, (iv) biotic activity including the microbial biomass, (v) erosion control, (vi) nonpoint-source pollution abatement, (vii) sedimentation reduction and control of hypoxia, (viii) C sequestration, (ix) increase in use efficiency of input, and (x) increase in biomass production. Increase in aggregation and available water capacity are among important benefits of SOC (Emerson, 1995; Huntington, 2003).

More (1994) assessed the yield response of wheat (*Triticum aestivum* L.) and rice (*Oryza sativa* L.) to increase in the SOC pool in the root zone of a Vertisol in Central India. These and other data show that positive effects on crop yields are generally more at lower than at higher magnitude of the SOC pool, and at lower than higher level of external inputs such as fertilizers and other soil amendments. The data in Fig. 3 from Mandan, ND, show that yield response of wheat to increase in the SOC pool is more at low than at high level of N input. The data in Fig. 4 from Australia clearly demonstrate that yield of wheat decreased with reduction in the SOC pool and increased with increase in the SOC pool. The data in Fig. 5 for a Russian Chernozem show a linear increase in crop yield with increase in the SOC concentration. There occurred a logarithmic increase in maize grain yield in Thailand with increase in the SOC concentration (Fig. 6). The slope of regression equations of these graphs relating crop yields to SOC concentration–pools in Fig. 3 to 6 indicates increase in the yield per unit increment in the SOC amount. In this regard, the data in Fig. 4 from Australia indicate the decline in yield of wheat with depletion of the SOC pool and increase in wheat yield with accretion of the SOC pool. Wheat grain yield of ~2.75 Mg ha^{-1} was obtained with a steady-state level of the SOC pool. Synthesis of data from several experiments show that increase of the SOC pool in the root zone by 1 Mg C ha^{-1} yr^{-1} can cause increase in grain yield (kg ha^{-1} Mg^{-1} C) of food crops in a developing country by 200 to 300 for maize,

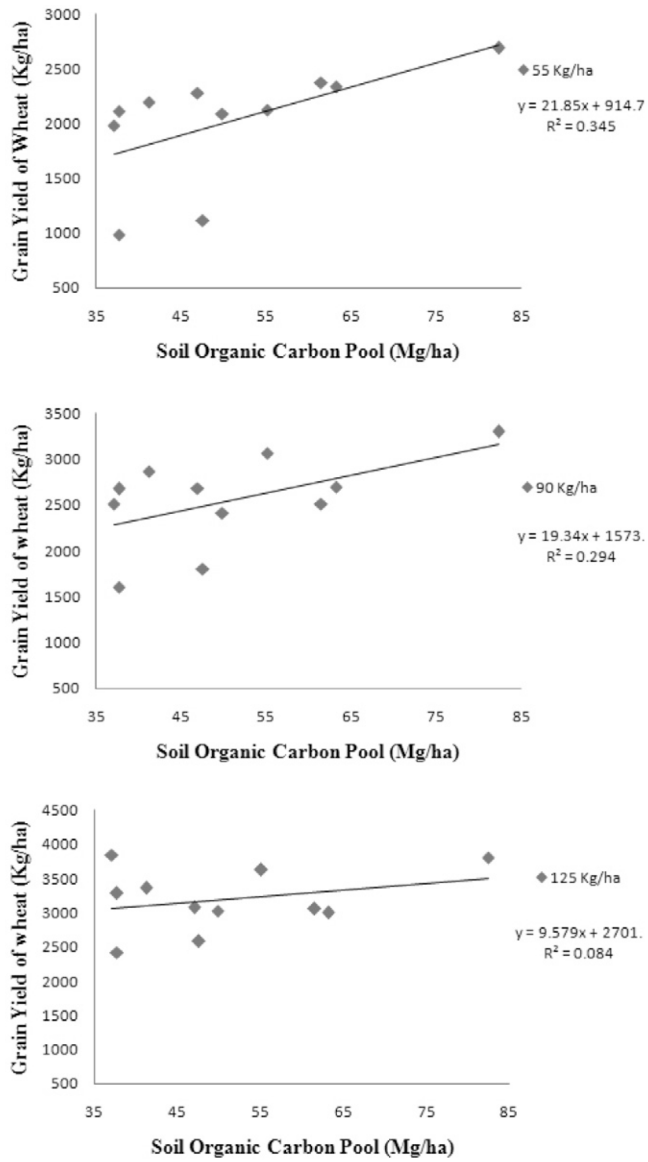

Figure 3. Response of wheat grown in Mandan, ND, to soil organic carbon pool at 30-cm depth for three rates of nitrogen application (redrawn from Bauer and Black, 1994).

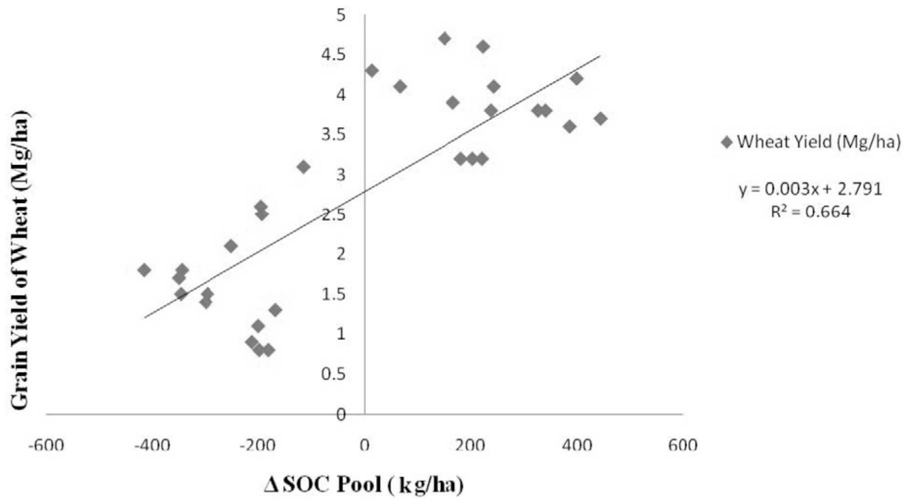

Figure 4. Effects of changes in soil organic carbon (ΔSOC) pool in the root zone on grain yield of wheat in Australia (redrawn and recalculated from Farquharson et al., 2003).

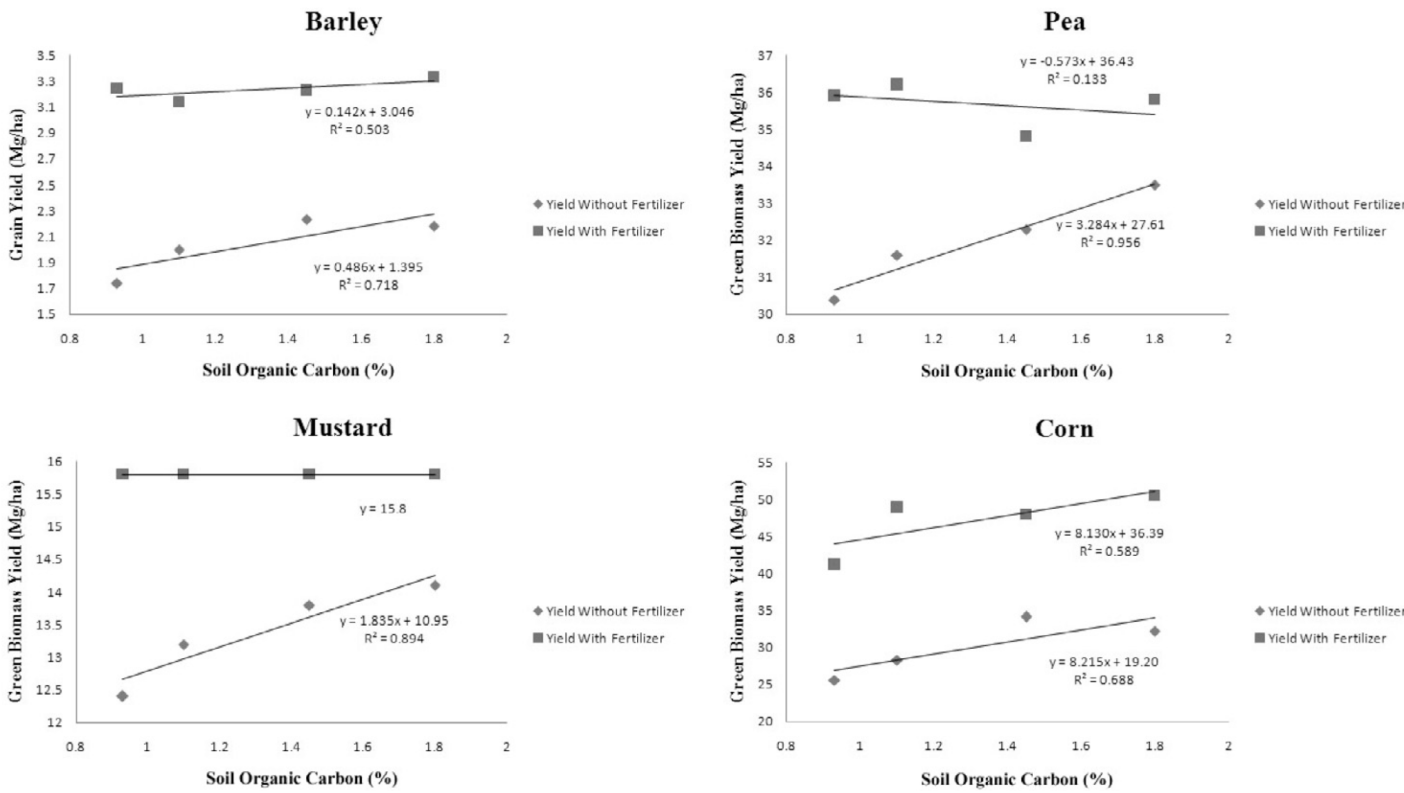

Figure 5. Effects of soil organic carbon concentration in the root zone on agronomic production for a Russian Chernozem (recalculated and redrawn from Ganzhara, 1998).

20 to 40 for wheat, 20 to 50 for rice, 80 to 140 for sorghum, 30 to 70 for millet [*Pennisetum glaucum* (L.) R. Br.], 30 to 60 for bean (*Phaseolus vulgaris* L.), and 20 to 50 for soybeans (Lal, 2006a).

Most agro-ecosystems contain lower SOC pools than their natural counterparts (Lal, 2004a) because of land misuse, soil mismanagement, and the attendant depletion of the SOC pool. Restoration of the SOC pool to above the critical/threshold level is essential to enhancing soil quality and improving agronomic productivity (Lal, 2006a). Therefore, the benefits of increase in SOC concentration and pool are high for depleted soils of the developing countries (Lal, 2006a). As a corollary, the detrimental effect of the loss of the SOC pool on agronomic productivity would be higher in coarse-textured than in fine-textured soils. Eco-efficiency of agro-ecosystems can be enhanced through adoption of farming–cropping systems that observe the basic laws of sustainable soil management (Lal, 2009b), and those that create positive C and nutrient budgets in the root zone. Sustainability of the rice–wheat system of SA also depends

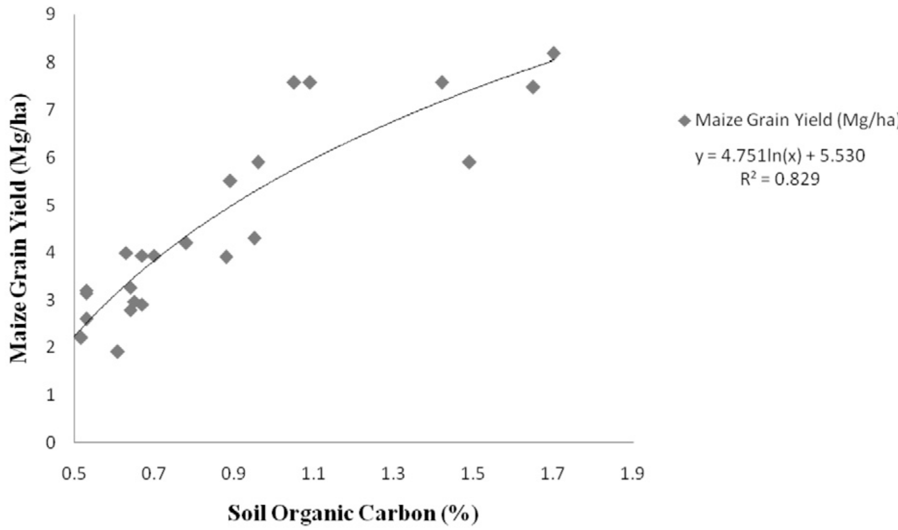

Figure 6. Effects of soil organic carbon concentration in the root zone on grain yield of maize grown in northeastern Thailand (redrawn from Petchawee and Chaitep, 1995).

on management of soil quality (Duxbury, 2002), and adopting water-saving technologies such as growing aerobic rice (Bouman et al., 2007). The goal is to adapt agriculture to climate change (Howden et al., 2007; Batisti and Naylor, 2009), through restoration of soil quality by improving the quantity and quality of the SOC pool (Lal, 2004a). Eco-efficient systems, with numerous co-benefits and enhanced ecosystem services, will be the drivers of change in global agriculture (Hazell and Wood, 2008).

Eco-efficient Production Systems for Advancing Global Food Security

The eco-efficiency concept, although scale-neutral and useful in enhancing the profit margin and environment quality of large-scale commercial farming in North America/Western Europe and Australia, is especially relevant to improving production of resource-poor and small landholders of SSA and SA. The strategy is to minimize soil erosion, conserve water in the root zone, recycle plant nutrients, create positive budgets of C and plant nutrients, optimize soil temperature and moisture regimes, and minimize losses of water and nutrients from the ecosystem. The goal is to build on the indigenous systems (e.g., Ngoro in Tanzania [Malley et al., 2004]; half-moon soil and water conservation systems in Burkina Faso [Zougmoré et al., 2003]; use of manuring and biosolids in SSA [Pieri, 1992; Gicheru et al., 2004; Kapkiyai et al., 1999], among others). Enhancement of the SOC pool (Nandwa, 2001; Batino and Buerkert, 2001) is essential to sustaining agronomic production in depleted and degraded soils of SSA, SA, and elsewhere in the tropics. The beneficial impacts of long-term manuring (Kanchikerimath and Singh, 2001; Gong et al., 2009), legume cover cropping (Venkateswarlu et al., 2007), conservation agriculture (no-till, mulch farming, INM, and complex rotations) (Lal, 1976, 1981; Diaz-Zorita et al., 1999, 2002; Diaz-Zorita and Grosso, 2000; Govaerts et al., 2009), and biodegradable mulches (Shogren, 2000) have been proven under diverse agro-ecosystems. Recycling crop residues as mulch is important to maintaining soil quality (Wilhelm et al., 2004; Powell and Unger, 1998), even when there are competing demands (biofuel) for this precious resource. The SOC pool can also be enhanced by complex farming systems including agroforestry (Zhukov et al., 2002). Furthermore, the impact of these production systems can be quantified through use of soil/land quality indicators (Bindraban et al., 2008; Bastida et al., 2008) based on key soil properties. A quantitative approach of assessing the productivity and ecological contributions (Dalsgaard and Oficial, 1997) is relevant to small-holder farmers of the tropics. Measuring sustainable efficiency (Van Passel et al., 2007) through application of life cycle assessments (Narayanawamy et al., 2005) is an important tool to measure eco-efficiency of a range of agro-ecosystems (Lal, 2004b).

Among several examples of eco-efficient production systems, two described below are relevant to a wide range of soils of the tropics and subtropics. An 18-yr experiment conducted on a Humic Nitisol (Kikuyu Red Clay) under maize–bean in East African Highlands provides important data on eco-efficient production systems. Kapkiyai et al. (1999) reported from the long-term study in Kenya that total crop yield of maize and beans ranged from 1.4 Mg ha^{-1} yr^{-1} in traditional systems without external input to 6.0 Mg ha^{-1} yr^{-1} when stover was retained as mulch along with application of fertilizers and manure. The SOC pool to 15-cm depth increased from 23.6 Mg ha^{-1} in traditional systems to 28.7 Mg ha^{-1} in improved management, with average SOC sequestration rate of 280 kg ha^{-1} yr^{-1} for the 18-yr period. Another long-term experiment on integrated watershed management was conducted on Vertisols in central India for which Wani et al. (2003a, 2009) reported the data from a 30-yr study (Fig. 7). Improved systems of soil/crop/water management produced a 30-yr average grain yield of 5.1 Mg ha^{-1} compared with 1.1 Mg ha^{-1} with the traditional system (Fig. 7a). There was a decline in the ratio of grain yield with improved to traditional system over time (Fig. 7b) because the productivity of the improved system is reaching the maximum potential yield. The ecological potential of this ecoregion is 7 Mg ha^{-1} yr^{-1}, indicating scope for additional improvement in agronomic production. The rate of SOC sequestration with the improved system was 330 kg ha^{-1} yr^{-1}, similar to that of the study in Kenya. A large gap (1–3 Mg ha^{-1} in India, Thailand, Vietnam, and Kenya) that exists in on-farm vis-à-vis on-station (research) yields (Table 4) can be bridged by the adoption of those technologies that enhance eco-efficiency, increase the SOC pool, improve soil quality, conserve water in the root zone, and create positive C and nutrient budgets.

Climate Change Mitigation by Eco-efficient Agro-ecosystems

World grain production is approximately 2500 million Mg annually. More than 54% of this is produced in developing countries, and the rate of increase must be higher in developing than developed economies, in the range of 1.5 to 2.25% per annum. These high rates of increase in grain production have to be realized despite the severe problems of soil degradation, especially those caused by strong depletion of the SOC pool. Enhancement of the SOC pool is essential to improving soil quality, and increasing the eco-efficiency of production systems. Increasing the SOC pool is a major challenge (Schlesinger, 1999), especially in developing countries where crop yields are low, climate is harsh, and there is a scarcity of water and nutrients (Lal, 2009c). Yet, with adoption of recommended management practices (RMPs), high rates of SOC sequestration have been reported. For an irrigated Vertisol in Central Mexico, Follett et al. (2005) reported a sequestration rate of 1.0 to 1.9 Mg C ha^{-1} yr^{-1}. Follett and colleagues also reported a significant correlation

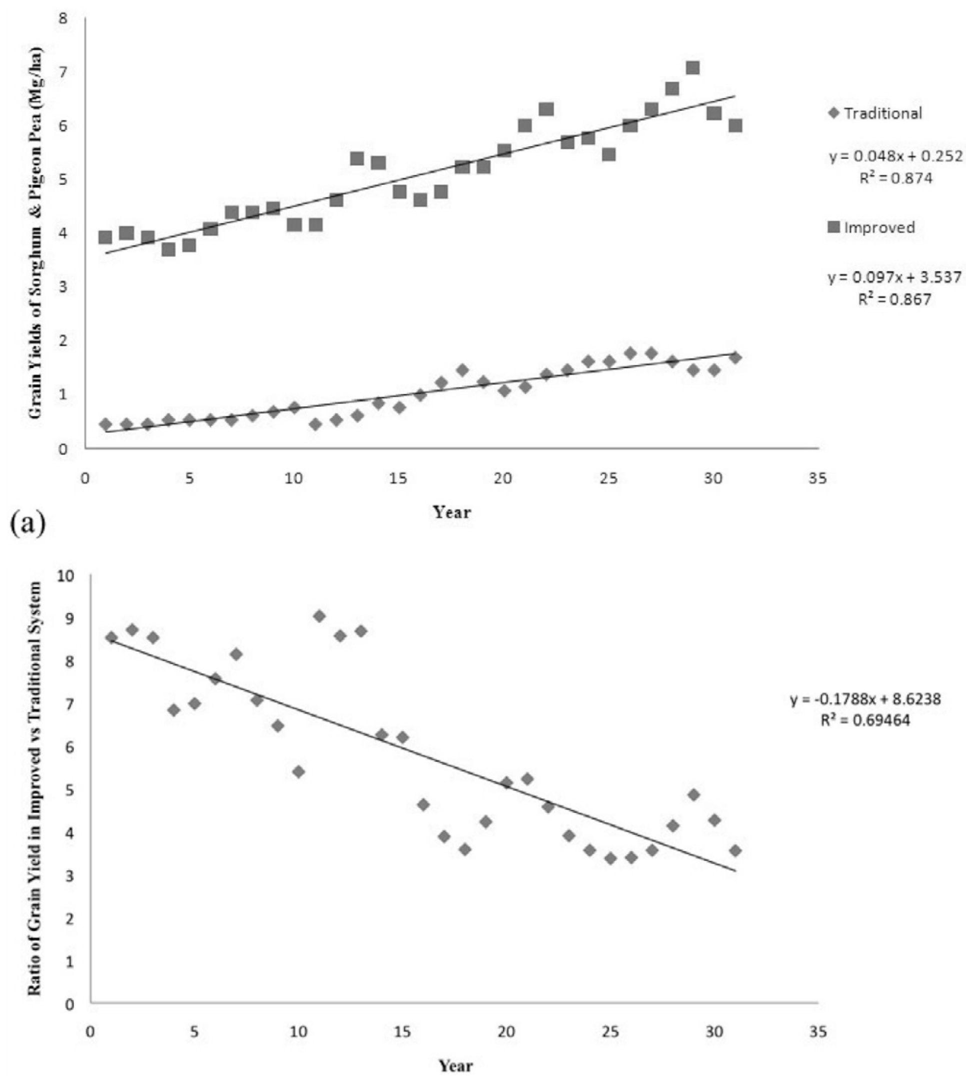

Figure 7. Changes in grain yields of sorghum and pigeonpea grown on Vertisols in central India under (a) traditional and improved systems of management, and (b) ratio of grain yield under improved to traditional systems of management (redrawn from Wani et al., 2008).

between the aboveground crop residue C produced and the amount of SOC sequestered. For sodic soils in northern India, recalculation of the data on the effects of agroforestry practices on the soil C pool indicated a rate of increase of 2 to 3 Mg C ha^{-1} yr^{-1} (Garg, 1998). These and other data (Lal, 2001) show that high rates of SOC sequestration can be achieved with restoration of degraded soils and adoption of RMPs. If that were the case, food grain production in developing countries can be increased by 24 to 39 (32 ± 11) million Mg yr^{-1} through improving soil quality by restoring the depleted SOC pool at the rate of 1 Mg C ha^{-1} yr^{-1} (Lal, 2006a). Similar to food grains, improvements in soil quality through SOC sequestration can also enhance production of roots and tubers, such as cassava (*Manihot esculenta* Crantz), yam (*Dioscorea rotundata* Poir.), sweetpotato [*Ipomoea batatas* (L.) Lam.], and taro [*Colocasia esculenta* (L.) Schott] by as much as 7 to 11 × 10^6 Mg yr^{-1} in developing countries (Lal, 2006b). Restoration of the SOC pool would involve widespread adoption of eco-efficient production systems based on mulch farming, retention and recycling of crop residues, and use of manure and other biosolids. These production systems also have the capacity to offset anthropogenic emission of CO_2 by 0.6 to 1.2 Pg C yr^{-1} in croplands (Lal, 2004a) and 0.4 to 0.7 Pg C yr^{-1} through desertification control (Lal et al., 1999). Technical potential of carbon sequestration through reclamation of salt-affected soils is 0.4 to 1.0 Pg C yr^{-1} (Lal, 2010).

Table 4. Potential and farmer yield under rainfed conditions (recalculated from Rockström et al., 2007).

Country	Crop	Yield: Potential	Yield: Farmer	Potential:Farmer
		Mg ha^{-1}	Mg ha^{-1}	
India				
	Soybean	2.19	0.94	2.3
	Groundnut	2.69	1.06	2.5
	Sorghum (summer)	3.50	1.19	2.9
	Sorghum (winter)	1.44	0.63	2.3
	Pearl millet	1.94	0.69	2.8
	Pigeonpea	1.50	0.56	2.7
	Chickpea	1.82	0.75	2.4
Northeastern Thailand				
	Soybean	1.94	1.19	1.6
	Groundnut	1.69	1.31	1.3
	Maize	4.69	2.38	2.0
	Sunflower	1.56	1.44	1.1
Vietnam				
	Soybean	2.19	1.31	1.7
	Groundnut	3.81	1.56	2.4
	Maize	5.19	3.31	1.6
Kenya				
	Maize	4.25	1.25	3.4

CONCLUSIONS

The schematic in Fig. 8 shows basic principles of managing soil properties and processes for enhancing

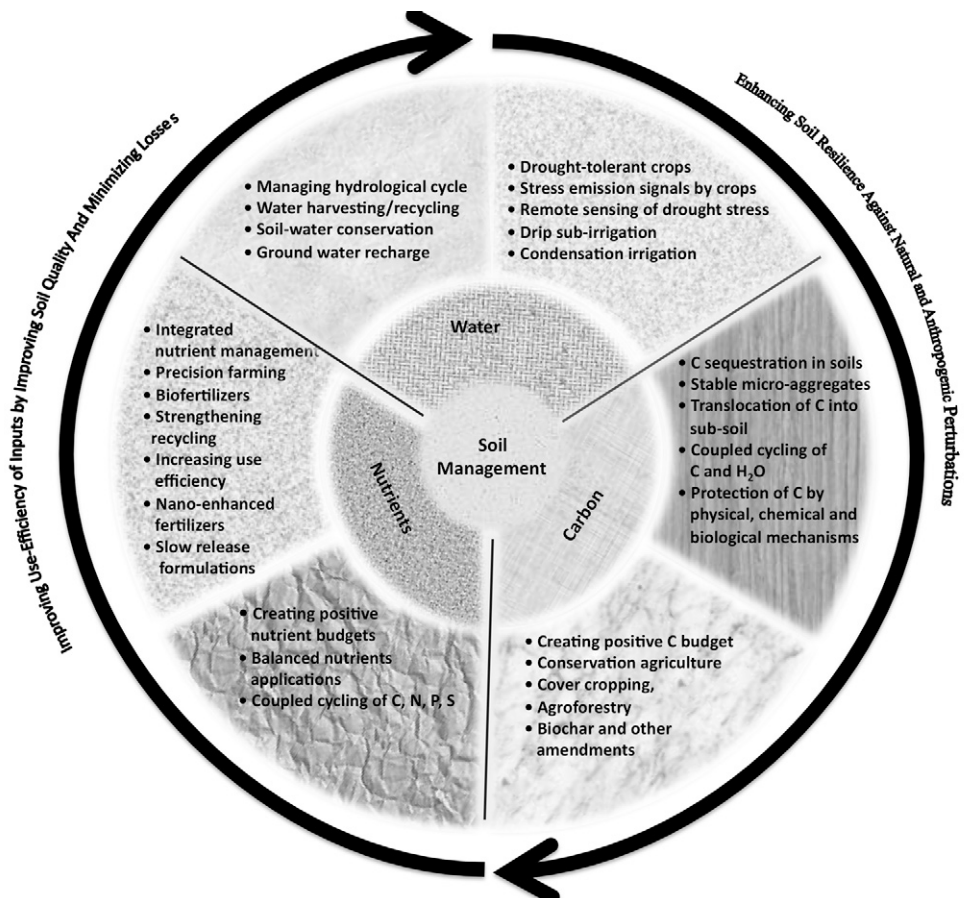

Figure 8. Managing soil properties and processes for enhancing eco-efficiency in production systems.

eco-efficiency of production systems. Three components to be judiciously managed are C, H_2O, and nutrients. The strategy of C sequestration in soils is by enhancing formation of stable microaggregates, translocation of C deep into the subsoil, and formation of recalcitrant substances through enhancement of protective mechanisms (e.g., physical, chemical, and biological), and manage the coupled cycling of C with H_2O, N, P, and S. The objective of management is to create positive soil and ecosystem C budgets through conservation agriculture, cover cropping, mulch farming, agroforestry techniques, and use of biochar and other amendments. Similar to C, there is a strong need to conserve and recycle water and enhance its use efficiency. Understanding and managing the hydrological cycle is needed at the landscape and watershed scales to maximize the green water component and minimize losses by runoff and evaporation. Use of drip subirrigation, drought-tolerant crops, and remote-sensing techniques to predict the onset of drought are among the modern innovations. Soils depleted of their nutrient reserves must be managed for creating positive budgets through adoption of the INM approaches. It is also important to apply both macro- (N, P, K, Ca, Mg) and micro- (Zn, Cu, Mo, Fe) nutrients. Using biofertilizers and nano-enhanced materials can reduce losses while improving the use efficiency of external inputs. The choice of eco-efficient technologies must be based on two criteria: (i) minimize the adverse environmental impact, and (ii) maximize the agronomic production. With the world population projected to reach 9.2 billion by 2050, it is not enough to merely minimize the environmental impact. Agronomic production must also be increased, for which improvement of the SOC pool is an important determinant. As Charles Mackay (1814–1889) stated, "In nature nothing dies. From each sad remnant of decay, some forms of life arise…."

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