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Original Research Article

Food security in a changing climate☆

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ABSTRACT

Challenges to global food security are: (i) population increase from 7 billion in 2011 to 9.2 billion in 2050, (ii) climate change, (iii) soil degradation by erosion, salinization, organic matter and nutrient depletion, and elemental imbalance, (iv) decreased availability of water, (v) land competition for urbanization, brick making, biofuel, and non-agricultural uses, and (vi) preferences toward animal-based diet. Global hotspots food insecurity are South Asia and Sub-Saharan Africa. Adopting concepts of ecohydrology, enhancing green water in the root zone, can create climate-resilient agriculture to advance food security and improve the environment. An effective governance is needed to implement policies which promote restorative land uses and recommended management practices. Furthermore, payments for ecosystem services may be a useful strategy to promote sustainable intensification of agriculture by resources-poor farmers.

1. Introduction

Whereas the achievements of global agriculture since the 1960s are among the greatest success stories, even greater challenges await in feeding more than 9 billion by 2050 (Godfray et al., 2010; Foresight, 2011). There are almost one billion hungry people in the world (FAO, 2009; Swaminathan, 2012; Conway, 2012) and about 10.9 million children under five die in developing countries by hunger-related causes (UNICEF, 2009). Two-thirds of the world's hungry live in only seven countries (India, China, Congo, Bangladesh, Indonesia, Pakistan, and Ethiopia) (FAO, 2010). Any further spikes in food prices (Economist, 2011; Swinnen and Squicciarini, 2012) and the increase in frequency of extreme climate events worldwide (Lyall, 2013) would also exacerbate the problem of food insecurity. Contrary to the general perception, food insecurity also exists in developed countries, including the USA (Himmelgreen and Romero-Daza, 2010). There are numerous implications of scarcity (Zwane, 2012).

The world demand (billion tons) for cereals was 1.2 in 1974, 1.84 in 1997 and is projected to be 2.50 in 2020. The global demand (million tons) for meat was 109 in 1974, 208 in 1997 and is projected to be 327 in 2020 (Rosegrant et al., 2001). The rate of increase in food demand is expected to be more in developing than developed countries. Yet, these are also the regions characterized by a wide yield gap (World Bank, 2008). Nonetheless, almost all the future increase in populations will occur in the developing countries. For example, the total population of Sub-Saharan Africa (SSA) will increase from 867 million in 2010 to 1.08 billion in 2020, 1.31 billion in 2030, 1.54 billion in 2040, and 1.76 billion in 2050 (UN, 2007). The population of developing countries is projected to increase from 4.93 billion in 2000 to 7.95 billion (U.N. medium variant) or 10.10 billion (high variant) by 2050 (Koning et al., 2008). On the other hand, the per capita cereal grain

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Table 1
World population and cereal production (calculated from FAO STAT, 2013).

Year	Population (10^6)	Total grain production (10^6 Mg)	Per capita production (kg)
1950	2557	631	246
1960	3043	847	278
1970	3712	1447	389
1980	4451	1780	399
1990	5287	2059	389
2000	6090	2252	369
2005	6474	2269	350
2010	6864	2458	358

production peaked at 400 kg in 1980 and declined to 350 kg in 2005 (Table 1).

Thus, world agriculture is at a crossroads (IAASTD, 2008) and has limited resources (Bruinsma, 2009). It must produce more from less per capita land and water resources and under changing and harsh climate. Ecohydrology, a study of interaction between ecosystem and hydrology, has an important role to play in advancing food security under changing climate by minimizing the risks of agronomic/pedological drought. Specific interactions involving hydrology and agroecosystems relevant to food security are the choice of management systems which may minimize losses of water by surface runoff and evaporation and maximize storage of soil-water in the root zone. The goal is to increase "green water" by judiciously managing "blue water" and recycling "gray water" (Rockström et al., 2009). Therefore, the objective of this article is to describe strategies of advancing food security in an era of rising demands, declining and degrading soil/water resources, and warming and uncertain climate. The article also focuses on management of green water as an example of the use of ecohydrology in achieving a climate-resilient agriculture.

2. Climate change and food

The record breaking weather events of 2011 and 2012 (Colleton, 2012) with 2012 being the warmest year ever in the records in the USA (Gillis, 2013), along with intense storms (Sandy in November 2012) and tornadoes are sobering reminders of the challenges that lie ahead in achieving global food security (Gornall et al., 2010). Extreme weather events have pushed tens of millions over the food cliff into hunger and poverty (Romm, 2011), and 100 million could die from climate change by 2030 (Koebler, 2012). Agriculture is extremely vulnerable even to the 2 °C limit on global warming (Vermeulen et al., 2012).

Unfortunately, the projected climate change may also exacerbate the extreme climatic events and aggravate the risks of drought, flooding, pest infestation, and water scarcity to agroecosystems already under great stress (Beddington et al., 2012). Climate change may affect food systems in several ways (Gregory et al., 2005). Not all effects of climate change may be adverse to agronomic/food production. Certainly, there will also be favorable effects in some regions. After all, it was the climate change 15–20 millennia ago, the so called, "Long Summer" (Fagen, 2006), which made settled agriculture possible. Thus, anticipating opportunities and identifying/realizing some favorable scenarios is an important strategy. Favorable effects of climate change have been reported for some regions because of northwards shift of maize (*Zea mays*)

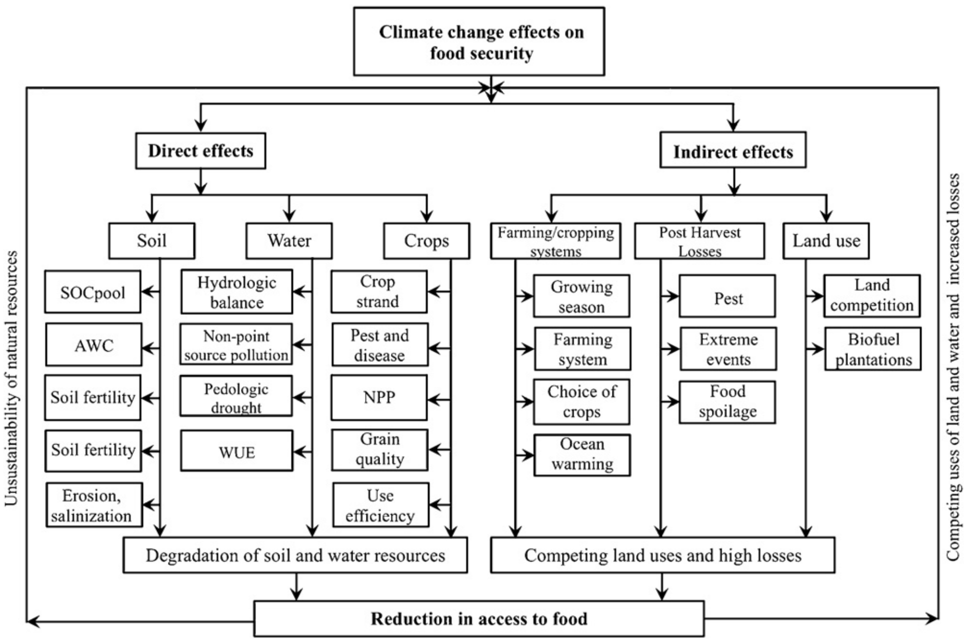

Fig. 1. Direct and indirect effects of climate change on food security. Direct effects on water resources can be reduced by utilizing basic concepts of ecohydrology (SOC: soil organic carbon, AWC: plant available water capacity, WUE: water use efficiency, NPP: net primary production).

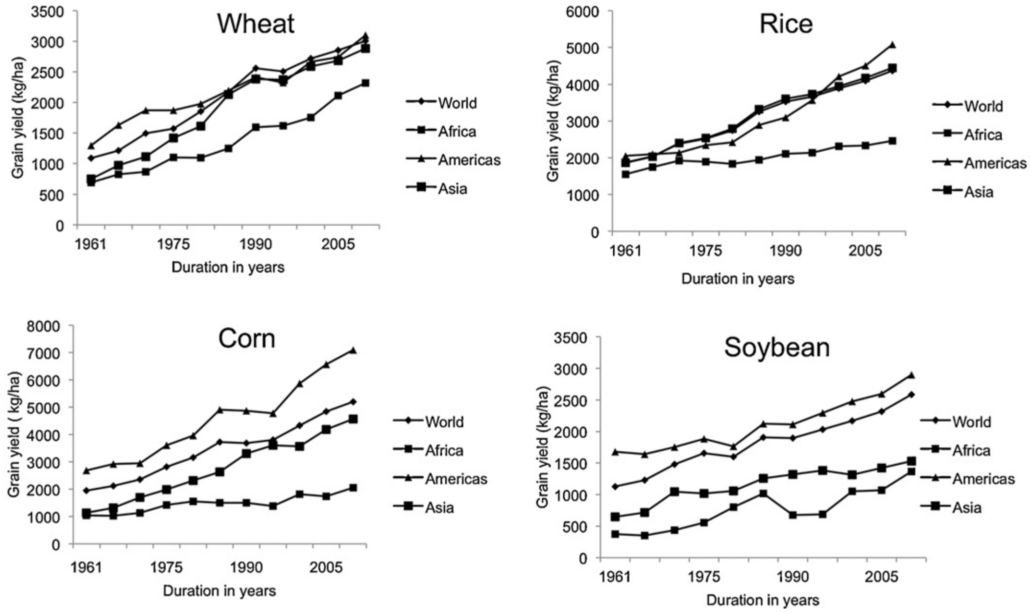

Fig. 2. Global and regional trends in grain yields of some crops between 1961 and 2010.
Redrawn from FAO STAT (2013).

cultivation in the U.S. (Hatfield et al., 2011), rice (*Oryza sativa*) in China (Hijmans, 2007) and wheat (*Triticum aestivum*) in Russia (Ivanov and Kiryushin, 2009). The positive response is partly attributed to the CO_2 fertilization effect (Wrigley, 2006; Erda et al., 2005).

Yet, there will be numerous adverse effects (Fig. 1), to which an effective adaptation is critical to human well-being. Among the direct adverse effects on food security are those related to soil, water, and crops. Adverse effects of climate change on soil quality may be due to depletion of soil organic carbon (SOC) pool, decline in plant available water capacity (AWC), reduction in soil fertility and use efficiency of nutrients (e.g., nitrogen), decline in structure with attendant adverse impacts on vulnerability to degradation including crusting, compaction, accelerated erosion and salinization (Fig. 1). Similar to the impacts on soil, climate change may also adversely affect water resources through alterations in the hydrologic balance (more runoff and evaporation), and high soil erosion may exacerbate non-point source pollution. Some examples of climate change include increase in frequency of drought such as in the U.S. Corn Belt in 2012 (Gillis, 2013), the extended drought during 2011 and 2012 in Texas (Fernandez, 2013), and bush fires in southeastern Australia in January 2013 (ABC, 2013). It is precisely in this context that the concepts of ecohydrology can be profitably used to minimize risks of pedological/agronomic drought. The higher growing season temperatures can adversely impact agricultural productivity (Battisti and Naylor, 2009). There may also be numerous indirect effects of climate change such as change in farming/cropping systems. For example, the land currently suited for corn in the savannah region of Africa may change to sorghum (*Sorghum bicolor*). Similarly, paddy rice in northwestern India (Punjab) may be converted to corn, cotton (*Gossypium hirsutum*), soybean (*Glycine max*), vegetables or aerobic rice. Warming of oceans may also threaten food security (Funk and Brown, 2009), impacting monsoonal rains and adversely affecting crop growth. There are also numerous implications of climate change to incidence of pests, pathogens and weed infestation (Fig. 1) (Lundqvist et al., 2008; Smil, 2000). Newton et al. (2011) observed that accelerated climate change affects components of complex biological interactions differentially, leading to changes which are difficult to predict. Climate-change induced salinity can adversely affect human health (Vineis and Khan, 2012).

Even with globally increasing trend in grain yields of principal crops (Fig. 2), those in Africa (and especially in SSA) remain to be the lowest. Further, the adverse effects of climate change on crop yields may be the most severe in SSA (Challinor et al., 2007; Parry et al., 2005). At present, a third of the African population faces widespread hunger, especially those in rural communities and dependent on traditional agriculture. Changes in weather patterns and extreme events may aggravate the situation (Haile, 2005). Thus, crop production in SSA has been portrayed as the most vulnerable to climate change because its agriculture is strongly influenced by weather and climatic factors such as temperature, rainfall, and frequency and intensity of extreme climatic events (Kotir, 2011). On the basis of survey of 9000 farmers across 11 African countries, Kurukulasuriya et al. (2006) reported a strong decline in revenues of farms based on dryland/rainfed crops and livestock, but rise in those of irrigated crops. Effects of climate change on crop production may also be highly heterogeneous because of variations in soil type, topography, and rainfall distribution (Moore et al., 2012). Thus, there are several hotspots of hunger in SSA in the context of climate change (Liu et al., 2008). These hotspots in SSA include northern and southwestern Nigeria, Sudan (both

countries), Angola, and parts of Ethiopia, Uganda, Rwanda, and Burundi, southwestern Niger and Madagascar. Risks of desertification and drought may also lead to delayed rains, such as in the Sudan-savanna agro-ecological zone of Ghana. Armah et al. (2011) reported that millet (*Panicum millaceum*) and sorghum production in Ghana can be adversely affected. Thus, an expansion of irrigated agricultural areas and improvements in rainfed agriculture may be a prudent strategy.

Similar to SSA, food security in several regions of densely populated Asia may also be affected by the uncertainties and harshness exacerbated by climate change. The sea level rise may affect a large productive area of Bangladesh (Lal et al., 2011). Food security in China, the largest and most populous country, is also a concern (Brown, 1995), which may be further exacerbated by the climate change (Tao et al., 2009). Another indirect effect of climate change is the air pollution in Beijing and other mega cities (Wong, 2013). There are also concerns about the vulnerability of Inuit food systems in the arctic due to climate change (Ford, 2009). Understanding climate change is pivotal to food demand even in developed countries of Europe, such as in U.K. (Bows et al., 2012). Thus, a science plan has been developed to sustainably increase European food security (Soussana et al., 2012).

Because global agriculture and food security are vulnerable to climate change (Ainsworth and McGrath, 2010; Tau et al., 2009), it is important to prioritize the climate change adaptation needs for future food security (Lobell et al., 2008). Adaptation of agricultural and food systems to climate change necessitate appropriate economic and policy interventions and private and public investment discussions. The global rate of cereal production has already been declining from about 2.8%/yr in 1970 to <1%/yr in 2010 (Ziska et al., 2012), and may decline even at a faster rate by climate change and a range of related biotic and abiotic factors. An important factor that affects crop response to climate change is the increased temperatures which can reduce grain yield up to 10% in rice with 1 °C increase in night-time temperature, and by 17% in maize for each day above 30 °C during the growing season under drought (HLPE, 2012). In general most vegetables are relatively sensitive to high temperatures (de la Peña and Hughes, 2007). Lobell et al. (2011) estimated the net impact of climate trends for 1980–2008 on yields with reduction of 3–7% for maize, 1–3% for rice, 5–14% for wheat and 1–7% for soybean. In view of the drastic impact of climate change, research and development in agriculture must integrate adaptation and mitigation (ADAM) strategies.

3. Soil and water resources

Soil resources are finite, unequally distributed, and vulnerable to degradation by land misuse and soil mismanagement. Global land area prone to degradation is estimated at 3.5×10^9 ha or 23.5% of the earth's land area (Bai et al., 2008). Soil is an important component of land (other components being vegetation, hydrology, physiography, fauna, micro and meso-climate). The extent of soil degradation by different processes (e.g., physical, chemical, biological) is estimated at $\sim 2 \times 10^9$ ha (Oldeman, 1994). Of the principal process of soil degradation, accelerated soil erosion (by water and wind), and salinization are the dominant processes. Upon conversion of land from natural to agroecosystems, depletion of SOC pool and of plant nutrients by extractive farming practices lead to degradation of soil structure and tilth and render soil vulnerable to crusting, compaction, and accelerated erosion, decline in activity and species diversity of soil biota and other forms of degradation.

Soil degradation reduces agronomic productivity and use efficiency of inputs. The magnitude of loss in productivity depends on the soil type, farming/cropping systems, management inputs, climate, prevalent weather conditions during the growing season, and the severity of degradation. The adverse impact of degradation on agronomic productivity may increase exponentially with increase in severity from slight to strong especially in a low-input system or extractive farming practices (Fig. 3).

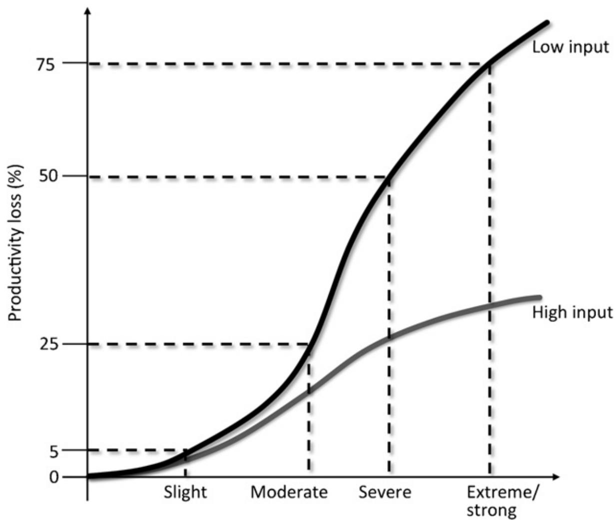

Fig. 3. A schematic indicating loss of agronomic productivity by the severity of soil degradation.

Table 2
Rate of population growth in some major cities in India between 1950 and 2025 (adapted from Kazmin, 2011).

City	Population (10^6)				Growth factor
	1950	1980	2010	2025	
New Dehli	1.4	5.6	22.2	28.6	20.4
Jaipur	0.3	1	3.1	4.2	14
Lucknow	0.5	1	2.9	3.9	7.8
Patna	0.3	0.9	2.3	3.1	10.3
Kanpur	0.7	1.6	3	4.5	6.4
Ahmedabad	0.9	2.5	5.7	7.6	8.4
Indore	0.3	0.8	2.2	2.9	9.7
Surat	0.2	0.9	4.2	5.6	28
Nagpur	0.5	1.3	2.6	3.5	7
Calcutta	4.5	9	15.6	20.1	4.5
Bombay	2.9	8	20	25.8	8.9
Pune	0.6	1.6	5	6.6	11
Hyperabad	1.1	2.5	6.8	8.9	8.1
Bangalore	0.7	2.8	7.2	9.5	13.6
Madras	1.5	4.2	7.5	9.6	6.4
% of population living in cities of >1 million	3.1	5.8	13	15.6	5

In a slightly or moderately degraded soil, supplemental use of input (e.g., fertilizer, irrigation, mechanical tillage) can mask the impact of degradation. Change in land use, from arable to pastoral or silvicultural can often reduce the magnitude of adverse impact. Similar to the "Hubert Curve" in relation to the concept of peak phosphorus (Hubbert, 1949; Abelson, 1999; Steen, 1998; Cordell et al., 2009; Jasinski, 2008) there may be "peak soil" because prime agricultural soils are finite in extent and most have already been appropriated to agroecosystems. Some argue that peak soil is like peak oil, only worse (Brown, 2010). Remaining soils are located either in marginal ecosystems (i.e., too dry, too cold, too hot, too steep, too shallow, too rocky) or in ecologically sensitive ecoregions (e.g., tropical rainforests, wetlands, peat soils, permafrost). Thus, per capita soil and water resources are extremely low and decreasing. For example, the per capita arable land area (ha) by 2050 is projected to be as low as 0.05 for Bangladesh, 0.06 for China, 0.03 for Egypt, 0.11 for Ethiopia, 0.12 for India, 0.14 for Nigeria, 0.07 for Pakistan, and 0.14 for Zimbabwe (Population Action International, 1995). Globally, the per capita arable land area decreased from 0.42 ha in 1960 to 0.22 ha in 2004. With per capita arable land only 0.06 ha, the severity of soil degradation in China (Ye and Van Ranst, 2009) can aggravate the food insecurity. Thusly, it has been argued that growing perennial grains may reduce risks to soil degradation (Glover et al., 2010). It is the scarcity of arable land and increase in food demand which has aggravated the "land grab" in Africa and South America (BBC, 2011; Cotula, 2011). However, direct investment must not be confused with the "land grab".

Similarly, water resources are also scarce and prone to pollution, contamination, and eutrophication. The demand of water for food production could reach 10–13 trillion m^3 a year by 2050. This is 2.5–3 times greater than the total human use of freshwater today (IME, 2013). While there is a substitute for oil/petroleum, there is no substitute for water. Renewable freshwater resources are especially scarce in arid and semi-arid regions. Water scarcity for agriculture is exacerbated by competing uses for industry, recreation, and urbanization. In addition to desertification (Kosmas et al., 2006), irrigation water scarcity is a major issue in the West Asia North Africa (WANA) region, and will become a serious concern in South Asia and other regions in the foreseeable future (Khan and Hanjra, 2008). Groundwater resources are being depleted at a high rate in northwestern India (Rodell et al., 2009). Thus, improving the intrinsic water use efficiency is important to achieving food security (Condon and Richards, 2002).

Urbanization is a global phenomenon in the 21st century (United Nations, 2008). Over and above diversion of prime agricultural soils by urban encroachment, topsoil is also used for brick making in some land-scarce countries. Use of topsoil for brickmaking is a serious issue in densely populated and rapidly urbanizing South and Southeast Asia. The problem is extremely severe in areas adjacent to large urban centers (Table 2). In these areas, brick making is causing a severe loss of fertile topsoil, shrinkage of agricultural lands, depletion of soil fertility especially micronutrients, fall in groundwater table (Santhosh et al., 2012), and emission of greenhouse gases by burning of topsoil and use of animal dung and crop residues as fuel for brickmaking. Total CO_2 emissions from the Indian brick making industry is estimated at $\sim$42 Tg or 4.5% of the national GHG emissions (Mital, 2005). The rate of growth of cities in India is phenomenal (Table 2). Over the 75-year period from 1950 to 2025, population is projected to increase by 20.4 times for New Delhi, 13.6 for Bangalore, 11.0 for Pune, 9.9 for Bombay, and 8.1 for Hyderabad (Table 2). Rapid urbanization in China is a major challenge to soil protection and food security (Chen, 2007), and urban agriculture must be integral to urban planning (Redwood, 2009). Safe and hygienic use of human manure may be important (Jenkins, 1994) in urban/peri-urban agricultures and elsewhere.

Per capita per annum brick consumption is estimated at 100 for India, 100 for Pakistan, 50 for Bangladesh, 650 for China, and 23 for Indonesia (Maithel et al., 2000). The brickmaking industry in India, the second largest in the world, has more than 100,000 brick kilns producing about 150–200 billion bricks annually (Shakti, 2012). It needs

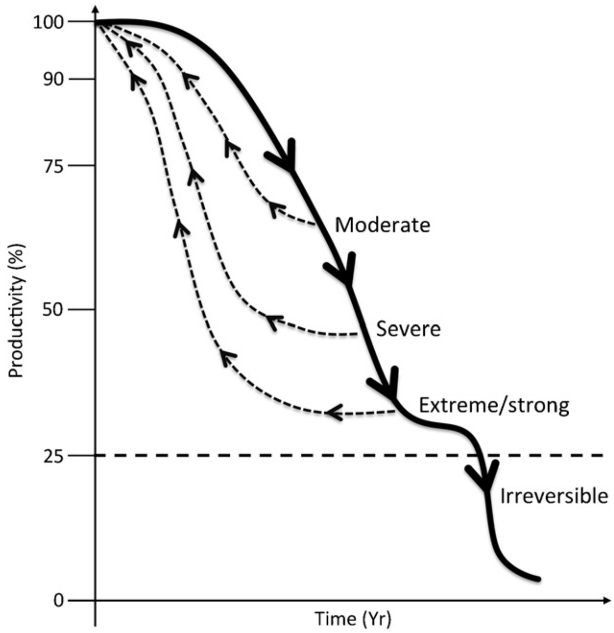

Fig. 4. Productivity restoration and the hysteresis in relation to critical limits of soil properties through adoption of restorative measures.

$28.31\ m^3$ ($1000\ ft^3$) of soil to produce 3500 bricks. This volume of soil can be mined from 30.5 m long, 3.05 m wide and 0.305 m deep space (Asaduzzaman, 2012). The present level of topsoil consumption by the brick industry in India is $420\ km^2$ per annum, and is expected to increase further with increased requirements (Mital, 2005).

With limited, if any, options of bringing new land under production, restoration of degraded/desertified soils is a high priority, such as in densely populated Asia (Ma and Ju, 2007). Thus, the concept of zero net land degradation proposed by UNCCD at the Rio + 20 convention (Lal et al., 2012) is a good strategy. However, soil restoration is a slow process and may take decades. The degradation–restoration curve has also a marked hysteresis (Fig. 4). Furthermore, the duration of time period (yr) for the restoration process to take effect and indicate notable improvements in critical soil properties depends on soil type and the severity of degradation (Fig. 4).

Extractive farming, based on few if any off-farm inputs, can exacerbate the problem and render the restoration process even more difficult. Resource-poor farmers practicing extractive farming in developing countries remove crop residues, practice open grazing, and use animal dung for cooking. These practices deplete SOC pool and mine plant nutrients. The amount of nutrients harvested per Mg (1 metric ton) of grain and stover of corn can be 52 kg/ha (Table 3). In general, 25 kg of N is required per Mg of grains. In sub-tropical conditions of India, a winter wheat producing 6.7 Mg grains/ha absorbs an average of 200 kg N, 24 kg P, 35 kg K. A crop yielding 4.6 Mg grains and 6.9 Mg of straw absorbs 128 kg N, 20 kg P, 30 kg K, 27 kg Ca, 19 kg Mg, 22 kg S, 1.8 kg Fe, 0.5 kg Zn, 0.5 kg Mn, and 0.15 kg Cu (Roy, 2009). These nutrients must be replaced to maintain a favorable balance (Tables 3a, 3b and 3c). Thus negative C and nutrient budgets are severe problems in depleted and degraded soils managed by the resource-poor farmers. Organic farming (King, 2004) and recycling waste (Anderson, 2004) are important strategies.

Table 3a
Nutrients removed per Mg of grains and of straw and corn (calculated from Bundy, 2004).

Nutrient	Nutrients removed (kg/ha)		
	Grains	Stover	Total
N	14.3	6.1	20.4
P	3	0.7	3.7
K	3.7	14.8	18.5
Ca	0.1	3.5	3.6
Mg	0.95	2.5	3.5
S	1.07	0.83	1.9
Zn	0.012	0.018	0.03
B	0.004	0.012	0.016
Mn	0.008	0.039	0.047
Fe	0.007	0.131	0.138
Cu	0.002	0.011	0.013
Total	23.2	28.6	51.8

Table 3b
Nutrient contents of major cereal grains (Anderson et al., 2012; Clough et al., 2001; Kara and Uysal, 2009).

Grains	N	P	K	Ca	Mg	Na	S
Barley	–	9.5	33.7	0.5	1.2	0.1	1.5
Corn	21.1	3.2	26	0.3	1.2	0.1	1.1
Wheat	20	4.4	23.7	0.5	1.3	0.1	1.4
Oats	–	4.1	30.2	1	1.6	0.2	2.1
Sorghum	–	3.4	26	0.4	1.7	0.1	1.4
Peas	–	3.9	60.4	1.1	1.2	0.4	2
Rice	18.2	2.6	9.5	–	0.8	–	–
Soybean	71.5	7.9	126.7	–	1.8	–	–

Table 3c
Nutrients removed per Mg of grains and straw harvested. Recalculated from Sawyer et al. (2011).

Commodity	Nutrients (kg)	
	P	K
A. Grains		
Corn	2.98	1.65
Soybean	5.88	3.5
Oats	5.51	4.34
Wheat	4.4	0.72
Sunflower	3.53	1
B. Straw/Stover		
Corn	1.31	1.75
Oats	1.11	2.3
Wheat	0.88	1.75
Soybean	0.62	0.69
Alfalfa	2.78	2.8
Switchgrass	2.66	4.62
Vetch	2.66	3.29
Perennial ryegrass	2.66	2.38

4. Anthropogenic factors affecting food security

Food demand and access also depend on several anthropogenic factors. In addition to the impact of increase in population, changing human values and demands have also strong impacts on global food security, and human pressure on the planet (Galli et al., 2012).

(a) *Meat-based diet*: An increasing preference for a meat-based diet by large populations of emerging economies (e.g., China, India, Mexico) can strongly impact the demand for grain consumption. Food consumption patterns have strong influence on climate change (Carlsson-Kanyama and Gonzalez, 2009). Energy used and greenhouse gas emissions are 10–20 times more for some animal-based food than that based on grains and vegetables (Table 4). Accordingly, the land area required per kg of food produced is also 45–105 times more for meat-based than potato-based (*Solanum tuberosum*) diets (Table 5; Gerbens-Leenes and Nonhebel, 2002). Therefore, less meat consumption may mean slightly more food for the hungry (Stockstad, 2010). For example, an area of 200 m^2 can produce 142 kg of wheat or 9.6 kg for beef. The number of persons which can be fed in one day is 210 for the vegetarian diet and 13 for the beef diet. The water footprint per person is 1234 L for wheat and 10,282 L for beef-based diet. Similarly, the energy footprint per person is 1.7 MJ for vegetarian versus 19.7 MJ for the beef-based diet (Global Soil Week 2012). It takes 20–50 times the amount of water to produce 1 kg of meat than 1 kg of vegetables (IME, 2013). Therefore, increasing global consumption of beef and animal-based diet is considered as a major driver of regional and global climate change (McAlpine et al., 2009). Indeed, the climate benefits of changing dietary preferences from meat-based to grain/vegetable-based are significant (Stehfest et al., 2009). What people eat does matter to the environment and climate (Marlow et al., 2009). In addition to large land areas and energy needs in meat production, food-miles or long-distance transport (Weber and Matthews, 2008) is another factor that cannot be overlooked. Yet, some rangelands in arid regions are suited only for livestock (and not grain) production.

(b) *The biofuel debate*: Growing emphasis on biofuel production is another strong determinant of food security. Production of the first-generation biofuel diverts food grains to biofuel exacerbating scarcity and increasing food prices. Such diversion has a potential to create scarcity of some grains such as corn; edible oils such as palm oil (*Elaeis guineensis*), canola (*Brassica napus*), soybean (*G. max*) and corn; and sugar from sugarcane (*Saccharum officinarum*) and beet roots (*Beta vulgaris*). Production of feedstocks for second-generation biofuel (i.e., cellulosic ethanol) competes with land, water, and nutrient resources, and has many environmental and social implications (Dauber et al., 2012). These issues have enhanced the "food vs. fuel" debate (Valentine et al., 2012). Removal of straw disrupts nutrient cycling (Table 3). Land clearing in the tropics for biofuel feedstocks can cause a large ecosystem C debt (Fargione et al., 2009). Water use intensity (liter of water evaporated per liter of biofuel produced) is estimated at 670 for sugarbeet, 1332 for corn, 1776 for sugarcane, 3108 for canola, 10,878 for soybean (Hoogeveen et al., 2009; SEI, 2011). Thus, there are major environmental concerns about biofuel production (Buerkert and Schlecht, 2009), and sustainability of biofuel production has been widely questioned (Solomon, 2010). Food must always come before

Table 4
Energy used and greenhouse gas emissions in the production of 1 kg of food transported from United Kingdom to Gottenberg, Sweden (adopted from Gonzalez et al., 2011).

Food	Energy used (MJ/kg)	Gaseous emissions (kg CO_2/kg of food)
Beef	40	23
Mutton and lamb	33	24
Pork	25	9.2
Chicken	18	6.6
Eggs	14	5.5
Beans	2.9	1
Wheat	2.9	0.83
Potatoes	1.8	0.27

Table 5
Land requirements for kg of food in the Netherlands (adapted from Gerbens-Leenes and Nonhebel, 2002).

Food	Land requirement (m^2)	Relative factor
Beef	20.9	104.5
Minced meat	16	80
Sausages	12.1	60.5
Pork	8.9	44.5
Eggs	3.5	17.5
Whole milk	1.2	6
Flour	1.6	8
Fruits	0.5	2.5
Vegetables	0.3	1.5
Potatoes	0.2	1

The relative factor is computed as a ratio of land requirement of specific food resource to that of potatoes.

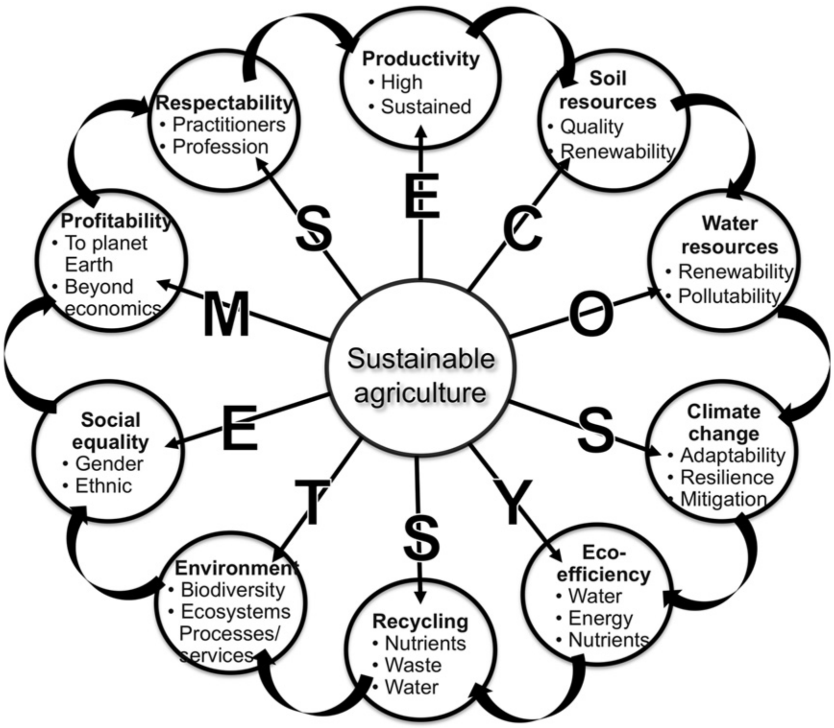

Fig. 5. Ten tenets of sustainable agriculture.

biofuel. Rosenthal (2013a,b) reported the squeeze that Guatemalans and other countries are experiencing because of diversion of land to biofuel production. Sustainable development of agricultural bioeconomy (Jordan et al., 2007), is a critical issue.

(c) *Food waste*: It is estimated that globally 30–50% of all food produced is wasted and uneaten both in poor and rich countries. The Global Water Week (2012) in Stockholm, Sweden, reported that more than one-fourth of all the water (550 km^3) used worldwide is taken to grow over one billion tons of food that no one eats. It is estimated that 30–50% (1.2–2 billion tons) of all food produced is lost before reaching a human stomach (IME, 2013). In poor countries, most of the food is wasted before it reaches the grocery store. In India, for example, millions of tons of wheat is stored under open sky where it is highly vulnerable to pests (rodents) and climatic elements (Bhardwaj, 2012). Losses by pests and pathogens can be reduced by improving storage facilities, building new silos, and adopting modern post-harvest technology. In rich countries (North America and Europe) the food is wasted after it reaches the grocery store. A large portion of food goes directly from grocery stores and restaurants into the rubbish bin. As much as 43 million tons of food were thrown away in 1997 in the USA and 4 million tons in the U.K. in 2006 (Parker, 2011). Per capita food waste in developed countries is estimated at 100 kg/yr, or 100 million tons/yr. In total, USA is losing up to 40% of its food from farm-to-fork-to-landfill (Gunders, 2012).

5. How to feed 9.2 billion by 2050?

The Cerrado region of Brazil has been developed since late 1980s for large scale, intensive and modern agriculture. However, creating another Cerrado miracle (Economist, 2010) would require additional land in a favorable climate. Thus, sustainable intensification of existing land is a high priority. Further, it is important to effectively preserve and efficiently use the food that is already produced. Thus, the strategy is to reduce post-harvest losses (as much as 10–50% in developed countries) and minimize waste (as much as 20–50% in developed countries). There is a potential to provide 60–100% more food by eliminating losses and waste while also freeing up land, energy and water resources (IME, 2013). Further, the strategy of diversion of food grains to biofuel in food-deficit regions must be reversed. Needless to say that there must be a widespread and persistent advocacy, supported by education of the general public, in favor of plant-based diet.

The challenges outlined in Sections 1–4 above also signify the importance of the sustainable intensification soils and water resources. In view of the finite extent of both soil and water, the goal is to adopt sustainable intensification. Ten tenets of sustainable agriculture outlined in Fig. 5. Of special significance to ecohydrology is the eco-efficiency of water through improvements in the water use efficiency by reducing losses and increasing soil-water storage. Technological practices to enhance water use efficiency include conservation agriculture, micro-irrigation, water harvesting, etc. Food and grains being wasted can be diverted to biofuels and other uses.

However, the regions prone to high wastage (e.g., India) do not have the industrial infrastructure for such value addition.

6. Feeding the world by producing more from less through sustainable intensification

In the context of numerous challenges of the 21st century outlined in Sections 1–5, there is a need to radically rethink agriculture (Federoff et al., 2010). Rather than bringing new land under cultivation, the strategy is "sustainable intensification" of existing land. Sustainable intensification implies producing more form the same area of land while reducing the environmental impact and negative externalities (Godfray et al., 2010). This may involve adopting soil and crop management practices such as conservation agriculture (no-till farming), cover-cropping, integrated nutrient management, agroforestry systems, aerobic rice and precision agriculture. Improved management of irrigation systems (Alauddin and Quiggin, 2008) need to be an integral component of sustainable intensification, especially with regards to South Asia's groundwater economy (Shah, 2007). Innovative agroecosystems must produce more from less in an era of changing and uncertain climate, degrading soils, and dwindling water resources. Modern scientific innovations are important to food security in SSA (Conway and Toenniessen, 2003), and Green Revolution in SSA need not be a mirage (Ejeta, 2010). There are innovative technologies such as for wheat (Reynolds and Borlaug, 2006). Some technological options are as follows:

(a) *Bridging the yield gap*: The term yield gap refers to differences in the national average yield and the attainable yield with the adoption of proven technology. For example, the data in Table 6 show yield gap for corn in different geographical regions of the world. The yield gap ranges from 3.1 Mg/ha for western Europe to 10.9 Mg/ha for central and eastern Europe. Thus, adoption of improved technology can strongly improve the agronomic production. Indeed, there exists a wide range of variation in yield of rice in Asia and of wheat in Europe, because differences in the extent of adoption of proven technology. Principal soil-related determinants of the yield gap are drought stress, nutrient deficiency and imbalance, soil compaction and anaerobiosis among others. These constraints can be alleviated through appropriate managerial interventions (Table 7), and promoting agroecologically efficient production systems for smallholder farmers (Altieri et al., 2012).

(b) *Breaking the yield barriers*: The attainable yield potential can be enhanced through innovative research (Ingram et al., 2008). With the growing threat of climate change, it is pertinent to understand the interaction of climate with soil and crops in relation to agronomic production. The strategy is to enhance resilience of soil/agroecosystems to the extreme events (e.g., drought) through the concepts of ecohydrology. In addition to crop varieties with a deeper root system (Gewin, 2010), there is also a need for research on enhancing use efficiency of water, fertilizer and other energy-based inputs. Precision agriculture is another innovation which involves a set of technologies that combine sensors and improved machinery with the information system to optimize the use of off-farm inputs (Gebbers and Adamchuk, 2010). The goal is to account for variability and uncertainties within agroecosystems by adapting site-specific production inputs to enhance use efficiency of resources. Remote and proximal sensing technologies are available to improve spatial resolution.

There are also opportunities to improve productivity of mixed crop/livestock systems (Herrero et al., 2010). This strategy is important because half of the world's food is produced by small-size landholders who practice mixed farming. Sustainable intensification of the mixed farming system through judicious management of fertilizer and water is needed to optimize production and minimize waste. Thus, sustainable management of grassland may be important to improving food security of the arid and semi-arid regions covering 37% of the Earth's terrestrial area (O'Mara, 2012). In addition to enhancing food production, improved management of the vast areas can accentuate sequestration of atmospheric CO_2 in soil and biomass (Follett et al., 2001; Gill et al., 2010). Grasslands can also generate biofuel feedstock, and produce carbon-negative biofuels (Tilman et al., 2006), under specific scenarios of inherently fertile soils.

Table 6
Corn grain yield gap by region (calculated from Hengsdijk and Langeveld, 2009).

Region	Yield gap (Mg/ha)
Latin and Central America	6.6
North America	5.7
Semi-Arid Africa and Middle East	9.7
Humid Africa	7
West Europe	3.1
Central and Eastern Europe	10.9
Northeast Asia	4.7
South Africa	7.8
Southeast Asia	7.4

Table 7
Some Do's and Don'ts in soil management for carbon sequestration.

Dos	Don'ts
1. Afforestation	1. Tropical deforestation
2. Re-inundation of drained wetlands	2. Drainage of wetlands
3. Restoration of peatland	3. Cultivation of peatlands
4. No-till farming	4. Intensive tillage
5. Composting and recycling	5. Biomass burning
6. Mulch farming	6. Removal of crop residues
7. Clean cooking fuel and improved stove	7. Use of dung/biomass for household energy/cooking with traditional stove
8. Using alternative construction materials	8. Use of topsoil for brick making
9. Aerobic rice	9. Puddling and flooding of rice paddies
10. Controlled grazing	10. Open grazing
11. Micro/drip irrigation	11. Flood irrigation
12. Complex farming systems	12. Monoculture

7. Linking food security with climate change mitigation

Thus, of the general belief that "climate is what you expect and weather is what you get" (Hienlein, 1973), there is a trichotomy (weather-macroweather-climate) rather than traditional dichotomy (weather-climate) (Lovejoy, 2013; Lovejoy et al., 2013). Regardless, the complex issue of climate change must be addressed at the grassroots level, through adaptation (Antle et al., 2010). The pedospheric carbon pool, the largest among the terrestrial ecosystems (Lal, 2004) can be a source or sink of atmospheric CO_2 and other greenhouse gases depending on the land use and management. Furthermore, the magnitude and properties (e.g., composition, turnover rate) of the SOC pool are important determinants of soil quality, use efficiency of inputs, resilience against natural and anthropogenic perturbations, agronomic productivity, and sustainability of land use and cropping/farming system. Most soils of agroecosystems have lost 25–75% of the antecedent SOC pool through land misuse and soil mismanagement. The magnitude of loss is more in soils managed by extractive farming than science-based agriculture, in soils of coarse than fine texture, and under tropical than temperate climates. Since the dawn of settled agriculture about 10–12 millennia ago, land use and agriculture practices (e.g., deforestation, biomass burning, drainage of wetland, plowing, manuring) have been source of CO_2 and other greenhouse gases (Ruddiman, 2003, 2005). However, the depleted soils and biotic C pools can be restored by adopting land use and soil/crop/livestock management systems which create a positive C budget. Land use and management systems which lead to C sequestration in soils of agroecosystems are outlined in Table 7. An important among these systems is the conservation agriculture based on no-till (NT) farming and cover cropping along with complex/diverse systems (agroforestry), and integrated nutrient management (e.g., compost, manure, biological N fixation, mycorrhizeal inoculation and fertilizers). Other practices include the use of biochar which is relatively resistant to decomposition, and it may have site-specific niche (e.g., rice husk, coconut shells, oil palm kernels, poultry manure). In addition to adoption of recommended management practices outlined in Table 7 there are other practices which must be avoided/minimized. Use of traditional biofuels (dung, crop residues) can emit soot/block carbon with severe implications to air quality and radiative forcing leading to accelerated greenhouse effect (Rosenthal, 2013a,b; Bond et al., in press).

Table 8
Grain yield increase with increase in soil organic carbon by 1 Mg C/ha (adopted from Lal, 2006).

Crop	Yield increase (kg/ha/Mg C)
Maize	100–300
Soybeans	20–50
Wheat	20–70
Rice	10–50
Sorghum	80–140
Millet	30–70
Beans	30–60

Soil quality and productivity of degraded/desertified soils can be improved by enhancing the SOC pool through soil carbon sequestration by following Do's and Don'ts outlined in Table 7. Increase in SOC pool of degraded/depleted soils can enhance agronomic productivity by improving the use-efficiency of inputs and enhancing resilience of soils and ecosystems against extreme events (e.g., drought). A no-till experiment at Coshocton, Ohio with different rates of crop residue retention showed significantly higher grain yield of corn with than without residues under extremely severe drought conditions experienced during 2012. Corn grain yield with 0% residue retention (complete removal) was 6.3 Mg/ha compared to 10.5 Mg/ha (an increase of 67%) with 100% residue retention. Similarly, the harvest index (ratio of grain yield: (grain + stover) yield) was 48.5% for 0% retention and 62.1% for 100% retention. Soil-water conservation, and favorable soil temperature and the attendant improvements in use efficiency of water and nutrients are important to high yield with residue retention.

The data in Table 8 show that increase in SOC pool in degraded/desertified soils of the developing countries can enhance agronomic yield of grain crops, by improving soil quality (Fig. 6). The cumulative impact of this improvement is a notable increase in food production in developing

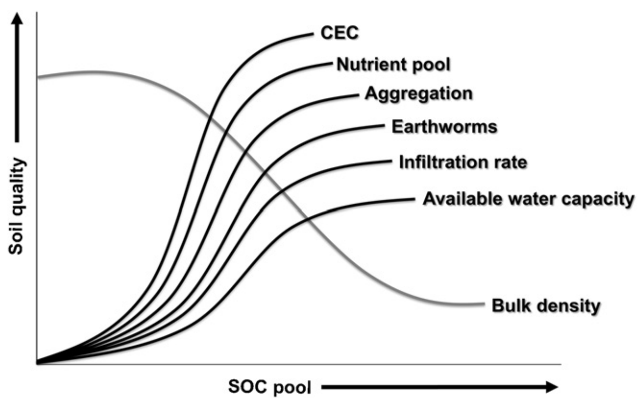

Fig. 6. Quality improvement of mineral soils and SOC pool.

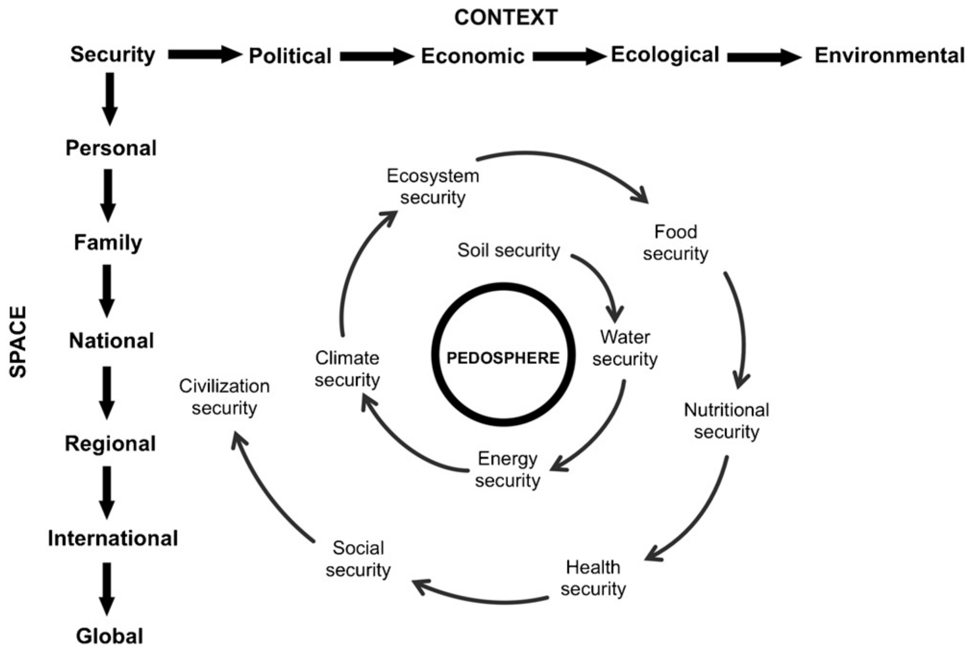

Fig. 7. Securitization of food environment and the civilization through soil sustainability.

countries by 30–50 million Mg/yr through increase of SOC pool in the root zone by 1 Mg/ha (Lal, 2006, 2010a,b). The global impact of C sequestration in degraded soils and desertified ecosystems is enormous. The schematic in Fig. 7 shows biophysical, economic and social impacts of improving soil quality at individual, family, community, national and global scale. There exists a close relationship between environment security and human security (Fig. 7, Brauch, 2007). In addition to food security, C sequestration in soils and forests could mitigate climate change through drawdown of atmospheric CO_2 by at least 50 ppm over the next century (Hansen et al., 2008).

Harnessing the benefits of C sequestration in soils necessitates incentivization of farmers, and especially of the resource-poor farmers who cannot afford the inputs such as retention of crop residues. Crop residues and other agricultural/livestock by-products are precious resources. Therefore, payments for ecosystem services through a fair pricing and a credible/transparent measurement and monitoring system are high priorities (Lal et al., 2013). Furthermore, techniques of SOC measurements, along with associated hydrological and pedological processes, are needed at scales ranging from molecular level (Angström, micron) to watersheds. Significant advances are being made in monitoring SOC pool by in situ measurement techniques (Wielopolski et al., 2011; Chatterjee et al., 2009).

8. Conclusions

Despite the revolutionary advances and classic success stories in improved agronomic production since 1960s, almost one billion people are vulnerable to hunger and malnutrition. Even much greater challenges lie ahead because the global food production must be almost doubled between 2010 and 2050. The quantum jump in food production must be achieved under conditions of changing climate with higher frequency of extreme events, degrading and desertifying soils, decreasing and polluting water, dwindling renewable resources, and increasing energy costs. Using the concepts of ecohydrology can reduce the risks of drought stress and improve water use efficiency. There is a need to educate the general public about the societal values such as reducing meat/animal-based diet in favor of plant-based food, minimizing the waste and enhance the use efficiency of inputs. The strategy of sustainable intensification and producing more from less can enhancing the production with minimal damage to the environment. It is important to enhance/restore soil quality by increasing the soil/ecosystem carbon budget through soil carbon sequestration. Furthermore, agriculture must be integral to urban planning. Adoption of recommended management practices (e.g., conservation agriculture, integrated nutrient management, precision agriculture, cover cropping, agroforestry, micro-irrigation) can enhance resilience of soils and ecosystems against perturbations and also mitigate climate change. In this context, there are numerous land use and management practices, which must be discouraged. Notable among these are tropical deforestation, drainage of wetlands, cultivation of marginal/poor soils, intensive tillage, removal of crop residues, flood irrigation and biomass burning. Crop residues and animal dung must be used as soil amendments rather than as sources of household energy. Rather than flooded paddy, direct seeded aerobic rice is an environmental-friendly and a sustainable option.

With adoption of improved technology and identification of new innovations, 9.2 billion people by 2050 can be fed with judicious/prudent diet while also restoring soil and water and mitigating the climate change.

Conflict of interest

None declared.

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