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ORIGINAL PAPER

# Soil degradation as a reason for inadequate human nutrition

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**Abstract** Soil degradation affects human nutrition and health through its adverse impacts on quantity and quality of food production. Decline in crops' yields and agronomic production exacerbate food-insecurity that currently affects 854 million people globally, and low concentration of protein and micronutrients (e.g., Zn, Fe, Se, B, I) aggravate malnutrition and hidden hunger that affects 3.7 billion people, especially children. Soil degradation reduces crop yields by increasing susceptibility to drought stress and elemental imbalance. Strategies include: improving water productivity, enhancing soil fertility and micronutrient availability, adopting no-till farming and conservation agriculture and adapting to climate change. There are also new innovations such as using remote sensing of plant nutritional stresses for targeted interventions, applying zeolites and nanoenhanced fertilizers and delivery systems, improving biological nitrogen fixation and mycorrhizal inoculation, conserving and recycling (e.g., waste water) water using drip/sub-drip irrigation etc. Judiciously managed and properly restored, world soils have the capacity to grow adequate and nutritious food for present and future populations.

**Keywords** Food security · Hidden hunger · Desertification · Soil quality · Sustainable agriculture

## Introduction

Soil is a three-dimensional natural body on Earth's surface that is essential to numerous ecosystem functions including production of biomass and net primary productivity (NPP), moderation of climate, purification of water, biodegradation of pollutants, storage of water and plant nutrients and recycling of elements. It is the essence of all terrestrial life. Soil quality refers to capacity of the soil to perform several of these ecosystem functions. Conversely, soil degradation implies decline in the quality and capacity of soil through natural or anthropogenic perturbations. In other words, soil degradation refers to diminution of soil's current or potential capacity to perform ecosystem functions, notably the production of food, feed and fiber as a result of one or more degradation processes. Principal soil degradation processes include physical (e.g., decline in soil structure, crusting, compaction, accelerated erosion), chemical (e.g., nutrient depletion, elemental imbalance, acidification, salinization) and biological (e.g., depletion of soil organic mater (SOM), reduction in the activity and species diversity of soil microorganisms) (Lal 1993, 1997).

Food security implies physical, social and economic access to sufficient, safe and nutritious food by all people at all times to meet their dietary and food preferences for an active and healthy life (FAO 1996). Food security has four distinct components: (a) food production through agronomic management of soil resources, (b) stability of food production and availability at all times, (c) food access through economic capacity of household or community, and (d) food safety through nutritious and biological quality (Schmidhuber and Tubiello 2007; Moyo 2007). In this regard, a sustainable food production/agronomic system is the one that: (a) maintains or enhances quality of soil resources, (b) provides sufficient, accessible, safe and nutritious food supply, and (c) creates adequate, economic and social rewards to all members of the society.

Global estimates of the extent and severity of soil degradation and vulnerability to degradation processes are

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alarming (Oldeman 1994; Dejoux 2001; Kaiser 2004; Reich and Eswaran 2004). However, information about the cause–effect relationship, linking soil degradation to agronomic/food production and its nutritional quality, is scanty especially for soils and crops of Sub-Saharan Africa (SSA) and South Asia (SA) where the problem is most severe. Soil degradation impacts agronomic productivity through its adverse effects on availability/imbalance of plant nutrients and water. Therefore, the adverse impacts are easily masked by application of fertilizers and use of supplemental irrigation, and are more severe in soil managed by resource-poor farmers who do not use chemical fertilizers, soil amendments or supplemental irrigation. Soil degradation is caused by biophysical, social, economic and policy factors. Drechsel et al. (2001a, b) indicated a strong relationship between increase in rural population density in SSA and decline in soil nitrogen (N) and phosphorus (P) reserves. Bugri (2008) indicated that poor agricultural production in Ghana, West Africa, was more due to non-tenurial factors (e.g., poor soil fertility, inadequate and unreliable rainfall and excessive tree cutting) that also hurt social and economic parameters than land tenure.

## The state of food security

Similar to the food crisis that occurred during the 1960s, there are alarming reports of the increasing vulnerability of large population to hunger and malnutrition. (FAO 2004, 2005, 2007; Magdoff 2004; Lobell et al. 2008; Anonymous 2008; Koning et al. 2008). There are also dire warnings of even bigger challenges of food insecurity by 2025 (FAO 2005; Rosegrant et al. 2000) and 2050 when the present population of 6.7 billion is projected to reach 9.5 billion before it stabilizes at about 10 billion by the end of the twenty-first century. There are 854 million food-insecure people globally, of which 70% live in Asia, predominantly in India and China (Borlaug 2007; Cakmak 2002). In addition, about 3.7 billion people globally suffer from Fe and Zn deficiencies (Welch and Graham 2004, 2005; Graham et al. 2001). It is widely recognized that food security will remain a major global concern throughout the twenty-first century (Rosegrant and Cline 2003), and the Millennium Development Goal of cutting hunger by half by 2015 will not be met (Bruinsma 2003a, b). Food security has also been linked to national security (Falcon and Naylor 2005), and global peace and political stability (Lal 2008a, b, 2009). Increasing risks of food insecurity are also related to increase in global energy demand which is expected to increase by 50% by 2030 (Hightower and Pierce 2008), decrease in worldwide per capita availability of arable land from 0.40 ha in 1961 to 0.25 ha in 1999 (Horrigan et al. 2002), decreasing renewable fresh water supply (Barnett et al. 2005), and the projected climate change (Parry et al. 2004; Rosenwzeig and Parry 1994). To eradicate hunger, global food production must be increased by 2% year$^{-1}$ (CNES 1999), and to eradicate malnutrition and hunger, soil quality must be restored rapidly (by 2050 or sooner) especially in developing countries.

The objective of this article is to describe the relationship between soil degradation and food insecurity, and outline technological options to enhance soil quality for advancing global food security. The geographical focus of this article is the developing countries of the tropics and subtropics with emphasis on SSA and SA.

## Soil degradation and food security

Soil and environmental sustainability are also essential to human health (Melnick et al. 2005). Depletion of natural resources and increasing competition for limited soil and water resources have been related to malnutrition and basic public health problems (McMichael et al. 2007). Soil degradation affects food insecurity directly and indirectly (Fig. 1). Direct effects are attributed to reduction in crop yields and decline in their nutritional values (protein content, micronutrients etc.). Indirect effects are primarily attributed to reduction in use efficiency of inputs (e.g., fertilizer, irrigation water) and additional land area required to compensate the loss of production. The loss of household income is another indirect cause with adverse impact on access to food. Other indirect effects of soil degradation are those related to pollution of soil, air, and water with severe impacts on human health (Pimentel et al. 2007). These effects are exacerbated by environmental change because the positive feedback between soil degradation and the projected global warming may also adversely impact food security (Fig. 2). Both direct and indirect effects of climate change on food security can be positive or negative depending on the geographic location and prevalent climate. Positive effects include $CO_2$ fertilization and increase in length of growing season among others. In contrast, negative effects include increase in respiration with the attendant decline in NPP, and increase in incidence of pests and diseases. An important indirect effect of the projected global warming on food security is through increase in risks of soil degradation with the attendant increases in losses of water and nutrients.

In addition to inadequate calorie intake, micronutrient deficiencies are an important cause of morbidity and mortality (Black 2003; Ezzati et al. 2002). Children are especially vulnerable to deficiency in Zn (Sazawal et al. 2001) and vitamin A (Humphrey et al. 1992). Approximately 24% of all children in China suffer from deficiency

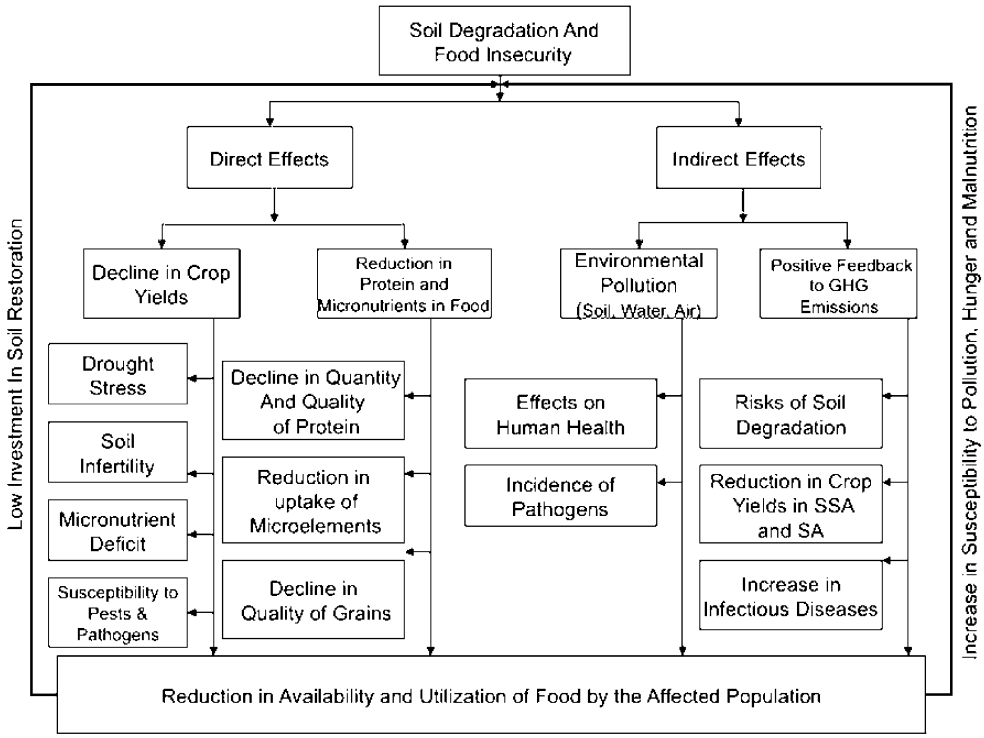


**Fig. 1** Interactive effects of soil degradation on food insecurity and human nutrition and health

of Fe, while over 50% show sub-clinical levels of Zn deficiency (Yang et al. 2007). Keshan and Kaschin–Beck diseases occur in regions where the soils are low in Se concentration (Yang et al. 2007). With rapid industrialization, soil pollution (e.g., Pb and As poisoning) is a severe health concern in China and other emerging economies (Chen 2007; Qi et al. 2007). Brick making, in rapidly urbanizing India, annually consumes 1-m of topsoil from 0.5% to 0.7% of cropland area in the northern states of Haryana and Punjab. Food crops grown on scalped soils are

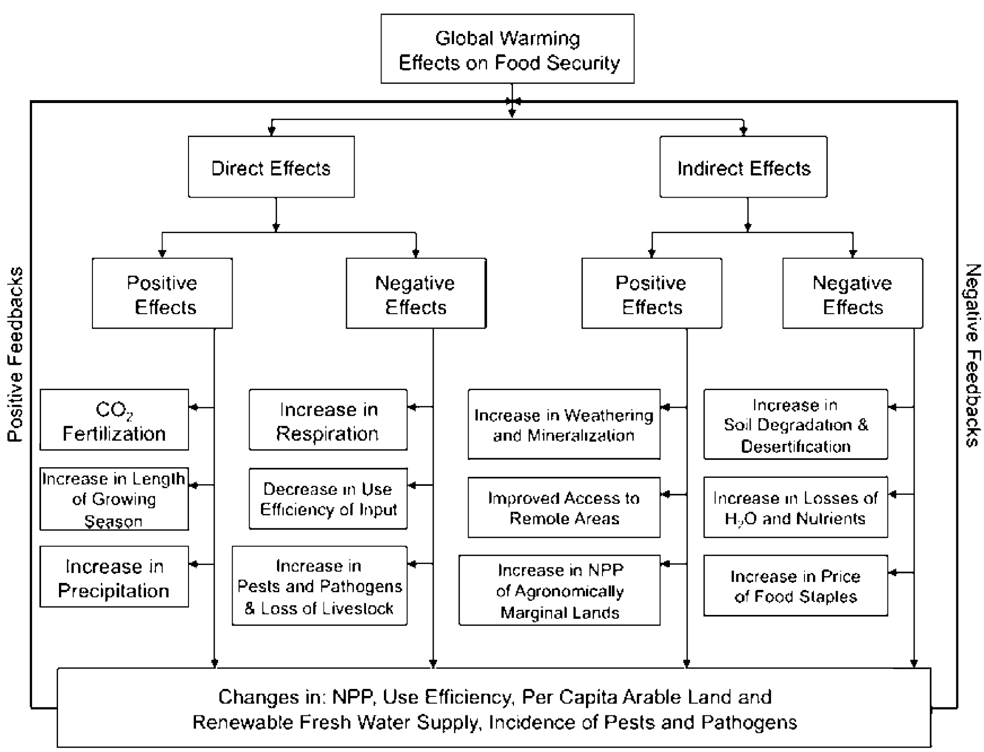


**Fig. 2** Direct and indirect effects of global warming on food security in developing countries

deficient in micronutrients. Pimentel et al. (2007) attributed prevalence of several human diseases to pollution of water, air and soil. Wind erosion can cause serious health problems by blowing soil particles and microbes into the air, aggravating allergies and asthma. Following large-scale deforestation, hookworm infection in Haiti increased from 0% to 12% of the population in 1990, and to 15% in 1996 (Lilley et al. 1997). Dry land salinity affecting 1.05 million hectare (M ha) in southwest Australia, and with a potential risk of spreading to 1.7 to 3.4 M ha, has severe human health implications. Jardine et al. (2007) identified three specific human health concerns of a salinized soilscape: (a) wind-borne dust and respiratory health, (b) altered ecology of the mosquito-borne disease, Ross River Virus, and (c) mental health consequences. Indeed, there exists a strong link between soil health and human health (Sing and Sing 2008).

Two predominant adverse effects of soil degradation and global warming on food security are (a) soil–water imbalance and specifically drought stress, and (b) nutrient imbalance and specifically soil infertility.

Drought stress

Frequency, duration and intensity of drought are aggravated by soil degradation (e.g., erosion by water and wind, soil compaction, crusting, salinization) and projected climate change. Arid and semi-arid regions, with seasonal and highly variable/erratic precipitation, are prone to frequent droughts. There are three types of droughts (Maybank et al. 1995) (a) meteorological drought occurs due to long-term decline in precipitation (Street and Findlay 1981), (b) hydrological drought refers to a prolonged period of decline in surface runoff and fall in the ground water levels, and (c) an agronomic drought implies reduction in soil moisture availability during the growing season (Dracup et al. 1980). While all three forms are inter-related, agronomic drought is often observed sooner than meteorological and hydrological droughts. Soil degradation affects agronomic droughts through reduction in plant available water (PAW) capacity due to: (a) decrease in rooting depth caused by accelerated soil erosion, (b) reduction in soil organic carbon (SOC) concentration and pool caused by removal of crop residues and excessive/uncontrolled grazing along with biomass burning, (c) decline in soil aggregation and stability by excessive tillage and residue removal leading to crusting, compaction, reduction in infiltration rate, and increase in losses by surface runoff, and (d) reduction in activity and species diversity of soil fauna (e.g. earthworms, termites) along with decline in volume and continuity of biopores.

Soil degradation leading to decline in water infiltration capacity in conjunction with climate change, leading to increase in frequency of extreme events (e.g. intense rainstorms), can also lead to inundation and anaerobiosis. Yields of upland crops (e.g. corn, cowpeas, cassava, beans, sorghum, millet) are adversely affected by prolonged inundation and lack of oxygen in the root zone.

Soil infertility

Nutrient imbalance, caused by deficiency of some and toxicity owing to excess of others, is a principal cause of yield decline in degraded/desertified soils. Those prone to deficiency include both macro nutrients (e.g. N, P, K, Ca, Mg, S) and micro elements (e.g. Zn, Cu, Mo, B, Se) and those prone to toxicity have excess Al, Mn, As, and Fe. Nutrient deficit is caused by prevalence of extractive farming practices including removal of crop residues, lack of or low rate of application of inorganic fertilizers and organic amendments, excessive and uncontrolled grazing etc. Nutrient depletion is exacerbated by accelerated erosion (Stocking 2003), which also has strong adverse impacts on crop yields and agronomic production such as in SSA (Lal 1995). In addition to land area affected by accelerated erosion, it is estimated that 95 M ha of arable land in Africa have reached such a state of degradation that only huge investments could make them productive again. Nutrient mining is worst in East and Central Africa and in the West African Sahel (Anonymous 2006). Mining of soil nutrients in Africa is estimated at annual depletion rates of 22 kg N, 2.5 kg P and 15 kg K per hectare of cultivated land over the past 30 years since 1975 (Sanchez 2002; Henao and Baanante 2006). This annual loss is equivalent to US $4 billion in fertilizers (Sanchez and Swaminathan 2005). Nutrient mining is also a serious problem in SA in general but India in particular. Annual rate of soil NPK depletion is estimated at >80 kg $ha^{-1}$ for the states of Jammu and Kashmir, Himachal Pradesh, M.P., Haryana, Tamil Nadu, Kerala, Bihar, Jaharkhand, Assam, Tripura and Rajasthan. High rates (40–80 kg $ha^{-1}$ $year^{-1}$) of $K_2O$ depletion are observed in most of northern India (Roy 2003). In addition to macronutrients, deficiency of Zn and other micronutrients is also a serious problem in soils of SA and SSA.

## Opportunities for advancing food security through soil management

While doomsayers expressed apprehension and pointed fingers, agricultural scientists ushered in the Green Revolution and saved hundreds of millions from starvation during the 1960s and 1970s (Evenson and Gollin 2003; Borlaug 2007). Globally, the implementation of Green Revolution technology increased average cereal yield from 1.2 t $ha^{-1}$ in 1951 to 3.4 t $ha^{-1}$ in 2008 (Ingram et al. 2008). In Europe, grain yields also increased linearly between 1960 and 2005 (Ewert et al. 2005). Despite impressive gains in crop yields and total food grain production in SA and elsewhere around the world during the second half of the twenty-first century, the Green Revolution by-passed SSA. Crop yields in SSA have stagnated at about 1 t $ha^{-1}$ for cereals (e.g., sorghum, millet, maize), 3 to 5 t $ha^{-1}$ for roots and tubers (e.g., cassava, sweet potato and yam) and 100 to 200 kg $ha^{-1}$for legumes (e.g., cowpeas), because of soil degradation caused by erosion, nutrient mining, and depletion of the SOC pool. Adoption of proven soil management technologies has a potential to quadruple production of food crop staples in SSA and also improve their nutritional quality. Globally, adoption of recommended management practices (RMPs) could enhance average cereal grain yields from 3.4 t $ha^{-1}$ in 2008 to 4.2 t $ha^{-1}$ in 2020 (Ingram et al. 2008).

Yet application of the Green Revolution technologies has been a debatable issue for both biophysical (Postel 1999) and social reasons (Shiva 1991). Environmental consequences of agricultural intensification in India (Singh 2000) and China (Thajun and Van Ranst 2005) must be addressed. Furthermore, the problem is not with the Green Revolution technology. Rather, it is its misuse and mismanagement, which have created the environmental problems. It is over fertilization, overuse of pesticides, over simplification of crop rotations, excessive application of flood-based irrigation, unnecessary plowing, complete removal of crop residues, and uncontrolled communal grazing which have exacerbated soil and environmental depredation. This problem lies in using "technology without wisdom" (Lal 2007b).

## Intensification vs. extensification

With global population expected to increase to 8.3 billion by 2030, per capita food consumption is also expected to increase to 3,050 kcal $day^{-1}$ (Eickhout et al. 2006). Consequently, total cereal demand will increase by 718 million t in 2020, and more than 80% (591 million t) of the required increase in demand will come from developing countries (Rosegrant 1997). Most food increases in Asia and elsewhere, with scarce arable land resources, will have to come from land already in production. Land area will increase to 1,609 M ha for arable land (7.7% increase compared to 1995 and 14.5% increase compared with 1970) and remain at 3,416 M ha for grazing land (no change compared to 1955 but 4.5% decline compared with 1970) (Eickhout et al. 2006). Most of the increase in agricultural land area will occur in South America and SSA. Additional areas that can be brought into production in Asia (between 1993 and 2020) are estimated to be 0.8 M ha in China, 2.0 M ha in India and 1.2 M ha in other South Asian countries and 1.2 M ha in Southeast Asia. There will be a net decrease of 0.4 M ha in cropland area in East Asia (excluding China) (Rosegrant 1997). The mean ratio of expected production for 2020 relative to 1990 will be 1.57 for cereals, 1.77 for soybeans and 3.28 for roots and tubers (Table 1). In comparison, the mean ratio of cultivated land area in 2020 relative to 1990 will be merely 1.09 for cereals, 1.14 for soybeans and 1.15 for roots and tubers (Table 1). Therefore, additional production must come either from intensification of land already in agriculture or from restoration of degraded/desertifed soils.

## Technological options to increase agronomic production

Productivity improvements can be made through plant breeding, crop management, tillage methods, fertilizer management, weed and pest control, water management, nutrient management, tillage methods, and adaptation to climate change. The most important options include judicious management of water, macro- and micronutrients and mulch tillage, and adaptation to climate change.

### Improving water productivity

The overall objective is to reduce vulnerability to agronomic drought (Barron et al. 2003) through an ecohydrological approach that enhances use efficiency of the rain received, and taking action beyond the desertification narrative (Slegers and Stroosnijder 2008). Only 10% to 30% of the rainfall received is used by crops (Falkenmark and Rockström 2004), while 70% to 90% is lost. Therefore, water use by crops can be improved by decreasing losses caused by surface runoff and evaporation. Technologies to enhance water use by crops include rainwater harvesting, conservation agriculture (CA), and other measures to alleviate biophysical constraints to attaining high yields (Rockström 2003; Rockström and Falkenmark 2000). Growing sorghum and millet in clumps can improve early season growth in dry areas, enhance grain yields, and increase use efficiency of scarce rainwater. Bandaru et al. (2006) observed that grain yields were improved by clump planting by as much as 100% when yields were in the 1 t $ha–^{1}$ range and 25% to 50% when in the 2 to 3 t $ha^{-1}$ range. Productivity of the Asian rice–wheat

**Table 1** Expected ratio of crop production and cultivated land area in 2020 relative to those in 1990 (Evenson 1999; Cakmak 2002)

| Crop | Production | Cultivated land area |
|---|---|---|
| Wheat | 1.58 | 1.06 |
| Maize | 1.56 | 1.13 |
| Rice | 1.66 | 1.07 |
| Other grains | 1.48 | 1.09 |
| Soybeans | 1.77 | 1.14 |
| Roots/tubers | 3.28 | 1.15 |
| Mean | 1.89 | 1.11 |

system, which has stalled (Timsina and Conner 2001), can also be greatly enhanced through management of nutrients and water, and by improving use efficiency of input.

Water productivity (WP) is defined as the amount of agricultural output (kilogram per hectare, $ per hectare) per unit of water consumed or applied (Mutiro et al. 2006):

$$\mathrm{WP} = \frac{Y}{\mathrm{WA}} \tag{1}$$

Where WP is in kilogram per cubic hectare, $Y$ is yield in kilogram per hectare and WA is water applied in cubic meter per hectare. About 90% of the populations in SSA rely solely on rainfed agriculture for their livelihood (Mutiro et al. 2006), where WP is as low as 0.18 to 1.33 kg $m^{-3}$ of water. There is a close link between food security and WP or an efficient use of limited water resources. Uppugunduri (2006) outlined the following strategies for sustainable management of water resources in developing countries (e.g., India), and to increase WP by producing more crop per drop:

1. Data base: Strengthening the database with regards to surface water inventories, ground water mapping, vegetation cover, soil moisture regime, and aquifer depletion/recharge using remote sensing, geographic information systems (GIS), global positioning systems (GPS), and variable rate technology (VRT)
2. Hydroclimate calendar: Preparing a hydroclimate calendar by using the satellite-based, climate-related information for use in planning of farm operations
3. Improving/restoring soil quality: Restoring degraded soils especially with regards to soil structure, available water capacity, soil fertility (N, P, K, Zn, S, B), microbiological properties, and earthworm activity
4. Supplemental irrigation: Increasing area under supplemental irrigation, and using drip sub-irrigation and other modern innovations, including the use of waste water
5. Conserving soil water: Improving yields of rainfed crops through conserving and efficiently using soil water by adopting CA and mulch farming and
6. Aerobic rice: Growing rice with direct seeding and without continuous flooding and using a wider spacing to enhance tillage.

Improvements in crop varieties and selection of appropriate species can also improve WP in drought-prone areas. Condon et al. (2002) proposed the term "intrinsic water-use efficiency" ($W_t$) to assess differences among cultivars or species. It is defined as the ratio of the instantaneous rates of $CO_2$ assimilation ($A$) and the transpiration ($T$) at the stomata. Both $A$ and $T$ are the product of two factors: stomatal conductance ($g$) to either $CO_2$ ($g_c$) or water ($g_w$) and concentration gradient of either $CO_2$ ($C_a - C_i$) or water vapor ($w_i - w_a$) between the air outside the leaf and the air inside the leaf.

$$A = g_a(C_a - C_i) \tag{2}$$

$$T = g_w(w_i - w_a) \tag{3}$$

By subtraction, and re-arranging Eqs. 2 and 3, it is possible to calculate $W_t$ for cultivars or species (Eqs. 4 and 5).

$$W_t = A/T = [g_a(C_a - C_i)]/[g_w(w_i - w_a)] \tag{4}$$

$$W_t = 0.6C_a(1 - C_i/C_a)/(w_i - w_a) \tag{5}$$

Where the factor 0.6 refers to the relative diffusivities of $CO_2$ and water vapor in air (Condon et al. 2002).

### Improving nutrient management

Soil infertility owing to deficiency of essential plant nutrients, is a major constraint affecting crop yields in developing countries. It is estimated that as much as 50% of the increase in crop yields worldwide during the twentieth century was due to adoption of chemical fertilizers (Borlaug and Dowswell 1994; Loneragan 1997). Fertilizers played a major role in increasing agronomic production in Asia, where the fertilizer input between 1969 and 1995 increased from 20 to 145 kg $ha^{-1}$ $year^{-1}$ (Hossain and Singh 2000). Among macronutrients, N is the most limiting factor to enhancing crop yield (Eickhout et al. 2006). In addition to N, productivity of the rice–wheat system in Asia operates at low yield because of inadequate supply of other nutrients and inappropriate water use. Low productivity in SSA is to a large extent attributable to soil infertility (Sanchez 2002).

Plant nutrients to replenish what is annually removed from the soil to meet the global demand of food and fibers are estimated at 230 million t (Vlek et al. 1997). Thus, it is important to adopt a holistic approach based on the strategy of integrated nutrient management (INM) (Gruhn et al. 2000). The INM strategy recognizes the importance of nutrient recycling using crop residues and other biosolids such as manure and compost, increasing biological N fixation (BNF) through leguminous cover crops, using mycorrhizal inoculation, and applying chemical fertilizers and organic amendments. In this connection, establishing links between livestock and land is very important (Naylor et al. 2005). The INM strategy is also in accord with organic farming (Macilwain 2004). Elements of organic farming, nutrient recycling and liberal use of compost and biosolids, are integral components of INM.

Enhancing micronutrients in soil

Agricultural produce must provide about 50 nutrients (e.g., vitamins, minerals, trace elements, amino acids, essential fatty acids) essential to human health (Welch and Graham 2005). Because of the widespread problems of soil degradation and prevalence of extractive farming, cropping systems in the developing countries cannot meet the nutritional needs of society, especially with regard to microelements. A healthy human diet must contain seven macrominerals (Na, K, Ca, Mg, S, P, Cl) and 17 microelements (Fe, Zn, Cu, Mn, I, F, B, Se, Mo, Ni, Cr, Si, As, Li, Sn, V, Co) (Welch and Graham 2004). These elements must be supplied through soil, including application of S and N (Soliman et al. 1992) and Zn (Wijesundara et al. 1991). There are several strategies for improving availability of macrominerals and microelements in soil. These include (Welch and Graham 2004/2005):

1. Conducting soil tests for assessing fertility status and using appropriately targeted interventions
2. Use of micronutrient fertilizers in appropriate formulations and at desired rates based on soil tests (e.g., Zn, Mo, Ni, Se, Si, Li, I), and supplying others through organic amendments (e.g., Fe, Cu, Mn, B, Cr, V)
3. Adopting diversified cropping systems including indigenous food crops and
4. Growing microelement-dense varieties including genetically modified (GM) crops to improve bioavailability of essential elements (Hirsch and Sussman 1999; Yang et al. 2007). Mapping soil micronutrients (White and Zasoski 1999) is essential to choosing appropriate management strategies. Micronutrients status can also be used to index soil quality (Erkossa et al. 2007) and to identify strategies for its improvement.

Econutrition is another approach being proposed to enhance nutritional values of agricultural produce. Deckelbaum et al. (2006) defined econutrition as the "interrelationship among nutrition and human health, agriculture and food production, environment health and economic development". The econutrition concept is based on the realization that there exists a strong link between soil quality and human health (Fig. 3):

In accord with its significance to improving soil fertility, INM in general but organic farming in particular can also enhance vitamin and mineral contents of some food crops (Warman and Harvard 1998). Biofortification in the soil–plant system is another approach to improve human micronutrient nutrition.

Mulch farming and conservation agriculture

Adopting CA is another soil management approach proven useful for sustaining soil quality. Converting to CA comprises: (a) adopting no-till (NT) farming with minimal or no soil disturbance, (b) maintaining crop residue mulch on the soil surface. (c) Adopting complex/diverse crop rotations, (d) following INM strategy to enhance soil fertility, and (e) using integrated pest management (IPM) techniques to eradicate weeds and control pests and pathogens. Mulch farming and CA are improvements over the traditional systems (Lal 1989), and are important to improving food production when used also in conjunction with planted fallows (Chalwe et al. 2002), and other RMPs. Improved soil and water management, and increasing SOC concentration and pool have been widely proven to enhance productivity and carrying capacity even in the harsh environments of SA and SSA (Kapkiyai et al. 1999; Wani et al. 2003; Lal 2006a, b).

Despite its proven usefulness through 50 years of research since the late 1950s, NT farming with the use of crop residue mulch is practiced on hardly 100 M ha out of a total cropland area of 1,500 M ha (Derpsch 2007). There are several constraints to adopting NT farming in developing countries, where this technology is most needed (Lal 2007a). Crop residue mulch has numerous advantages to soil and water conservation and improving crop yields (Lal 1974, 1975, 1976; Lal et al. 1980; Beukert et al. 2000). Therefore, removal of crop residues for alternative uses has severe adverse impacts on soil quality (Lal 2005), and mining of plant nutrients contained in it (Singh et al. 2005). Competing uses of crop residues for other purposes (e.g., feed, fuel) rather than as soil amendment is a serious constraint. Lack of availability or high cost of herbicides, no-till seeder and other inputs are other factors. Further, it is a high-skill technique and requires some training of land managers and extension agents for its successful adoption.

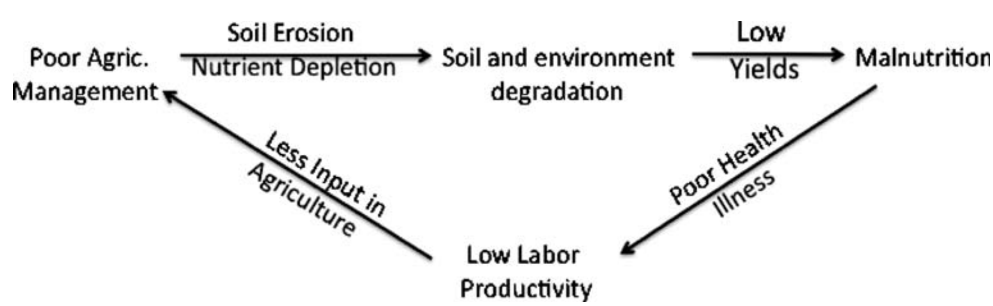


**Fig. 3** Link between soil degradation and human health (modified from Deckelbaum et al. 2006)

Managing soils for adapting to climate change

Soil degradation and climate change are interlinked through many parameters including the vegetation cover. For example, there is a close correlation between vegetation cover and soil degradation on the one hand, and vegetation cover and the rainfall amount in the West African Sahel on the other (Lotsch et al. 2003; Exlundh and Olsson 2003; Van den Hurk et al. 2003). Reduction in vegetation cover, due to increase in soil degradation and other anthropogenic activities, has led to a substantial decrease in the amount of rainfall over most of tropical Africa (Paeth 2004). The decrease in rainfall may be exacerbated by the near-surface warming due to the projected climate change. Reduction in soil moisture, aggravated by erosion-induced soil degradation and decline in SOC pool and clay content, also plays a major role in African and South Asian monsoon climates (Paeth and Thamm 2007). High soil moisture levels favor an abundant monsoon and vice versa (Douville et al. 2001). Indian summer monsoon, Sahara/Sahel/West African monsoon and the Amazon rainforest are among the tipping elements in Earth's climate system and are prone to drastic changes (Lenton et al. 2008). Asian monsoons are also affected by the Asian soot cloud, that covers most of the Indian Ocean, and is caused by the use of traditional biofuel (e.g., animal dung, crop residues, wood) for cooking in SA and SSA (Ramanathan et al. 2001; Venkataraman et al. 2005). Providing clean cooking fuel to rural populations in SA and SSA is important to minimizing the soot cloud and saving dung and crop residues for use as soil amendments. It is likely that the projected climate change will lead to drier conditions in the West African Sahel (Paeth and Stuck 2004). Attempts to improve agricultural production, through deforestation and bringing new land under production along with use of additional fertilizers and pesticides, may exacerbate the risks of global warming (Tilman et al. 2001) and soil degradation (Cerri et al. 2007). The projected climate change, along with increase in risks of erosion and the attendant degradation and desertification, will also adversely affect food production (FAO 2007). There is a strong link between food security and climate change (Sanchez 2000; Brown and Funk 2008). Jones and Thornton (2003) estimated an annual reduction in maize yield of ~10% in Africa and Latin America by 2055. Whereas most developed countries may experience increase in agronomic production due to the climate change, most developing countries are likely to experience a reduction in production (Parry et al. 2004; Rosenwzeig and Parry 1994) (Fig. 2). Fischer et al. (2005) estimated that projected climate change may deepen current production and consumption gaps between developed and developing worlds. It is imperative, therefore, that adaptive strategies are in place to mitigate the effects of climate change on soil degradation and the attendant decline in food production so that poor and vulnerable people are buffered against the severe consequences.

Soil and crop management strategies to adapt to climate change include adjustments in: (a) time of sowing, (b) methods of seed bed preparations, (c) use of crop residues, mulch and cover crops, (d) adoption of complex crop rotations including agro-forestry and mixed farming, (e) water management systems such as drainage or irrigation as necessary, (f) time, rate formulations and mode of application of fertilizers and amendments, and (g) choice of species and varieties suitable for the changing climate. Adaptation is crucial to survival.

## Managing soil to address food security and environmental issues

Soil degradation, by tightening its grip on the poverty trap, is an important cause of food insecurity, malnutrition, social/ethnic conflicts and civil political unrest. While the adverse effects of soil degradation on food security can be buffered somewhat by crop management involving GM crops and biotechnology, there is no viable alternative to soil quality restoration for alleviating malnutrition. Furthermore, the potential of improved varieties can only be realized when grown under optimal soil and agronomic management (Lal 2008a, b). Plant breeders also argue that there is a greater challenge in tailoring cropping systems to an environment that is still incompletely quantified, highly heterogeneous, and unpredictable over time scales of days to decades (Reynolds and Borlaug 2006). Soil scientists have to work with plant breeders to improve nutrient capture from soil by the genetic manipulation of crop plants (Hirsch and Sussman 1999). Engineering plants with improved micronutrient uptake can alleviate malnutrition and hidden hunger.

In view of the increasing demand for food production and improvements in its nutritional quality, there is a need for change in the context of agricultural science (Evans 2005, Brklacich et al. 1991). It is equally important to understand how sustainable agriculture can address both the environmental concerns and human health issues (Horrigan et al. 2002), diffuse and minimize pollution from agricultural practices (Burkart 2007), predict changes in crop productivity over time (Ewert et al. 2005) and adapt to ecological systems (Giloli and Baumgärtner 2007) of changing societal needs. Sustainable and efficient practices must address global environmental impacts (Tilman 1999; Singh 2000; Thajun and Van Ranst 2005). There is a need for a paradigm shift in land husbandry (Gowing and Palmer 2008), and principles and practices of soil management. Principles (Table 2) and sustainable practices (Table 3) of

**Table 2** Global soil resources and their characteristics in relation to food security (adapted from Lal 2008a, b)

| Soil resource | Action plan |
|---|---|
| Soil resources are unequally distributed among biomes and geographic regions | Choose land use and farming system on the basis of climatic, physiographic and hydrologic parameters |
| Most soils are prone to degradation by land misuse and soil mismanagement | Select cropping systems, tillage methods, water conservation and nutrient management options on the basis of soil quality and desired output |
| Soil erosion and erosion-induced degradation depend on "how" rather than "what" crops are grown | Adopt CA, mulch farming, cover cropping, contour hedges of perennials, and controlled grazing considering low tolerable level (<1 t $ha^{-1}$ $year^{-1}$) of erosion for soils of the tropics |
| Susceptibility to soil degradation increases with increase in mean annual temperature and decrease in precipitation | Identify management systems with cow cropping and grazing intensity, and based on water harvesting, ground water recharge and multiple use of scarce eater resources |
| Processes of soil degradation operate at a faster rate than those of restoration | Identify key soil properties and processes and understand their critical/threshold levels to avoid irreversible soil degradation |
| Soil resilience depends on inherent physical, chemical and biological properties and processes | Identify land use and soil management practices that will maintain and enhance soil's ability to recover from anthropogenic and natural perturbations (e.g., positive C and elemental/nutrient balance) |
| Soils are a non-renewable resource over the human time scale | Choose preventative measures for erosion, salinization and SOC depletion over restorative inputs and rehabilitational techniques |
| Optimal levels of soil physical properties and processes are important to effectiveness of chemical and biological properties and processes | Improve soil structure and optimize soil temperature and moisture regimes to enhance use efficiency of fertilizers and realize the benefits of BNF, mycorrhizal inoculation and yield potential of GM crops |
| Soil structure depends on volume, stability, and continuity of retention and transmission pores | Promote activity of earth worms, include cover crops with a deep tap root system, and use compost and organic amendments |
| Soil productivity is constrained by the weakest parameter/link (e.g., PAW, micronutrients, SOC concentration, rooting depth) | Use INM to replace macroelements, and micronutrients harvested in crops and animal products, and adopt micronutrient-dense varieties |

**Table 3** Principles and practices of maintaining healthy soils for healthy life (adapted from Lal 2009)

| Principles | Practices/strategies |
|---|---|
| The biophysical processes of soil degradation are driven by social, economic and political forces | Involve farmers, land managers and policy makers in the decision making process of restoring degraded soils |
| When people are poverty stricken, desperate and hungry, they pass on their suffering to the soil | Meet the basic necessities (food, feed, fuel) before emphasizing the need to improve the environment and stewardship of land |
| Marginal soils, cultivated with marginal inputs produce marginal yields and support marginal and unhealthy living | Cultivate the best soils by best management practices to produce the best yields to support a healthy living while saving the land for nature conservancy |
| It is not possible to take more out of a soil than what is put in it without degrading its quality | Maintain a positive/favorable C and plant nutrient budgets in soils for the desired level of agronomic production |
| Plants cannot differentiate the nutrients supplied through organic manures or inorganic fertilizers, as long…as all essential nutrients are available at the critical stages of growth and in the quantities required | Adopt INM strategy involving nutrient recycling, BNF, mycorrhizal inoculations, GM varieties, and judicious use of chemical fertilizers to supply macronutrients and microelements using nanoenhanced materials and slow-release formulations |
| Even the elite varieties cannot extract water and nutrients from any soil where they do not exist | Integrate genetics and soil management options to achieve the desired impacts on food security |
| Soils are in part the cause and also the victims of the global warming | Restore degraded soils and improve SOC pools to off-set industrial $CO_2$ emissions through terrestrial C sequestration with a potential of ~3 Pg C $year^{-1}$ |
| Improving soil quality is essential to sustainable development | Make soil management and agricultural improvements as the engine of economic development is SA, SSA, and elsewhere |
| Traditional systems by themselves are not adequate to meet the growing demands of increasing population with rising aspirations | Build upon the traditional knowledge and use modern innovations of nutrient management, water productivity improvement, disease suppressive soils, nanoenhanced materials and deliverance systems, satellite imagery, and remote sensing technologies, and precision farming |
| There is a strong historic link between soil degradation and the extinction of numerous ancient civilizations (e.g., Mayans, Incas, Mesopotamians, Indus) | Never ever take soils for granted |

soil management must be fine-tuned to site-specific needs and the growing aspirations of rapidly increasing populations in developing countries.

Ecologically restored and judiciously managed, global soil resources are adequate to meet the essential needs of the present and future populations. Soil scientists, in cooperation with agronomists and crop breeders, have the technology to feed a population of 10 billion (Dyson 1999; Reynolds and Borlaug 2006; Lal 2006). Integrating genetics and soil management options is essential to achieving great impact of agricultural technology on food production in harsh environments (Twomlow et al. 2008). The adoption of this technology, however, depends on the infrastructure, support services and political will. Innovative technologies also exist to bring about a quantum jump in food production, especially in SA and SSA (NRC 2008). These technologies include the following:

1. Assessing by remote sensing critical plant nutritional stresses for managing soil quality by using the Normalized Difference Vegetation Index or NDVI (Raun et al. 2001)
2. Using zerolites and nanoenhanced materials to enhance use efficiency of fertilizers and improve plant-available water capacity of the soil (Kijne 2001, 2004), increase the availability of micronutrients (e.g., Zn) (Oren and Kaya 2006), and improve the quality of irrigation water through wastewater treatment (Daubert et al. 2003)
3. Inoculating soils with endophytic bacteria that can increase BNF capacity and improve soil fertility (Lodewykx et al. 2002)
4. Using microbial processes to increase P uptake (Jackobsen et al. 2005), and improve drought tolerance in plants (Marulanda et al. 2007) and increase tolerance to salinity (Harmaoui et al. 2001) or irrigation with saline water (Sarig et al. 1990) and
5. Conserving water in the root zone and enhancing the efficiency of its use through improving soil structure and quality by using organic amendments, NT and CA (Rockström et al. 2007), and using drip irrigation and drip sub-irrigation for decreasing losses and increasing plant uptake (Wallace 2000; Aujla et al. 2005; Vishwanathan et al. 2002).

## Conclusion

The adverse effects of soil degradation on human health and well being can be alleviated through strategies involving soil restoration based on management of drought stress, soil infertility, and deficiency of micro-elements. Adaptation to climate change can minimize the adverse impacts on food production while realizing potential benefits related to $CO_2$ fertilization and lengthening of the growing season in northern latitudes. With adoption of proven management options, global soil resources are adequate to meet food and nutritional needs of the present and future population. In addition, there are also emerging innovative technologies (e.g., remote sensing of plant stresses, nano-enhanced materials, BNF, mycorrhizal inoculation, drip sub-irrigation) with great potential for improving food production and restoring degraded soils and ecosystems.

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