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Soils and food sufficiency. A review — Source link

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Review article

Soils and food sufficiency. A review

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Abstract – Soil degradation, caused by land misuse and soil mismanagement, has plagued humanity since the dawn of settled agriculture. Many once thriving civilizations collapsed due to erosion, salinization, nutrient depletion and other soil degradation processes. The Green Revolution of the 1960s and 1970s, that saved hundreds of millions from starvation in Asia and elsewhere, by-passed Sub-Saharan Africa. This remains the only region in the world where the number of hungry and food-insecure populations will still be on the increase even by 2020. The serious technological and political challenges are being exacerbated by the rising energy costs. Resource-poor and small-size land-holders can neither afford the expensive input nor are they sure of their effectiveness because of degraded soils and the harsh, changing climate. Consequently, crop yields are adversely impacted by accelerated erosion, and depletion of soil organic matter (SOM) and nutrients because of the extractive farming practices. Low crop yields, despite growing improved varieties, are due to the severe soil degradation, especially the low SOM reserves and poor soil structure that aggravate drought stress. Components of recommended technology include: no-till; residue mulch and cover crops; integrated nutrient management; and biochar used in conjunction with improved crops (genetically modified, biotechnology) and cropping systems, and energy plantation for biofuel production. However, its low acceptance, e.g. for no-till farming, is due to a range of biophysical, social and economic factors. Competing uses of crop residues for other needs is among numerous factors limiting the adoption of no-till farming. Creating another income stream for resource-poor farmers, through payments for ecosystem services, e.g., C sequestration in terrestrial ecosystems, is an important strategy for promoting the adoption of recommended technologies. Adoption of improved soil management practices is essential to adapt to the changing climate, and meeting the needs of growing populations for food, fodder, fuel and fabrics. Soil restoration and sustainable management are essential to achieving food security, and global peace and stability.

food security / soil restoration / sustainable development / soil degradation / conservation agriculture / no-till farming / biochar / integrated nutrient management

1. INTRODUCTION

Global estimates of food-insecure populations comprise 825 million (Lobell et al., 2008) to 850 million (Borlaug, 2007). Regional estimates of the food insecure population include 263 million in South Asia (SA), 268 million in China and Southeast Asia, 212 million in sub-Saharan Africa (SSA), 60 million in South and Central America and the Caribbean, and 50 million in other regions of the world. Contrary to the United Nations' (UN) Millennium Development Goals of cutting hunger by half by 2015, the number of food-insecure populations in the world will increase. The stock of food grains in the world in 2007–2008, the lowest in decades, was only 75 million tons for milled rice and 105 million tons for corn in early 2008 (USDA-FAS, 2008). An estimated 75% of the world's poor (< $2/day income) live in rural areas and depend directly or indirectly on agriculture (FAO, 2006). Food prices are rising (Normile, 2008), leading to riots in 30 countries around the globe (Brown, 2008; Hoyos and Blas, 2008). Share of family income spent on food is estimated at 10% in the US, 20% in Brazil, 30% in China, 50% in Kenya and 65% in Bangladesh (Hoyos and Blos, 2008). Thus, the world's poor are under great stress, and increase in food prices is a threat to global peace and stability. There is a shortage of good quality soil to bring about the desired increase in food production. Soil fertility decline is an important factor (Sanchez, 2000; IFDC, 2006) that cannot be ignored. Indeed, agriculture requires more land, water and human labor than any other industry (FAO, 2007; Kiers et al., 2008). Several studies have documented that the potential of genetically modified (GM) crops is appropriate in some contexts, unpromising in others, and unproven in many more (Kiers et al., 2008). The potential of GM crops remains unfulfilled, especially for the subsistence farmers of SSA and SA, where crop yields are strongly constrained by the severe problems of soil degradation and desertification. Furthermore, policy-makers are torn between allocating resources to food security and biofuel production. The objective of this article is to deliberate the need for a soil-based approach to enhance and sustain agronomic production and eliminate world hunger and malnutrition.

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2. PREHISTORIC FARMING TECHNIQUES AND SOIL DEGRADATION

The literature is replete with prehistoric agriculture and its impact on soils and the environment of the Middle East, and in the valleys of the Nile, Yangtze, Indus and others. However, little is known about prehistoric farming and soil quality in other sites of ancient cultures. Yet, maintaining soil fertility and agronomic productivity has been a serious issue facing humanity ever since the dawn of settled agriculture. For example, it has long been recognized that catenal processes result in large fertility contrasts between summit/shoulder slopes and footslope landscape positions (Scholes, 1990), and that these contrasts were accentuated by the activities of prehistoric cultures such as addition of charcoal to creat the "terre preta de Indio" (Mann, 2002). Two important soil-related constraints faced by prehistoric farmers, drought stress and nutrient depletion, were alleviated by use of the innovative technologies of supplemental irrigation and nutrient recycling, respectively.

Irrigation and water management played a major role in the so-called "hydric civilizations". In addition to the well-known use of irrigation in Asia (Groenfeldt, 1991; Andrianov, 1989; Knauss, 2000) there are examples of using irrigation in the prehistoric Americas (Park, 1983; Lange, 1992). In the Lake Titicaca Basin, covering the Andean Highlands of Peru and Bolivia, archaeological investigations have shown a massive landscape modification throughout prehistory to intensively cultivate marginal lands. These modifications, over 82 000 ha of land area, included raised beds and large earthen platforms to improve drainage, increase soil fertility by recycling nutrients and improve the micro-climate (Erickson, 1992). In the Pampa de Chaparri hyper-arid region of Peru, prehistoric irrigation canals and furrowed fields have been preserved for 500 years (Nordt et al., 2004). On Easter Island (Rapa Nui), Chile, cultivation of yams (*Dioscorea* spp.) and taro (*Colocasia esculenta*) began in the 12th century and continued through the 15th century (Stevenson et al., 2006).

Archaeological evidence of early irrigation systems has also been discovered in southeastern Arizona. Palacios-Fest et al. (2001) identified several stages of water management in the Santa Cruz River Valley of Southeastern Arizona in the prehistoric era. These researchers reported that prehistoric people first operated their irrigation system in a simple mode involving diversion of ephemeral flows following storms, and later in a complex mode involving diversion of perennial flows. Berger (2004) reported the use of canal irrigation from 1600 years to 800 years ago (400 AD to 1200 AD) in the flood plains of Salt River in Phoenix, Arizona. Masse (1981) used aerial photographs to reveal complex and extensive remains of ancient Hohokam irrigation systems in the Salt River Valley near Tempe, Maricopa County, Arizona. These systems were probably constructed and used between AD 850 and 1450, and consist of over 2100 km of canals in the north and south of the Salt River.

Nutrient depletion was also a major problem in settled agriculture, except in the flood plains where soil fertility was renewed by alluvial deposition. Prehistoric depletion of soil nutrients was documented after centuries of indigenous agriculture in Hawaii. Hartshorn et al. (2006) observed that farmers began growing dryland taro and sweet potato (*Ibomea batatas*) using a digging stick on the leeward slopes of East Maui beginning approximately 500 years ago. Centuries of this extractive farming lowered concentrations of Ca^{2+} (49%), Mg^{2+} (28%), Na^{+} (75%), K^{+} (37%) and P (32%) in cultivated compared with uncultivated soils. Similar to the problem of accelerated water erosion faced by the Mayan culture in Central America, wind erosion was a serious constraint faced by the prehistoric farmers of the Kalaupapa field system, Molakai Island, Hawaii (McCoy and Hartshorn, 2007). In New Zealand, there is strong evidence of prehistoric cultivation of four introduced Polynesian plants: bottle gourd (*Lagenaria siceraria*), paper mulberry (*Broussonetia papyrifera*), sweet potato and taro (Horrocks et al., 2004). These data identify combinations of early Polynesian crops, including both field – and tree – cropping systems, and provide evidence of prehistoric taro cultivation in the South Island. Lepofsky (1995) observed the prehistoric agricultural production and human-induced environmental changes in the Society Islands dating back to the 7th-10th century AD. Valleys with the greatest arable potential were cultivated earlier than less preferred sites. Similar to the prehistoric civilizations, the problem of nutrient depletion has aggravated the food insecurity in SSA even during the 21st century (Smaling et al., 1993; Henao and Baanante, 2006; IFDC, 2006).

Increase in population, because of the transformation of the hunter-gatherer system into settled agriculture, necessitated development of an "ard" or a prehistoric plow (Highman et al., 1981; Lal et al., 2006). Introduction of the plow exacerbated the problem of soil erosion and depletion of soil organic matter (SOM). The plow-induced soil degradation plagued mankind even during the prehistoric era. Accelerated soil erosion had a devastating effect (Bunney, 1990) throughout the Middle East and the Central American Mayan culture (Diamond, 2006). With the world's population of 6.7 billion in 2008 and projected to be 9.5 billion by 2050, the issue of producing adequate and nutritious food, the basic human right, is more important now than the challenges faced by sparsely-populated prehistoric farmers.

3. CONSTRAINTS TO TRANSFORMING TRADITIONAL AGRICULTURE IN SUB-SAHARAN AFRICA

Sub-Saharan Africa (SSA) remains the only region in the world where the number of hungry and malnourished populations will still be on the increase even by 2020 (Rukuni, 2002). While other regions have improved per capita food availability since the 1970s, food production and availability have perpetually declined in SSA. It is both a technological and a political/economic challenge, and cannot be ignored any longer. Agrarian stagnation in SSA has defied numerous attempts at transforming subsistence agriculture, even with due consideration to issues related to biophysical constraints and the human dimensions challenges (Otuska, 2006; Vermeer, 1983; Nieuwoudt and Vink, 1989). Traditional agricultural practices in SSA have been addressed in relation to soil degradation (Choker and Odemerho, 1994), soil nutrients and SOM depletion (Stromgaard, 1991; Dakora and Keya, 1997; Sanchez and Leakey, 1997; Nye and Greenland, 1958), soil pests (Hillocks et al., 1996), pest management (Abate et al., 2000), and plant defense mechanisms (van der Westhuizen, 2004). Among commonly promoted strategies for achieving food security in SSA are: cooperative regionalism (Ugwuanyi and Obinne, 1998), drought management (Hubbard et al., 1992), improvement of roots and tuberous crops such as cassava (*Manihoc esculenta*) (Prudencio and Alhassan, 1994), use of indigenous knowledge (Oniang'o et al., 2004), integrated food systems (Hulse, 2004), macroeconomic and public policy (Rukuni, 2002), structural adjustment programs (Amalu, 2002), multiple livelihood strategies of women farmers using micro-enterprises (Gladwin et al., 2001), political economy of urban population (Sutherland et al., 1999), income-generating employment (Duncan, 1998; McCalla, 1999) and policy framework (van Rooyen and Sigwele, 1998).

Innovative technologies have been successful in improving agriculture in Asia, especially in China and India. Important among these innovations to intensify traditional agricultural systems are ecological agricultural techniques involving more input of skills, knowledge and labor (Ellis and Wang, 1997; Xu, 2004; Shi, 2002; Battershill and Gilg, 1998), integrated farming systems (Li and Min, 1999), improved germplasm/transgenic plants grown with efficient systems (Xu and Jeffrey, 1995; Soleri et al., 2005) and diversification of farming systems (Short, 1997). Yet, repeated attempts at adoption of improved technologies have been met with modest success in SSA, where food insecurity remains a major issue. The agrarian stagnation in SSA has defied all approaches and strategies. The stubborn problem will be solved only when Africans (scientists, farmers, policy-makers and the public at large) collectively resolve to solve it in a manner pertinent to the site-specific situations. SSA must enhance, restore and prudently manage soil and water resources to improve and sustain soil quality. Soil-related constraints to be addressed in SSA and other developing countries are accelerated erosion, SOM depletion, drought stress and soil nutrient management.

4. CROP YIELD AND SOIL EROSION

Accelerated erosion is an important factor adversely affecting sustainability of cropping and farming systems. Erosion is more serious in the tropics than in temperate climates because of the prevalence of fragile soils of high erodibility, harsh climates of high erosivity, and predominately resource-poor farmers who cannot afford to adopt conservation-effective measures. Thus, adverse effects of erosion on agronomic productivity are more severe in Africa, Asia and the Caribbean than in the US, Europe and Australia. Erosion affects crop yields and agronomic productivity both directly and indirectly (Fig. 1). Directly, it reduces the effective rooting depth and available water and nutrient retention capacities. Indirectly, it decreases use efficiency of inputs and increases the amount of fertilizers, water and energy needed to produce the same yield.

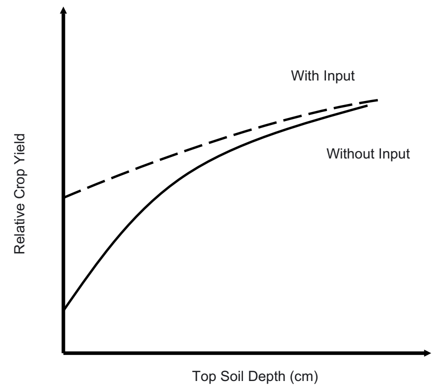

Figure 1. Relative effects of differences in topsoil depth due to differences in severity of soil erosion on relative crop growth and yield with and without off-farm input. Adverse effects of erosion on crop growth are marked by the use of off-farm inputs. Inputs include fertilizers, manure and mulch.

Erosion has both on-site and off-site impacts. On-site, it reduces seed germination, stand establishment, and plant growth and vigor. Off-site, through runon and deposition, it increases risks of inundation, pesticide damage, and seedling burial.

Experimental data on erosional impacts on yield of crops in soils of the tropics are scanty. Synthesis of available data (Lal, 1987, 1998; den Biggelaar et al., 2002a, b) indicates stronger adverse effects on farms that do not use off-farm inputs than on those under intensive management. In general, application of fertilizers and soil amendments masks the adverse impacts of accelerated soil erosion (Fig. 1). In Nigeria, Salako et al. (2007) reported 65–75% reduction in crop yield with 25-cm removal of topsoil when no fertilizers or manure were applied. However, productivity of eroded soils was restored more effectively by the application of manure than by use of chemical fertilizers. Similar experiments by Oyedele and Aina (2006), also conducted on Alfisols in Western Nigeria, indicated that grain yield of maize (*Zea mays*) decreased from 3.2 Mg/ha under control to 0.1 Mg/ha where 20 cm of topsoil was removed. Maize yield decreased exponentially with decrease in the depth/thickness of the remaining topsoil. Drastic reduction in maize grain yield on eroded soil was attributed to the low physical and chemical quality of the exposed sub-soil. Field experiments conducted in the West African Sahel indicated that the grain yields of pearl millet (*Pennisetum glaucum*) were severely reduced on eroded and unmulched compared with uneroded and mulched soils (Michels and Bielders, 2006). Furthermore, millet dry matter yield tripled with P application, and increased by a factor of 13.5 when additional N was applied. These researchers observed that the high P availability was the key factor to reversing decline in crop yields on erosion-affected soils, and manuring was more effective than mulching with straw. Conversely, some studies have documented the beneficial effects of adopting conservation-effective measures on crop yields. For example, installation of stone bunds in large areas of the Tigray Highlands in Northern Ethiopia have shown that average sediment accumulation

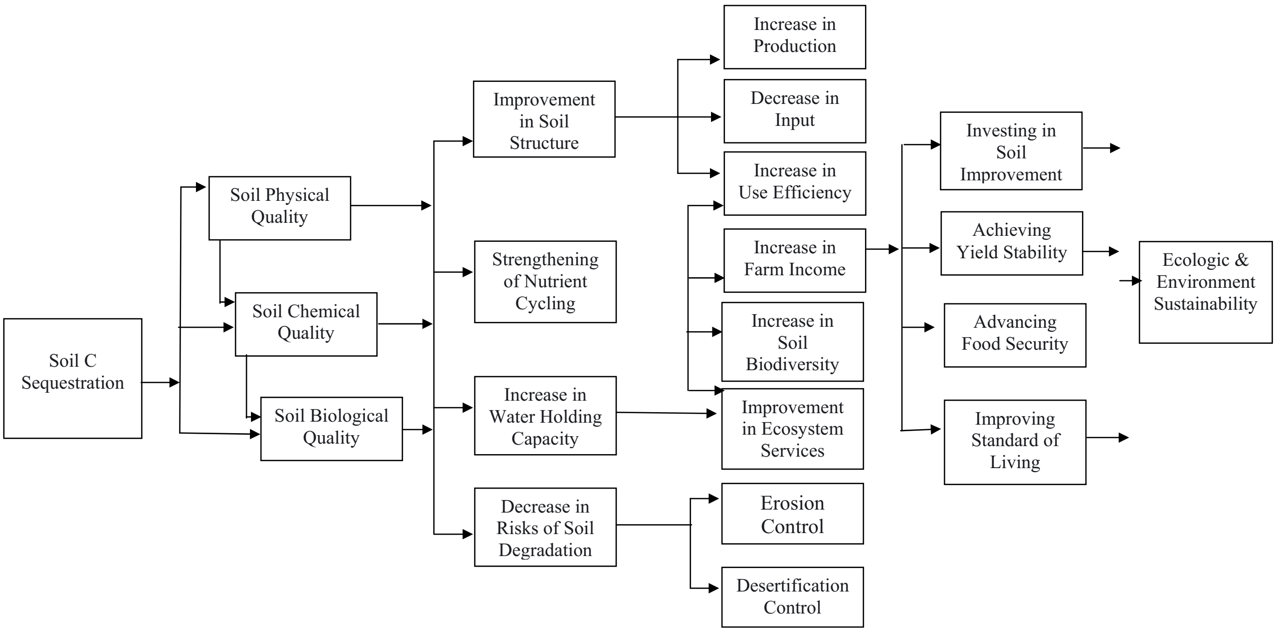

Figure 2. The importance of soil carbon sequestration in ecosystems and environmental sustainability.

behind 3–21-year-old stone bunds is 58 Mg/ha/yr (Nyssen et al., 2007). Consequently, there was an average increase in grain yield of 53% on the lower parts of the landscape in the vicinity of the stone bunds compared with the central and upper parts. Similar positive effects on crop growth and yields have been reported with regards to the use of conservation tillage and mulching. Long-term effects of no-till (NT) farming in conjunction with crop residue mulch are due to improvements in SOM and decrease in soil erosion (Scopel et al., 2005).

Effects of accelerated erosion on trends in crop growth and yield in intensively managed soils under commercial farming practices are similar to those of the tropics, but the magnitude of the adverse effects on crop yield is small (den Biggelaar et al., 2003a, b). Experiments conducted on an eroded prairie landscape in the US indicated that wheat (*Triticum aestivum*) yields were lowest on soils subject to tillage erosion, and were about 50% of those on uneroded or depositional sites (Papiernik et al., 2005). The data from field experiments, used to validate the results of modeling studies, are in accord with those of experimental studies with regards to the adverse effects of accelerated erosion on soil quality (Izaurralde et al., 2007). The fact that increase in risks of soil erosion hazard due to climate change would have similar adverse effects on crop growth and yield (Zhang, 2005) necessitate planning for the use of adaptive measures, especially in the tropics and subtropics where the climate change impacts would be more drastic (Cline, 2007), and resource-poor small land-holders do not have the capacity to adapt to the abrupt climate change.

The fate of erosion-displaced soil carbon is also a debatable issue that needs to be addressed through long-term research conducted on a watershed scale. Some researchers argue that soil erosion is a source of atmospheric CO_2(Lal, 2003). In contrast, others hypothesize that C transported into aquatic ecosystems is a major sink (Van Oost et al., 2004), and may account for the so-called missing or fugitive CO_2. Resolving this issue is important to enhance the scientific understanding of the complex global C cycle and its impact on the projected climate change.

5. SOIL ORGANIC MATTER AND CROP YIELD

Regardless of the farming system, e.g. traditional, commercial or modern and innovative, maintenance of soil organic matter (SOM) above the critical level (Aune and Lal, 1998) is essential to sustaining productivity and minimizing the risks of soil and environmental degradation (Lal, 2006). There are numerous benefits of increasing the SOM concentration and pool on enhancing ecosystem services and improving the environment (Fig. 2). The key factor is the improvement in soil quality with the attendant positive impact on soil processes and properties (Lal, 2004). Similar to the effect of erosion, adverse effects of decline in SOM concentration on crop yields are also more severe without than with application of fertilizers and soil amendments (Fig. 3). These generalized trends are supported by the data from experiments conducted on representative soils and cropping systems in diverse agroecoregions of sub-Saharan Africa (Pieri, 1991).

The data from a field experiment conducted in Burkina Faso, West Africa, indicated that optimum SOM concentration and crop performance results from a judicious combination of the use of organic/biosolids and inorganic fertilizers (Ouedraogo et al., 2007). In the Sudano-Sahelian zone of Burkina Faso, Mando et al. (2005, b) observed that application of manure enhanced SOM concentration and increased

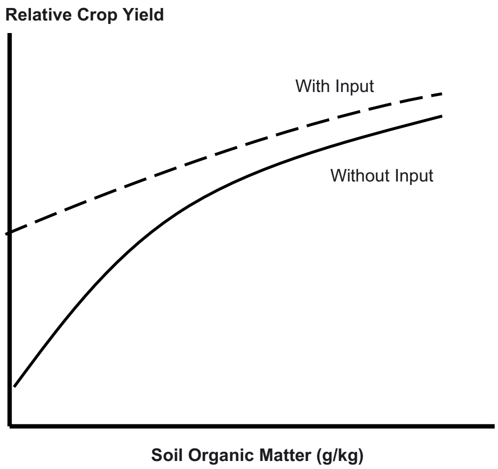

Figure 3. Relative effects of differences in soil organic matter concentration in the root zone on crop growth and yield. Similar to the effects of accelerated soil erosion, decline in crop yield due to reduction in soil organic matter is more without than with application of fertilizers and other inputs.

sorghum (*Sorghum bicolor*) grain yield by 56–70%. Furthermore, grain yield was positively correlated with the particulate organic matter (POM) fraction. A long-term field experiment in semi-arid Kenya, designed to assess the sustainability of cereal/legume intercropping, monitored the relationship between SOM concentration and crop yield. Grain yield of sorghum improved with application of manure, whose residual effect lasted for several years (Kihanda et al., 2006). In Morocco, Bessam and Mrabet (2003) reported that conversion of plow tillage (PT) to no tillage (NT) farming sustained crop yields by enhancing the SOM pool. The mean rate of soil C sequestration over the 11-year period was 0.66 Mg/ha/yr upon conversion from PT to NT farming.

Positive effects of enhancing the SOM pool on crop yield and agronomic sustainability have also been reported from experiments conducted in Asia. Shibu et al. (2006) synthesized the available literature on modeling SOM dynamics in the rice (*Oryza sativa*)-wheat (*Triticum aestivum*) system for different management scenarios, with impact on crop yield. Swarup et al. (2000) documented the positive effects of SOM on crop yields in India. In the Philippines, Manguiat and Rocamora (2004) reported that application of bio-organics significantly increased the average yield of 6 crops by 98 to 153% over the 3-year period. Some studies in South America have also documented the beneficial effects of improving SOM on crop yield. In Colombia, Basamba et al. (2006), observed that increase in maize (*Zea mays*) grain yield with adoption of conservation tillage was due to increase in SOM concentration. In the Pampas of Argentina, Quiroga et al. (2006) observed that the grain yield of barley (*Hordeum vulgare*) was strongly influenced by the improvements in soil quality caused by increase in SOM concentration. In Sao Paulo, Brazil, Silva et al. (2006) reported the beneficial effects of increase in SOM on growth and yield of radish (*Raphanus rativus*). In Cuba, biomass yield of leucaena (*Leucaena leucocephala*) increased with increase in application of worm humus on compost.

Similar to the tropics, there is also strong evidence about the positive effects of increasing SOM concentration on crop yields in North America and Europe (Lal, 2004, 2006). A strong and positive impact of applying sphagnum peat on the yield of potato (*Solanum tuberosum* L.) grown on a sandy soil was reported by Li et al. (2004). In Canada, Malhi et al. (2006) observed that practices which improve SOM concentration also enhance crop yields. The data from a study with long-term application of manure on tomato (*Solanum lycopersicum*) indicated similar yields and soil fertility status to applying inorganic fertilizers (Moccia et al., 2006). Martin-Rueda et al. (2007) documented the positive impacts of reduced tillage and crop rotations on SOM concentration and agronomic yield in some soils of Madrid, Spain. In Denmark, Thomeson and Sorensen (2006) observed that both grain yield and N uptake were highest on soil with the highest SOM level. Long-term field experiments in Estonia showed that rotation and tillage systems with positive impact on SOM concentration also increased and sustained crop yields (Viil and Võsa, 2005).

6. IRRIGATION AND FERTILIZATION MANAGEMENT

The Green Revolution of the 1970s, which saved hundreds of millions from starvation in Asia and South/Central America, by-passed sub-Saharan Africa (SSA). In Asia, the Green Revolution was ushered in by adoption of input-responsive varieties, grown on irrigated soils with liberal use of fertilizer, especially the heavily subsidized nitrogen. It is probable that agricultural land area could double in SSA (and West Asia) by 2050, and may also increase by 20 to 25% in the Asia-Pacific region and the zone of tropical rainforest in South America and Southeast Asia. Yet there is no substitute for intensification of agriculture on the existing cropland. Intensification implies cultivating the best soils with the best management practices (BMPs) to produce the optimum sustainable yield so that marginal lands in fragile ecosystems, e.g., steep lands, tropical rainforest, can be saved for nature conservancy. It is in this context that the importance of expanding cropland area under irrigation by using small-scale projects, judicious and prudent use of chemical fertilizers, and adoption of genetically improved (GM) crops cannot be over-emphasized. Adoption of these options of agricultural intensification can be easily quadrupled and sustained at the high level of production. Ecosystems utilized by humans can only be sustained if the outputs are balanced by inputs. The latter may be of organic or inorganic origin, because plants cannot differentiate the nutrients supplied through the organic or inorganic sources. It is a question of logistics and availability rather than of the natural or synthetic origin. In addition to these inputs, conversion of traditional hoe-based and plow-based methods of seedbed preparation to no tillage (NT) farming is also essential. The promises of NT farming, used in conjunction with crop residue mulch and cover cropping as integral components of complex cropping systems, can be realized by addressing the challenges (biophysical and socio-economic) that it faces.

Table I. Components of sustainable soil management system for advancing food security in the tropics.

Farming Operation/Objectives	Recommended Management Practices
1. Seed bed preparation	No-till farming, crop residue mulch
2. Rotations	Legume-based crop rotations
3. Water management	Mulch farming, water harvesting and recycling, efficient irrigation methods (e.g., drip)
4. Fertility management	Manuring, BNF, biochar, slow release formulations of fertilizers
5. Erosion control	No-till, agroforestry, cover cropping
6. Soil biotic activity	No-till, manuring, mulching, wormiculture
7. Enhancing SOM pool	Complex crop rotations, no-till, agroforestry, biochar application, using manures and biosolids

7. PROMISE AND CHALLENGE OF NO-TILL FARMING

Agronomic techniques to improve soil quality (Tab. I) include NT farming and crop residue management, nutrient management and use of biochar. Plowing and other mechanical methods of seedbed preparation are redundant if weeds can be controlled chemically or biologically, seeds can be sown through the crop residue mulch, and fertilizers can be applied without incorporation into the soil. In this regard, NT farming, used in conjunction with crop residue mulch and cover crops, has numerous advantages including conservation of soil and water, saving in time and energy, improvement in SOM concentration, increase in soil biotic activity and decrease in weather-related impacts on crop yields. It is in this regard that the importance of the judicious management of crop residues cannot be over-emphasized. Therefore, planning for SOM management requires the data on the amount of crop residues produced under different cropping systems (Johnson et al., 2006).

Application of NT farming for erosion control and moisture conservation under row crop production in soils of West Africa was documented by long-term experiments conducted in Nigeria (Lal, 1976, 1989). The potential of judiciously using crop residues as a basis of SOM management was also reported by Shittu and Fasina (2006), who observed that residue mulching improved crop yields in Western Nigeria. Incorporation of a fallow (no cropping) period in the rotation cycle also improved SOM concentration and enhanced soil quality in Burkina Faso (Bostick et al., 2007). In the Mediterranean climate of north Africa, Masri and Ryan (2006) observed that incorporation of medic (*Medicago sativa*) and vetch (*Vicia faba*) increased the SOM pool compared with continuous wheat. In India, Mandal et al. (2007) concluded that the SOM level can be sustained with annual application of 2.9 Mg of biomass-carbon/ha through manure and other biosolids. Ghosh et al. (2006) also observed that the groundnut (*Arachis hypogea*) – wheat systems contributed more carbon through root biomass than groundnut – chickpea (*Cicer arietinum*) systems, and recommended that additional crop residues along with fertilizers are essential to maintaining SOM levels on Vertisols in Central India. In northeastern China, Xu et al. (2006) reported that SOM concentration increased for Ustepts with application of crop residues and fertilizers. In El Batan, Mexico, Govaerts et al. (2006, 2007) observed that NT farming with crop residue mulch was essential to enhancing SOM and improving soil quality. In western Mexico, Scopel et al. (2005) also observed significant yield benefits of growing NT maize under the semi-arid conditions. In southern Brazil, De Bona et al. (2006) observed that NT farming along with high input systems are needed to counter-balance the higher SOM decomposition rates in a sub-tropical Acrisol. In a clayey Oxisol of Brazil, Razafimbelo et al. (2006) reported the management of sugarcane (*Sacchrum rotundum*) residue (burning vs. no burning) had a strong impact on SOM dynamics.

A large body of literature available on the impact of crop residue management and NT farming in the US and Brazil is not reviewed in this report. Thus, a few recent examples are discussed herein. Venterea et al. (2006) assessed the effects of rotational (biennial) tillage on SOM dynamics under corn-soybean (*Glycine max* L.) rotation, and concluded that biennial chisel plowing in the upper mid-west USA can enhance C storage in soil, reduce fuel costs and maintain yields compared with intensive annual tillage. Long-term effects of tillage and crop residue management in the sub-Arctic region of Alaska were assessed by Sparrow et al. (2006). They observed that adoption of reduced tillage can improve soil quality and conserve SOM, but long-term NT may not be feasible because of the weed problem and progressive buildup of crop residues on the soil surface in the cold regions. In the northern Great Plains region, Sainju et al. (2006a–c) assessed tillage and crop rotation effects and concluded that reduced tillage and increased cropping intensity enhance the SOM pool. Furthermore, use of hairy vetch (*Vicia villosa Roth*) and rye (*Secale cereole*) biculture was effective in sequestering more C than monocultures or no cover crop. A long-term study in central Texas, USA, indicated that NT associated with enhanced cropping intensity and N fertilization increased SOM and N pools (Dou et al., 2006). Also in the hot climate of Texas, Zibilske and Bradford (2007) observed that SOM accumulation may be stimulated by growing cover crops with higher polyphenolic contents and restricting soil – O_2 availability with NT farming. In Michigan, USA, Kravchenko and Thelen (2007) observed that use of winter wheat residue decreased the amount of plant-available N and increased grain moisture and test weight of corn grains at harvest. In California's Mediterranean climate, Veenstra et al. (2007) concluded that conservation tillage alone does not accumulate or stabilize more C than conventional tillage. Therefore, addition of cover crop biomass is essential to increasing total soil C accumulation. Incorporating cover crop in the rotation cycle is even more significant for the cotton (*Gossipium hirsutum*)-based systems in Alabama to enhance SOM and improve soil quality (Paudel et al., 2006). In addition to the amount of chemical composition of crop residues, accumulation of SOM in soil using higher residue-producing conservation systems and manure is also scale-dependent. On the basis of their data from a 9-ha field in Alabama, Terra et al. (2005) observed that the potential to sequester C in degraded soils in the southeastern USA may be higher than previously expected. In the Colombia Basin of Washington state, Cochran et al. (2007) studied the SOM dynamics in a semi-arid shrub-steppe ecosystem recently converted to irrigated agriculture. They concluded that cultivation, crop residue incorporation and dairy manure compost amendments contributed to increase in the total soil C pool. Johnson et al. (2007) tested the hypothesis that SOM decomposition is a function of biochemical composition when all other variables are constant, e.g., particle size, temperature and moisture. Variation in biochemical composition was created by selecting residues of 5 species including alfalfa (*Medicago sativa* L.), corn, cuphea (*Cuphea viscosissi-ma Jacq*), soybean and switchgrass (*Panicum virgatum* L.). A stepwise multivariate regression indicated that chemical recalcitrance slows root decomposition and explained why roots contribute more C to the SOM pool than surface residues. Thus, root activity is also an important factor in total CO_2 production (Chen et al., 2005). In the mid-South USA, Brye et al. (2006) studied SOM dynamics in a wheat-soybean double crop system for a range of wheat residue management scenarios. Their data showed that SOM, along with total N and C concentrations, increased with NT at one of the two locations in east-central Arkansas but not in the other. Brye and colleagues concluded that in a wheat-soybean double-crop production system in a relatively warm and wet environment, numerous soil properties can be improved with NT when crop residues are left unburnt. Measurements, made on peat soils in Ohio (Elder and Lal, 2008a, b) and Florida (Gesch et al., 2007), indicated that respiration-induced subsidence can be reduced by conversion to NT farming. In Ohio, the rate of SOM buildup in NT soil increased with application of manure (Wang et al., 2006; Hao et al., 2002), and with retention of crop residue mulch (Blanco-Canqui and Lal, 2007, 2008).

Similar to the data from the US, the positive impact of residue mulch and NT farming on the SOM pool have been reported by several studies in Canada (Malhi et al., 2006; Campbell et al., 2007; Janzen, 2006; Wang et al., 2006; Liang et al., 2005; Singh and Malhi, 2006; Gregorich et al., 2006). These conclusions of improvements in soil quality are also supported by the data from Europe and Australia. Positive impacts of improving cropping intensity and eliminating tillage on increasing the SOM pool were also observed in Brazilian Cerrado by Machado et al. (2006). In addition to cropping intensity, the impact of the climate gradient (temperature and moisture regimes) is also important to SOM and N dynamics (Ortega et al., 2005). Similar to the environmental problems of burning sugarcane residues in Brazil and Colombia, there is a strong interest in a system of "green can trash blanketing" (GTCB). In addition to improving SOM, there may also be advantages in saving of fertilizers over a long time (Robertson and Thorbun, 2007).

The data from a long-term experiment in north-eastern Italy showed that residue incorporation enhanced the SOM pool at the mean rate of 0.17 Mg C/ha/yr (Lugato et al., 2006). Morari et al. (2006) also document the SOM dynamics under NT farming in north-eastern Italy. In semi-arid northern Spain, Bescansa et al. (2006) observed that conservation tillage improved the plant-available water capacity and increased crop yield during the dry years.

A critical analysis of the studies reviewed above, and others reported elsewhere, show that the effects of NT systems and crop residue management on the net gain of the soil C pool depend on a range of complex and often interacting factors. It is, therefore, highly challenging to generalize the results. The information available to date can be summarized as follows:

a. Ecosystem services: Conversion of plow tillage (PT) to no tillage (NT) and other reduced tillage or conservation tillage systems, along with use of crop residue mulch and cover crops, provides numerous ecosystem services regardless of the biophysical and socio-economic environment. Important among these are: erosion control, water conservation, reduction in non-point source pollution, savings in time and energy and other inputs, stabilization of crop yields against drought, and decrease in the C footprint of the agricultural systems.

b. Crop yields: Effects of conservation tillage and residue mulching on crop yields are variable and depend on many factors. Important among these are soil use history, soil quality at the time of conversion to NT farming, soil properties and profile characteristics, crop species (e.g., cereal, legume, root and tubers), climate, amount and composition (C:N ratio) of crop residues, the rate of N application, effectiveness of the seed drill in cutting through the crop residues and establishing seed-soil contact, drainage conditions, soil temperature at the time of seeding and during seed germination and seedling establishment, and the duration since conversion to NT farming. Some reduction in crop yields may occur in soils that have been recently converted to NT, and also in soils with persistent weeds and incidence of other pests (stem borer, slugs, etc.). Despite reduction in crop yields, the net benefit may still be higher with NT farming because of lower costs (e.g., diesel, machinery, fertilizers).

c. Soil C pool: It is widely recognized that conversion of plow till to NT leads to C sequestration in soils (Campbell et al., 2007; Sa et al., 2001; West and Post, 2002; Vagen et al., 2005). These are some concerns about the hidden C costs (Schlesinger, 2006), and the net C gains. Despite the low C footprint, it is also possible that the total soil C pool in NT is either equal to, or in some cases even lesser than, that in the PT soil. In most cases, there is an increase in the soil C concentration in the surface 0–20 cm depth in NT compared with the PT soil. In others, however, the PT soil may have more C in the sub-soil than in the surface layer (Fig. 4) (Blanco-Canqui and Lal, 2008; Baker et al., 2007). Location of crop residue in the soil (surface vs. deep incorporation) can strongly affect its decomposition (Coppens et al., 2006). Soil texture, initial soil C pool and internal drainage also play an important role in determining the net C gains with regards to the tillage system (Puget and Lal, 2005). There exists a strong interaction between availability of N and the soil C pool. Addition of N may increase the soil C pool in N-deficient soils (Jaycinthe et al., 2002; Jagdemme et al., 2008), or decrease it while enhancing mineralization in others (Khan et al., 2007). Soil aggregation plays an important role in retention and turnover of root-derived C (De Gryze et al., 2006). The overall goal of

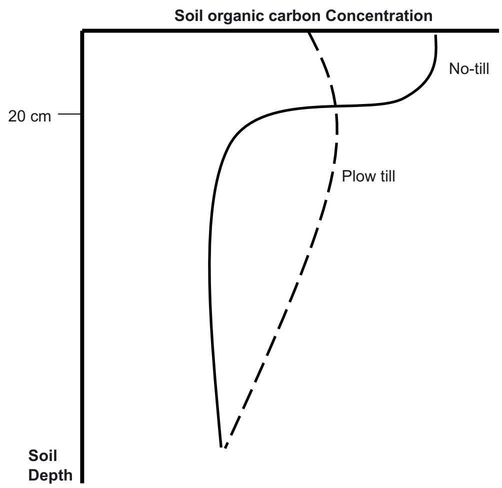

Figure 4. Schematics of carbon profile in some soils managed by no-till and plow till.

managing the soil C pool is to create a positive C budget in the soil by increasing input more than the output (through moderation of erosion, mineralization and leaching), and increase its mean residence time (MRT).

Despite the promise of NT farming in revolutionizing agriculture, its adoption rate is disappointingly low, especially so in developing countries of the tropics where it is needed the most. Total cropland area under NT farming is less than 100 Mha or merely 6% of the world's cultivated area (Derpsch, 2007). Most of the NT farming is practiced by large-scale commercial farmers in the USA, Brazil, Argentina, Canada, Australia, Chile, Paraguay, etc. The lack of adoption of this important innovation by small land-holders is attributed to a range of biophysical and socio-economic factors (Tab. II). The adoption of this innovation can be facilitated only if these constraints are effectively addressed. The issue is not that NT farming does not work; the goal is to make it work by alleviating constraints through site-specific and adaptive research conducted under on-farm conditions and with a participatory approach.

8. INTEGRATED NUTRIENT MANAGEMENT

Similar to the C budget, the nutrients removed from the soil must also be replaced. Nutrient depletion, with the attendant adverse impacts on crop yield, occurs when the nutrient removal (harvest, erosion, leaching and volatilization) exceeds the nutrient input: recycling, biological nitrogen fixation (BNF), animal manure, fertilizers, runon and aerial deposition. Nutrient depletion by indiscriminate mining through extractive farming has adversely impacted crop yields in SSA, SA and elsewhere in developing countries (IFDC, 2006; Tan et al., 2005). There is a need to adopt management strategies which create and sustain a positive nutrient and C budget in managed ecosystems.

9. SOIL FERTILITY MANAGEMENT

Judicious management of soil water and plant nutrients is one of the strategies to adapt to climate change. Nutrient depletion and imbalance in soil adversely affect crop growth and yield, and are serious issues in soils of sub-Saharan Africa (SSA) (IFDC, 2006; Smaling and Dixon, 2006) and elsewhere in Asia, Central America and the Caribbean. Tan et al. (2005) estimated that globally nutrient depletion occurs at the rate of 18.7 kg/ha/yr of N, 5.1 kg/ha/yr of P and 38.8 kg/ha/yr covering 59%, 85% and 90% of harvested area in 2000. Tan and colleagues estimated the global annual nutrient deficit at 5.5 Tg of N, 2.3 Tg P, and 12.2 Tg K, causing a total production loss of 1136 million tons of food grains. Soil nutrient depletion is attributed to lack of or insufficient use of fertilizers, unbalanced fertilization, and losses caused by erosion, leaching, volatilization and weeds. Increasing the input of plant nutrients into the ecosystem is crucial to creating a positive nutrient budget. Nutrients may be applied from inorganic or organic sources (Goulding et al., 2007). Nitrogen is the most limiting factor in crop production, and its use efficiency remains low because of the severe losses caused by volatilization and leaching (Eickhout et al., 2006). Nitrogen management is closely related to the soil C pool and its dynamics, and soils of the tropics are highly depleted of their soil C pool because of extractive farming practices used for centuries and millennia.

Using INM techniques is important for enhancing and sustaining soil fertility (INM: integrated nutrient management). INM involves combined use of mineral and organic fertilizer sources along with the adoption of legume-based, tree-based and animal-based farming systems. Several studies conducted in sub-Saharan Africa (SSA) and South Asia (SA) have documented the long-term and positive impacts of using INM techniques for improving soil fertility (Alemu and Bayu, 2005; Smaling and Dixon, 2006). The use of fire must be minimized because of numerous adverse impacts on ecosystem processes (Shriar, 2007).

10. BIOCHAR

Application of biochar (charcoal or black C) to soil can improve soil fertility. Ever since the discovery of "terra preta do Indio" (Indian Black Earth) in the Amazon (Sombroek et al., 2003; Marris, 2006; Lima et al., 2002; Rumpel et al., 2006), there is a growing interest in using biochar as a soil amendment and for sequestering C and improving soil quality. There are several mechanisms by which application of biochar can enhance soil quality: (i) increase in soil's cation exchange capacity, (ii) decrease in losses of nutrients by leaching, runoff and volatilization, (iii) increase in soil's microbial activity that accentuates soil's resilience, (iv) increase in soil structure and water retention capacity, (v) increase in buffering against soil acidification, and (vi) reduction in emission of CH_4 and N_2O (Fowles, 2007). A pot experiment with three rates (10, 50 and 100 Mg/ha) of biochar showed that application of biochar without application of N fertilizer had no impact on the yield of radish (*Raphanus sativus*) grown in a degraded Alfisol.

Table II. Biophysical, socio-economic, political and cultural factors affecting the adoption of no-till farming in developing countries.

Biophysical	Economic	Social	Political
1. Soil type (texture, clay, minerals)	1. Competing uses of crop residues	1. Land tenure	1. Policy interventions
2. Climate (drought)	2. Availability of inputs (herbicides, seed drill, fertilizers)	2. Mindset	2. Infrastructures
3. Terrain (slope gradient)	3. Yield reduction	3. Community participation	3. Institutional support
4.Weeds	4. Small size farm	4. Gender and social equity	4. Subsidies or lack thereof
5. Insects and pathogens	5. Lack of credit	5. Inappropriate demonstration techniques	5. Lack of political leadership, willpower and vision
6. Nitrogen immobilization	6. Price control	6. Lack of innovative platform	
7. Susceptibility to erosion			
8. Soil health at the time of conversion to NT			

However, higher yield increases were observed with increasing rates of biochar in the presence of N fertilizer, indicating an increase in N fertilizer use efficiency (Chan et al., 2007). A field experiment in Manans, Brazil, showed that charcoal (11 Mg/ha) significantly improved plant growth and doubled grain production only if applied in conjunction with NPK fertilizers. The highest crop yield of 12.4 Mg/ha was obtained with application of poultry manure. Similarly, there are a range of soil processes that increase C sequestration through application of biochar: (i) it is a relatively stable/recalcitrant C with long residence time, and (ii) it is translocated into the sub-soil away from the zone of natural and anthropogenic perturbations. Furthermore, black C is also translocated into the ocean (Dickens et al., 2004; Schmidt, 2004). Therefore, it is argued that charcoal can be used in a climate-neutral manner whereby one mole of CO_2 emitted can be balanced by one mole of CO_2 sequestered (Seifritz, 1993). Air-dried wood can be used to produce charcoal as per equation (1):

$$CH_{1.44}O_{0.66}(\text{drywood}) + 0.43O_2(\text{fromair})\ \text{suit}0.6C(\text{charcoal}) + 0.4CO_2(g) + 0.72H_2O. \quad (1)$$

The process shown in equation (1) can produce 750 kg of charcoal from 3 Mg of air-dried wood, with 60% of C in the wood converted into charcoal (Seifritz, 1993). Charcoal conversion efficiency of wood is about 50%. A coal-fired power plant of 1 MW h power plant produces 6800 Mg of CO_2 or 1855 Mg of C. The CO_2 thus released can be sequestered in 1130 ha (11.3 km^2) plantation of poplar. Therefore, biochar sequestration in terrestrial ecosystems is considered a viable option of enhancing soil fertility while mitigating climate change (Lehmann et al., 2006; Laird, 2008). Despite its potential, three issues which remain to be addressed are: (i) the logistics of producing a large quantity of biomass for making biochar to be used at high rates of application on soils at 10 to 20 Mg/ha or more, (ii) loss of humus or the soil organic carbon (SOC) pool because of the removal of biomass for charcoal (Wardle et al., 2008), and (iii) possible increase in mineralization of the SOC pool due to soil application of biochar (Wardle et al., 2008).

11. CROP YIELDS AND AGRONOMIC INPUT

Strategies for improving soil quality may be built upon traditional knowledge, but must strongly rely on proven scientific innovations (Lal, 2007). With the world average crop yield of milled rice at 4 Mg/ha, the yield is about 3 Mg/ha in India compared with 8.5 Mg/ha for the US. Similarly, for the world average yield of 5 Mg/ha for corn, the grain yield is 2 Mg/ha in India compared with 9.5 Mg/ha in the US.

Crop yields in developing countries are strongly related to input, especially of fertilizer and irrigation. The data in Figure 6 show that fertilizer use has drastically increased in all regions, except in Sub-Saharan Africa. Yields of crops in India have increased with increase in fertilizer use (Fig. 7), especially in irrigated wheat and rice. Because of low fertilizer use, and degraded/depleted soils, crop yields in countries of Sub-Saharan Africa are extremely low, as is shown by the data in Figure 8 for Nigeria, Figure 9 for Senegal, Figure 10 for Uganda, Figure 11 for Ghana and Figure 12 for Kenya. Fertilizer response also depends on the cropland area under irrigation. Similar to trends in fertilizer use, cropland area under irrigation is also low in Africa (Fig. 13). Out of the total world irrigated area of about 275 million ha (Fig. 14), that in Africa is about 5 million ha, or < 2% of the world total.

In the long run, therefore, it is important to make these inputs available to minimize the adverse impacts of weather and soil degradation, and advance food security. There is no reliable substitute for the judicious use of inputs. Improved germplasm cannot extract water and nutrients from degraded/depleted soils where those do not exist. Therefore, making water and nutrients available at the critical time and in appropriate forms is essential to obtaining high yields. Growing improved varieties can help, but these are not substitutes for the essential inputs.

The scientific challenge lies in: (i) understanding soil processes, (ii) characterizing and mapping soil resources, and (iii) predicting soil behavior under a variety of land uses and management scenarios (Miller and Mail, 1995). The strategy is to make economic-agricultural development congruent with ecological, social and political realities, use and conserve indigenous genetic resources, and restore degraded soils and ecosystems (Miller and Mail, 1995). Using the ecological footprint, Kitzes et al. (2007) and Hazell and Wood (2007) proposed two scenarios to balance human demands and

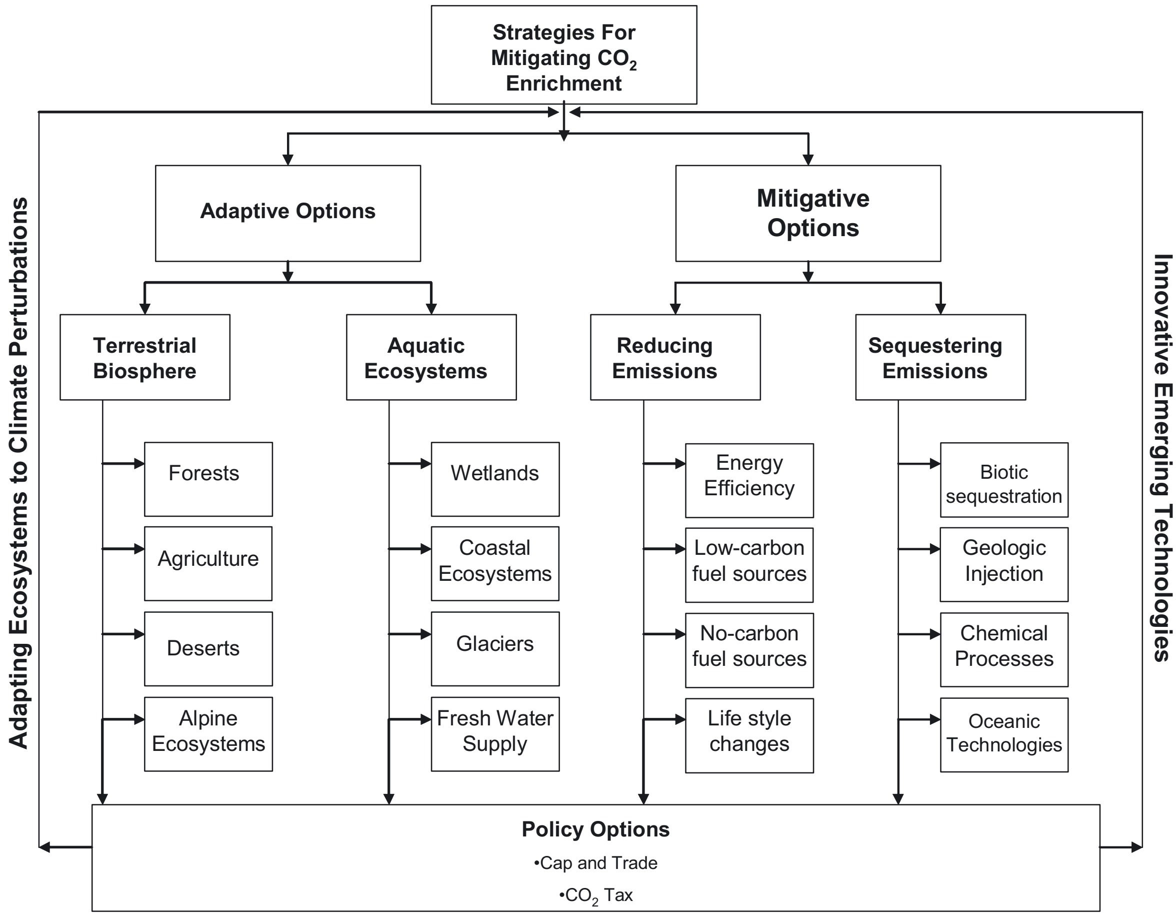

Figure 5. Technological options for adapting to and mitigating atmospheric abundance of CO_2.

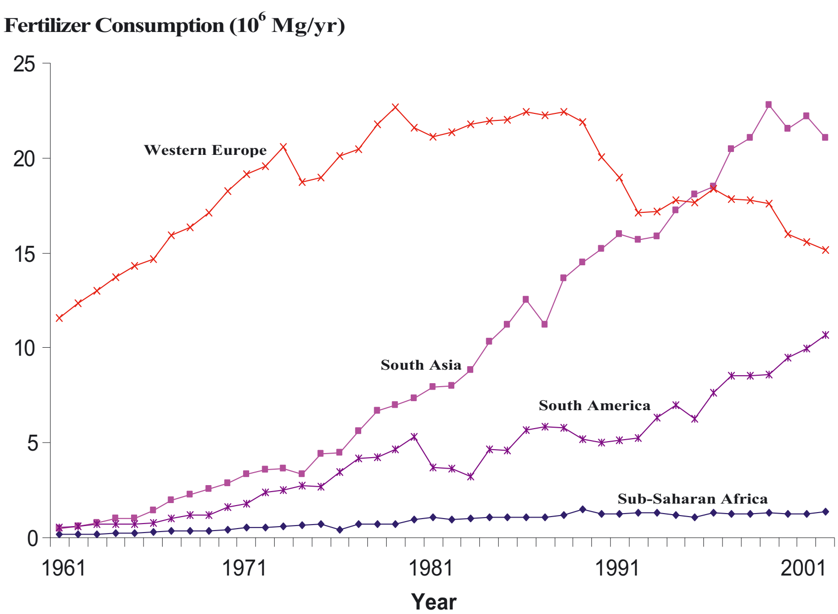

Figure 6. Trends in regional and national fertilizer use (reported from IFDC, 2004).

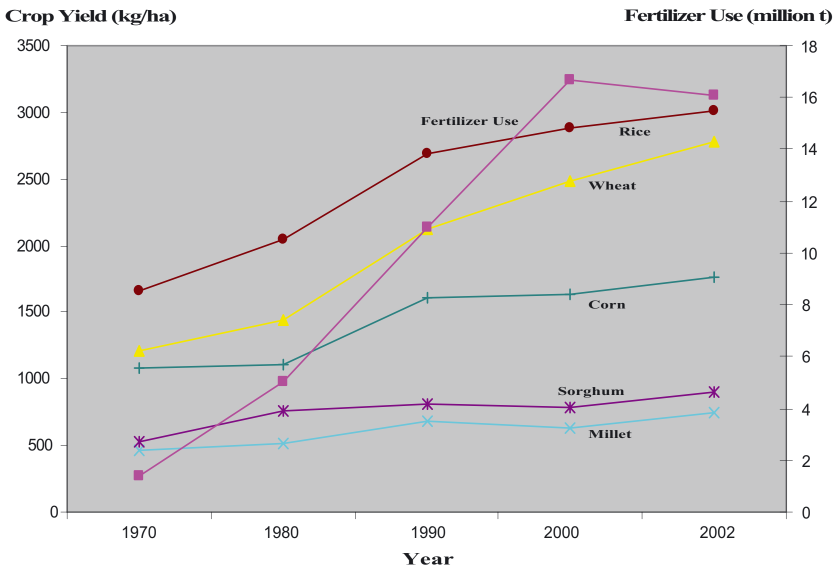

Figure 7. Trends in fertilizer use and crop yields in India (data compiled from FAO Production Yearbooks, and IFDC, 2004).

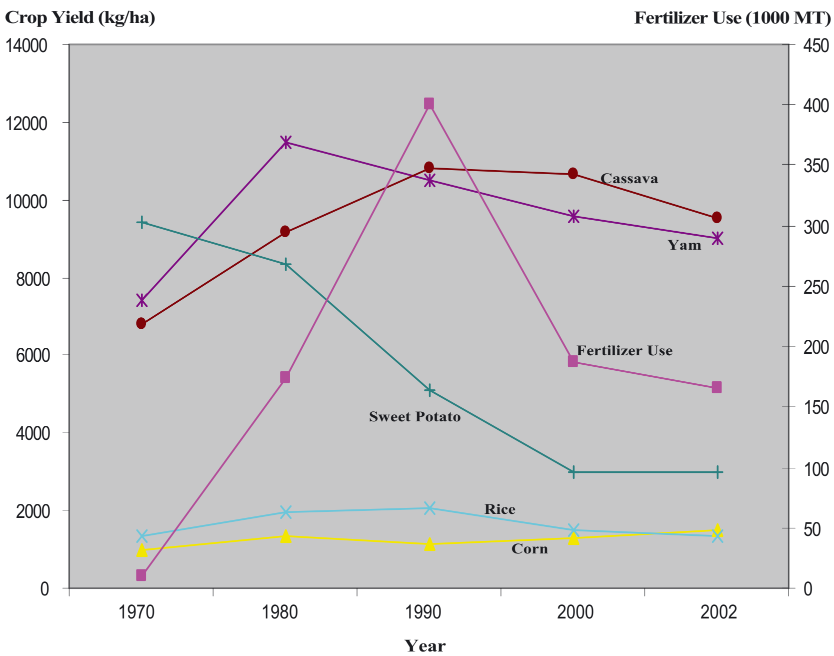

Figure 8. Trends in fertilizer use and crop yields in Nigeria (data compiled from FAO Production Yearbooks).

ecosystem supply: (i) managing the consumption of food, fiber and energy, and (ii) maintaining and increasing the productivity of agricultural ecosystems. It is important to understand the linkages between human needs, agriculture and the environment. The strategy is to develop agricultural systems which balance the positives and negatives of farming and to protect the production capacity and wellbeing of the land (Pollock et al., 2007). Several technological options relevant to achieving these goals include: agrobiodiversity (Thrupp, 2000), conservation agriculture (Hobbs et al., 2007) and social/political factors which determine farmers' interest in adopting recommended practices (Shriar, 2007). Recommended practices are those that enhance eco-efficiency or the sustainable use of resources in farm production and land management (Wilkins, 2007; Pretty, 2007).

In addition to advancing food security, soil C management is also important for controlling the abundance of CO_2 in the atmosphere (Dyson, 1977). While the precious natural resource (SOM pool) competes with biofuel for alternate uses of crop residues (Jenny, 1980) and for improving nutrient flow

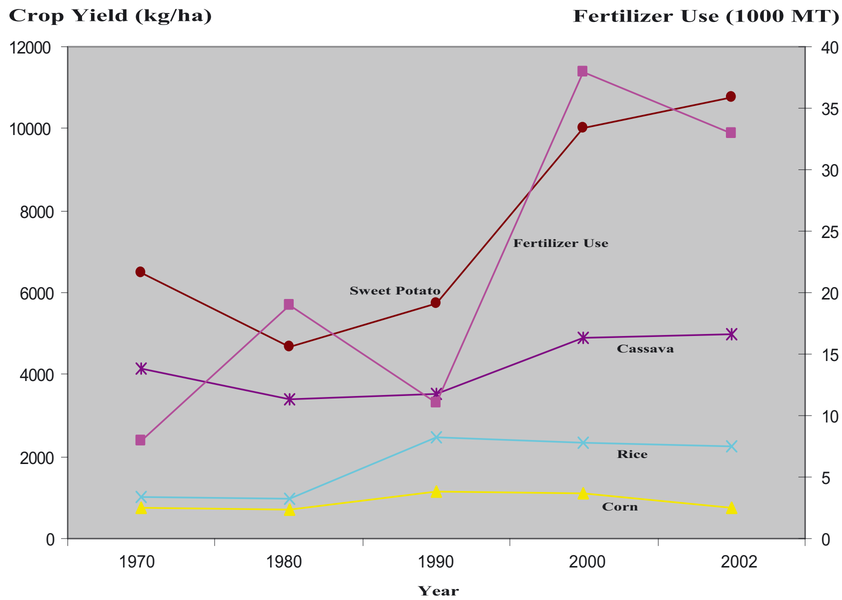

Figure 9. Trends in fertilizer use and crop yields in Uganda (data compiled from FAO Production Yearbooks).

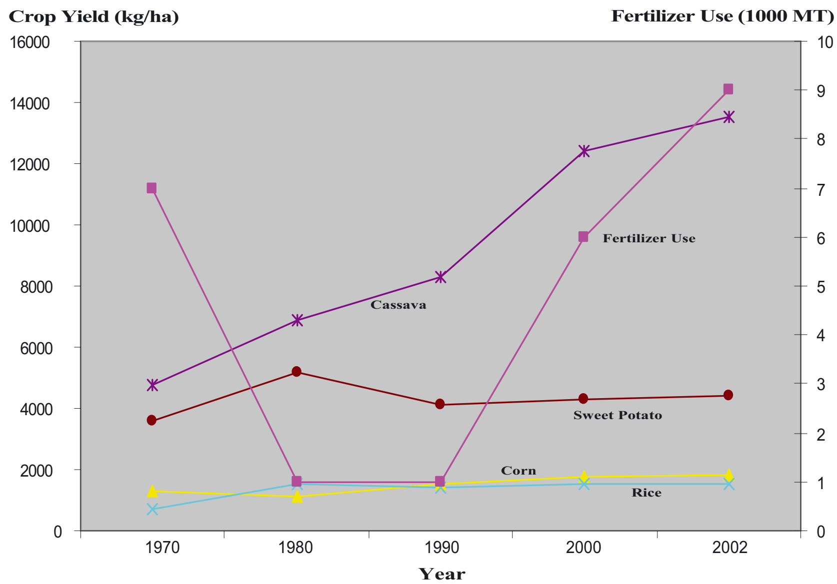

Figure 10. Trends in fertilizer use and crop yields in Senegal (data compiled from FAO Production Yearbooks).

to plants (Janzen, 2006), its judicious management is important for sustainable use of soil resources.

12. CLIMATE CHANGE AND FOOD SECURITY

Three biophysical factors which need to be addressed are soil quality, water availability or drought stress, and climate change. There is a strong interaction among these factors. For example, adverse effects of soil degradation and drought stress are exacerbated by differences in the amount and distribution of rainfall, and increase in temperature, especially during the flowering stage of crop growth. Adverse effects of soil erosion may also be exacerbated by climate change (Meadows, 2003). Over and above the effect of extreme events, equally important is the impact of more gradual changes as well as interaction with social and economic factors (Vogel, 2005). The effect of governance and economic development cannot be ignored. In some cases, however, there may be a positive effect of increase in atmospheric concentration of CO_2 on grain yield. Walker and Schulze (2006) observed that doubling of CO_2 and increase in rainfall by 10% may increase maize grain

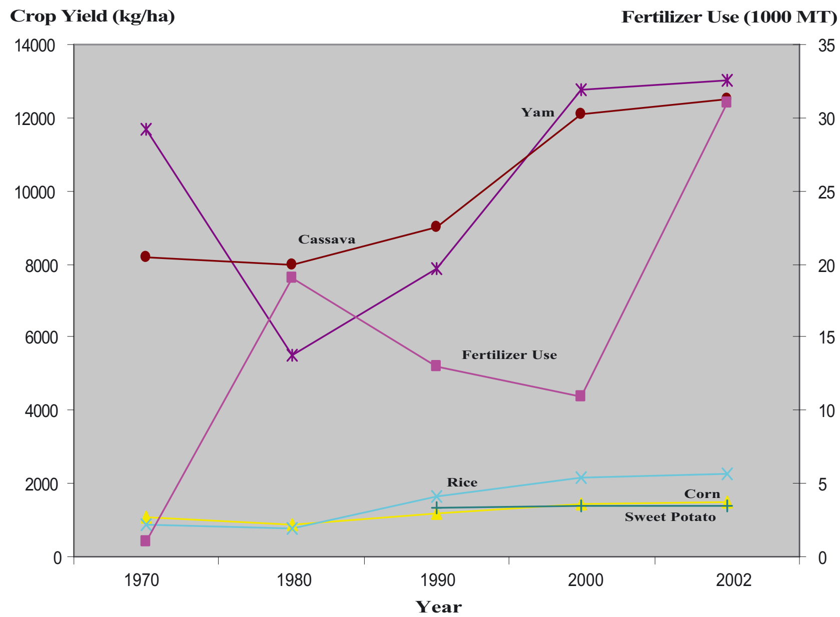

Figure 11. Trends in fertilizer use and crop yields in Ghana (data compiled from FAO Production Yearbooks).

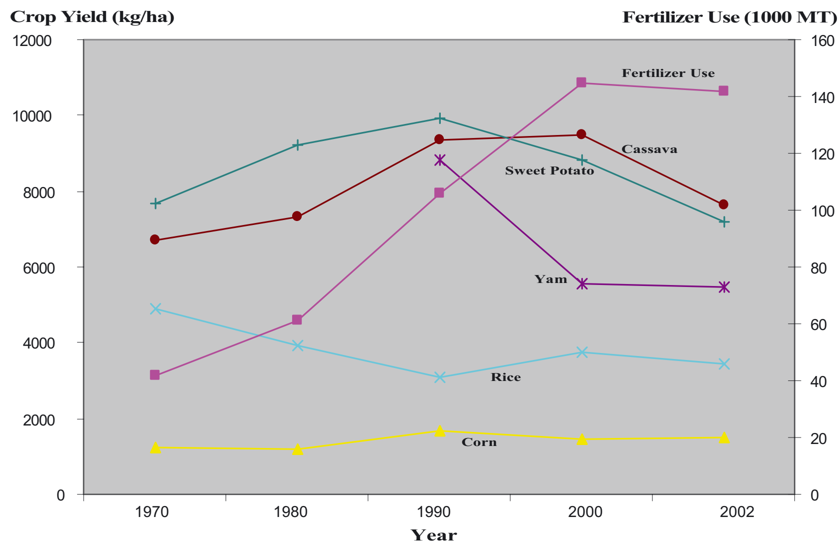

Figure 12. Trends in fertilizer use and crop yields in Kenya (data compiled from FAO Production Yearbooks).

yield by 200 to 1000 kg/ha depending on the use of manure and chemical fertilizers, respectively.

Land-use conversion and soil cultivation can be both a source and sink of atmospheric CO_2 (IPCC, 2007). Adoption of sustainable practices can make the world's soils a major C sink. Soil C sequestration can off-set fossil fuel emissions and mitigate climate change. Soil C sink capacity is about 78 ± 12 Pg, equal to the historic C loss from the world's soils (Lal, 1999, 2006). The land-based C sink may be decreasing (Canadell et al., 2007), probably due to soil/ecosystem degradation. The rate of C sequestration depends on soil and crop management, and soil type and climate (Lal, 2004; IPCC, 2000), and can be as much as 1 Pg C/yr for the next several decades (Pacala and Socolow, 2004). Increase in the soil C pool is important for improving soil quality, and enhancing agronomic production (Lal, 2003, 2006). It is in this context that C sequestration in soils is deemed a win-win situation. While advancing food security through increase in use efficiency of input in soil of improved quality, it also accentuates numerous ancillary benefits (e.g., water quality, biodiversity).

Most productivity models, however, have indicated adverse effects of climate change on agronomic production in Africa. Parry et al. (2005) predicted that the region of greatest risk to decline in food production is SSA. Furthermore, the impact

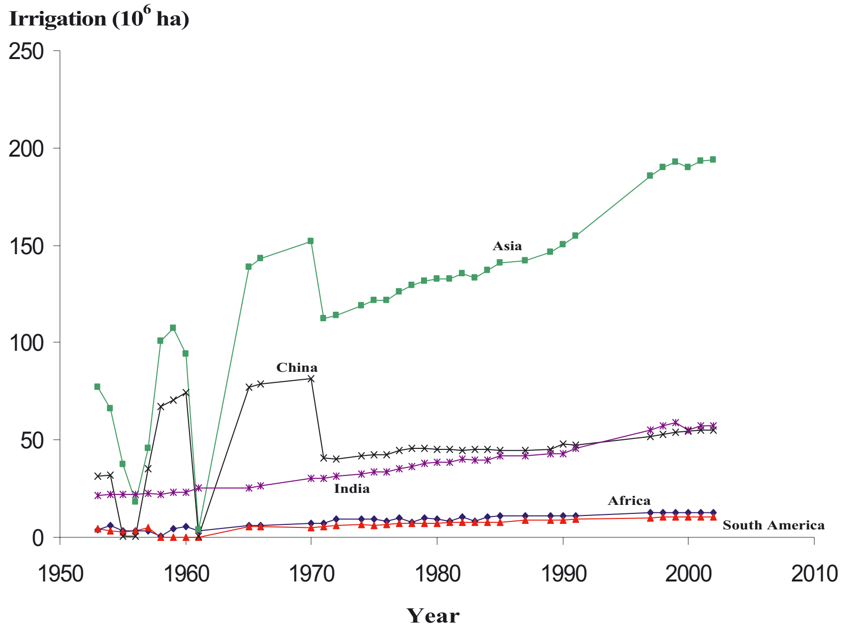

Figure 13. Regional and national trends in irrigated land area (data compiled from FAO Production Yearbooks).

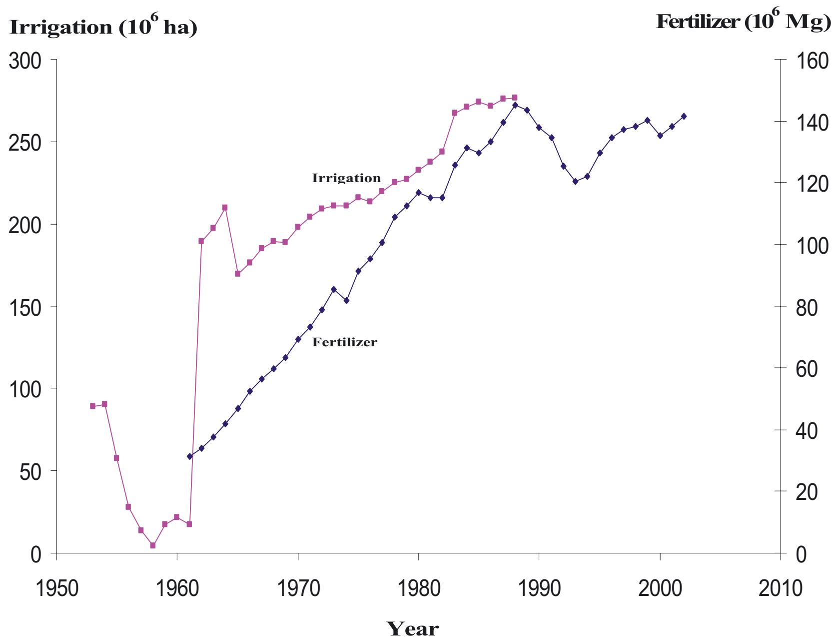

Figure 14. Trends in global fertilizer use and irrigated agricultural land area (data compiled from FAO Production Yearbooks, and IFDC, 2004).

of climate change on risk of hunger depends on the degree of economic development, with the most adverse effect on low-income and poorly developed communities. Kurukulasuriya et al. (2006) conducted a survey of 9000 farmers across 11 countries in SSA. They observed that farm revenues are likely to fall with warming for dryland crops and livestock. In contrast, revenues may rise for irrigated crops. In general, irrigated farmers are less sensitive to climate change than dryland/rainfed farmers. Verdin et al. (2005) reported that Ethiopia will need special attention because of persistent dryness and the positive trends in the Indian Ocean sea surface temperature. Gbetibouo and Hassan (2005) observed a distinct shift in farming practices and patterns due to climate change. These include a shift in the crop calendar and growing seasons including disappearance of some crops from climate-sensitive regions. Jones and Thornton (2003) estimated an overall reduction of only 10% in maize production by 2055, equivalent to losses of $2 billion/yr. However, the impact will be highly variable among regions.

13. BIOFUEL AND FOOD SECURITY CONUNDRUM

Modern biofuels, bioethanol and biodiesel produced from grains (corn, soybean) or biomass (crop residues and biosolids from energy plantations such as switch grass, poplar, willow, etc.) are important for the future of sustainable energy (Goldemberg, 2007), but are also intimately linked with food security. One of the major issues is the source of feedstock for cellulosic ethanol (Somerville, 2006; Kennedy, 2007). Maintenance of SOM being closely linked to the soil application of crop residues, it has been widely recognized that it is either humus or ethanol (Jenny, 1980) but not both. Soil application of crop residues is extremely important for soil quality (Wilhelm et al., 2004; Blanco-Canqui and Lal, 2007, 2008). It is in this context that Tilman et al. (2006) proposed low-input high-density grassland biomass as a potential source for biofuel feedstock. Despite its importance and the urgency to replace fossil fuel by alternative energy sources, the impact of using grains or crop residue on food security must be objectively and critically addressed. In addition to the direct impact, food security is also impacted by competition for land, water and nutrients, to establish biofuel plantations. It is the question of a sustainable use of limited resources in a world of a growing population of 6.7 billion in 2008, projected to be 7 billion by 2012 and increasing at the rate of 3%/yr.

14. CONCLUSION

The food crisis of 2008 is attributed to numerous interacting factors. Important among these are drought and soil degradation, both of which are especially severe in SSA and South Asia (SA). Then, adverse effects on crop yields are aggravated by high energy costs and poor support services. With predominantly small-sized land-holders, who do not have the resources to purchase the much-needed input, crop yields are low and highly dependent on weather. Weather-dependence of crop yields can only be reduced by improving soil quality, its waterholding capacity and overall soil fertility.

The resource-poor small land-holders in economically less developed regions of the tropics may be more vulnerable to climate change than large-scale commercial farms in developed economies of temperate regions. Therefore, making agriculture less susceptible to climate change implies development of irrigation, establishment of conservation-effective techniques, making fertilizers and soil amendments available to farmers, and development of farming/cropping systems which are less vulnerable to declining effective rains and warming temperatures.

Several promising technologies for restoration of degraded ecosystems and sustainable management of soil resources have existed since the 1960s and 1970s (e.g., no-till farming, mulching, growing cover crops and integrated nutrient management). However, these proven technologies have not been adopted, especially in the developing countries of SSA and SA. Creating another income stream for farmers, through payments for ecosystem services (e.g., C sequestration, water quality, biodiversity) may be an important strategy to promote adoption of improved technology. Involving farmers in the decision-making process, in choosing and implementing technological packages, is another important consideration.

Soils must not be taken for granted. While adoption of improved varieties is important, agronomic production can neither be improved nor sustained unless soil quality is restored and maintained. Maintaining soil quality and water resources at optimal level is essential to realizing the potential of improved varieties. Degraded soils do not respond to other inputs unless their physical, chemical and biological quality is restored. Even the GM crop varieties cannot extract water and nutrients from soil where they do not exist. Agronomic management of soil and water must go hand-in-hand with improved germplasm.

Seeds of the second Green Revolution will be sown in improved and restored soils which have a favorable soil moisture regime, optimal soil structure, and positive carbon and nutrient budgets.

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