Perspective
Managing soils for feeding a global population of 10 billion

INTRODUCTION

Justus Von Liebig (1803–1873),[1] a German scientist who developed the mineral nutrition theory which states that plants can grow solely with inputs of chemical fertilisers,[1,2] said that 'agriculture is, of all industrial pursuits, the richest in facts and the poorest in their comprehension'.[3] This statement remains true even during the 21st century, because the challenge of feeding a population of 6.5 billion in 2006, and expected to reach 10 billion towards the end of the century, is more daunting now than ever before. Despite the unprecedented progress in global food production during the second half of the 20th century through the adoption of Green Revolution technologies, bringing about further increases in agronomic productivity while restoring degraded soils and ecosystems and minimising the risks of climate change remains a major challenge to soil scientists, plant breeders and agronomists. Liebig further stated that 'facts are like grains of sand which are moved by the wind, but principles are these same grains cemented into rocks'.[3] Thus unlocking these basic principles is essential to sustainable management of soils, so that with intensive farming soil quality is progressively restored rather than diminished, the soil organic carbon (SOC) pool is enriched rather than depleted, susceptibility to erosion and other degradation processes is reduced rather than exacerbated and agronomic/biomass productivity per unit input and time is increased rather than reduced or plateaued. Therefore the objective of this paper is to deliberate the critical role of soil management in enhancing productivity to feed the world population of 10 billion people while restoring the degraded ecosystems, improving water quality and mitigating climate change caused by anthropogenic enrichment of CO_2 in the atmosphere.

The mother of the necessity of bringing about a quantum jump in agronomic production has been and will be the increase in world food demand due to the increase in population. The world population was merely 1 million about 10 000 years ago, 10 million 7000 years ago, 100 million about 3000 years ago and still only 200 million 2000 years ago.[4] It grew exponentially to 0.31 billion in 1000 AD, 0.40 billion in 1250, 0.50 billion in 1500, 0.79 billion in 1750, 0.98 billion in 1800, 1.26 billion in 1850, 1.65 billion in 1900 and 2.52 billion in 1950.[5] The second half of the 20th century witnessed the most rapid increase in world population (Fig. 1). Between 1950 and 2000 the population increased from 2.52 to 6 billion. The maximum rate of annual increase, 86–87 million people per year, occurred between 1986 and 1989. The rate of increase has since declined to about 75 million people per year during 2004–2005 (Fig. 1). The world population is presently increasing at the rate of 1.3% $year^{-1}$ and is projected to be 7.5 billion by 2020, 9.4 billion by 2050 and stable at around 10 billion by 2100.[8–10] Of the projected 3.4 billion increase in population between 2000 and 2050, 2 billion will occur in Asia and 1.4 billion in Africa. Most of the future increase in world population will occur in developing countries where the natural resources are already under great stress. During the last 10 000 years the world population has doubled at least ten times. However, it will never double again. This remarkable landmark in human demographics is determined by the agricultural revolution which started with the onset of settled agriculture about 10 000 years ago. Future advances in soil science will also have a strong impact on identifying the strategies for enhancing food production to meet the demands of an additional 4 billion people along with a likely change in food habits from vegetarian to meat-based diets in several rapidly developing economies (e.g. China, India).

SOIL AND WATER RESOURCES

The increase in world population is causing a rapid decline in per capita arable land area (Fig. 2). The global per capita arable land area decreased exponentially between 1960 and 2025 (area (ha per person) $= 0.3e^{-0.024}$, $r = 0.96$).[11] The data in Table 1 show that the per capita arable land area will be <0.1 ha by 2025 in many densely populated countries of Asia and Africa. The decline in per capita land area is also exacerbated by the conversion of agricultural land to other uses (e.g. urbanisation, biofuel plantation) and the severe problem of soil degradation (e.g. erosion, salinisation). It is the finite extent of arable land area that necessitates the development and use of improved technologies to enhance production per unit area and unit time on the existing cropland. Most of the potentially new land exists in sparsely populated regions. In general, these regions are ecologically sensitive, because soil resources are fragile and the climate is harsh (e.g. tropical rainforests, steeplands).

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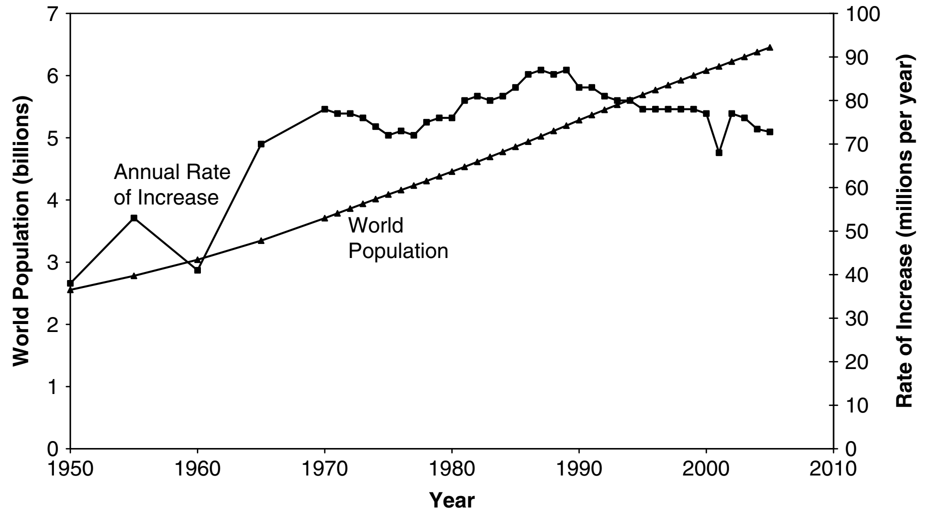

Figure 1. World population and rate of annual increase for 1950–2005 (redrawn from Refs 6 and 7).

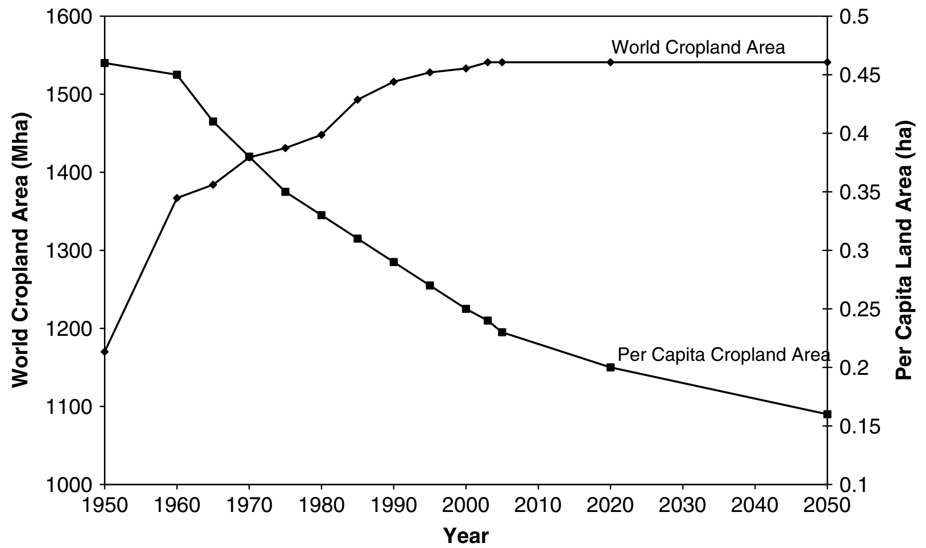

Figure 2. Total and per capita arable land area in the world (redrawn from Refs 7 and 12).

Table 1. Per capita arable land availability (ha per person) in some countries (adapted from Ref. 12)

Country	1960	1990	2025[a]
Bangladesh	0.17	0.09	0.05
China	0.16	0.08	0.06
Congo	0.14	0.08	0.03
Egypt	0.09	0.05	0.03
Ethiopia	0.50	0.29	0.11
India	0.36	0.20	0.12
Mexico	0.64	0.29	0.18
Nigeria	0.68	0.34	0.14
Pakistan	0.34	0.17	0.07
Tanzania	0.31	0.13	0.05
Zimbabwe	0.50	0.28	0.14

[a] Projected per capita arable land area is for medium population growth rate.

Table 2. Soil degradation (Mha) in developing countries (adapted from Ref. 13)

Degradation process	Developing countries	World
Water erosion	837	1094
Wind erosion	457	548
Loss of nutrients	132	136
Salinisation	72	77
Pollution	21	21
Acidification	5	6
Compaction	32	68
Waterlogging	10	11

Degradation of soil and water resources is another issue that needs to be addressed. The data in Table 2 show the severe problem of soil degradation in developing countries, especially due to accelerated erosion by water and wind, salinisation, acidification and nutrient imbalance, and decline in soil structure leading to crusting and compaction.[13] It is estimated that 77% of the world land area affected by water erosion, 97% by loss of nutrients, 94% by salinisation, 100% by pollution, 83% by acidification and 90%

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by waterlogging occurs in developing countries. The resource-poor farmers of developing countries degrade soil resources by using extractive farming practices and cannot afford to invest in soil restorative measures. The demand for increased food production can only be met if these soil degradation trends are reversed and soil quality is restored. However, soil degradation and desertification can also occur in arctic regions such as Iceland (Fig. 3) if the delicate ecological balance is disturbed by deforestation and grazing.

Similar to the cropland, renewable fresh water resources are also scarce in many countries with predominantly arid and semi-arid climates (Table 3). About 1 billion people, mostly in rural Asia and sub-Saharan Africa, do not have access to hygienically clean water, which is the principal cause of 2 million infant mortalities a year.[15] Among 30 densely populated countries which will face severe water shortages by 2025 are Egypt, India, Iran, Nigeria and Tunisia.

REVISITING THE GREEN REVOLUTION TECHNOLOGIES

Global grain production increased by a factor of three during the second half of the 20th century, from about 650×10^6 Mg in 1950 to more than

(a)

(b)

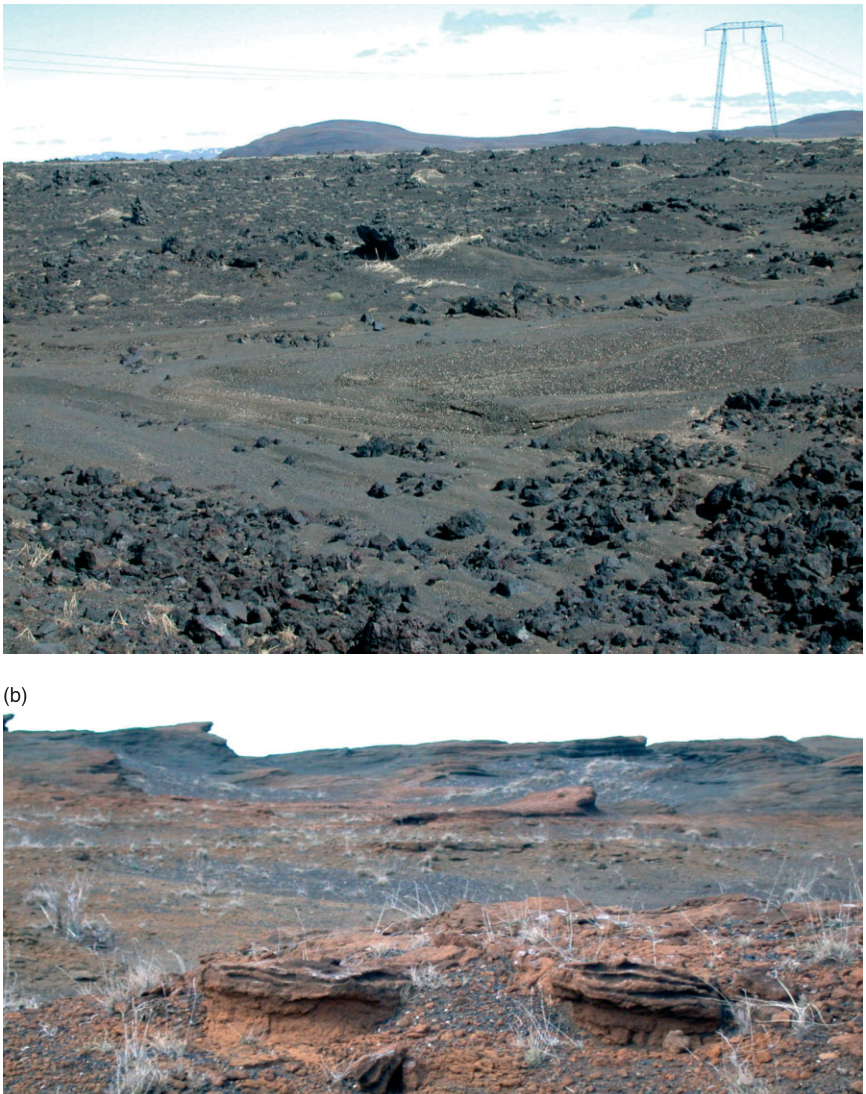

Figure 3. (a) Serious erosion on soils of Iceland is caused by the lack of protective vegetation cover. The land was denuded of its native vegetation cover by deforestation and uncontrolled grazing since the Viking settlement around 875 AD. (b) The severity of soil erosion in Iceland, caused by both wind and water, is exacerbated by the harsh climate, short growing season and poor soil quality.

Table 3. Per capita annual renewable fresh water availability (m^3 per person) (adapted from Ref. 14)

Country	1950	1995	2025	2050	Total available water (km^3)
Afghanistan	5582	2543	1105	815	50
Burkina Faso	7663	2672	1194	791	28
China	5047	2295	1891	1846	2800
Egypt	2661	936	607	503	58
Ethiopia	5967	1950	807	517	110
India	5831	2244	1567	1360	2085
Iran	6947	1719	916	690	118
Nigeria	8502	2506	1175	827	280
Pakistan	468	11 844	3435	1740	1310
UAE	28 471	902	604	543	2
Zimbabwe	2730	1787	1034	803	20

1900×10^6 Mg in 2000 (Fig. 4). The rate of increase in grain production exceeded that of the population until between 1950 and 1985. Thus per capita grain consumption increased between 1950 and 1985 but decreased during the 1990s (Fig. 4). The increase in food production was brought about by an increase in fertiliser consumption. Global fertiliser consumption increased from about 30×10^6 Mg in 1960 to 140×10^6 Mg in 1985 and stabilised at this rate during the 1990s (Fig. 5(a)).

A rapid increase in fertiliser consumption occurred in South Asia (Fig. 5(b)) and East Asia (e.g. China). In contrast, there was no increase in fertiliser consumption in sub-Saharan Africa (SSA) (Fig. 5(b)). There was a linear increase in world grain production ($Y = 15X + 611$, $r = 0.96$) with an increase in global consumption of nitrogenous fertiliser (Fig. 6). Each 1×10^6 Mg of N fertiliser applied produced 15×10^6 Mg of additional grain.

Similar to fertiliser consumption, there was also a rapid increase in irrigated land area, which grew exponentially during the 20th century (Fig. 7(a)). The increase in irrigated land area was especially rapid in India, China (Fig. 7(b)), Egypt, Iran, Pakistan and the USA (Table 4). Globally, 17% of irrigated cropland area produced 40% of world grain during the 1990s.[18] The data in Table 5 show that the global average cereal grain yield of 2.64 Mg ha^{-1} and total cereal production of 1267×10^6 Mg in 2000 will have to be drastically increased by ushering in another Green Revolution. Global average cereal grain yield will have to be increased to 3.60 Mg ha^{-1} and total cereal production to 1706×10^6 Mg by 2025 and to 4.30 Mg h^{-1} and 1995×10^6 Mg respectively by 2050. Such increases (35% by 2025 and 58% by 2050) are required just to maintain the same caloric input and diet habit.[19] In reality, cereal grain yield and total production will have to be increased even more strongly because of the likely change in diet of the population towards more animal-based food, especially in emerging economies (e.g. China, India). With consideration of change in diet, cereal grain yield and total production respectively will have to be increased to 4.40 Mg ha^{-1} and 2045×10^6 Mg by 2025 (62% increase) and to 6.00 Mg ha^{-1} and 2786×10^6 Mg by 2050 (121% increase).[19] This quantum jump in food production, especially in food-deficient regions of Asia and SSA, will have to come through agricultural intensification and restoration of degraded soils and ecosystems.

WORLD HUNGER AND AGRARIAN STAGNATION IN SUB-SAHARAN AFRICA

Despite impressive gains in food production, severe problems of hunger and malnutrition persist (Table 6). While the reliability of statistics presented in Table 6 is debatable, some argue that the food-insecure population is 850 million in 2006 and increasing. Many fear that the UN Millennium Goal of reducing hunger by 50% by 2015 will not be met. Some studies

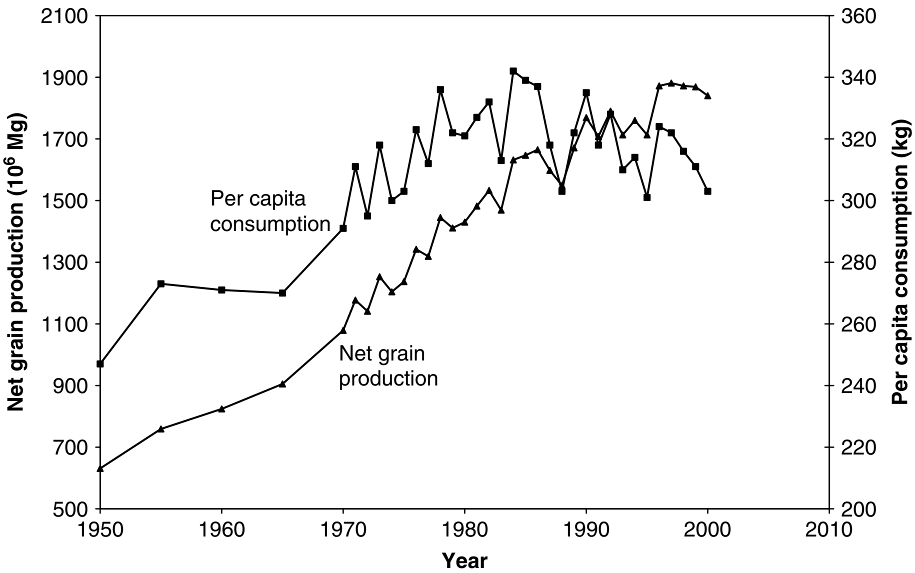

Figure 4. Global net grain production and per capita grain consumption between 1950 and 2005 (redrawn from Refs 6 and 7).

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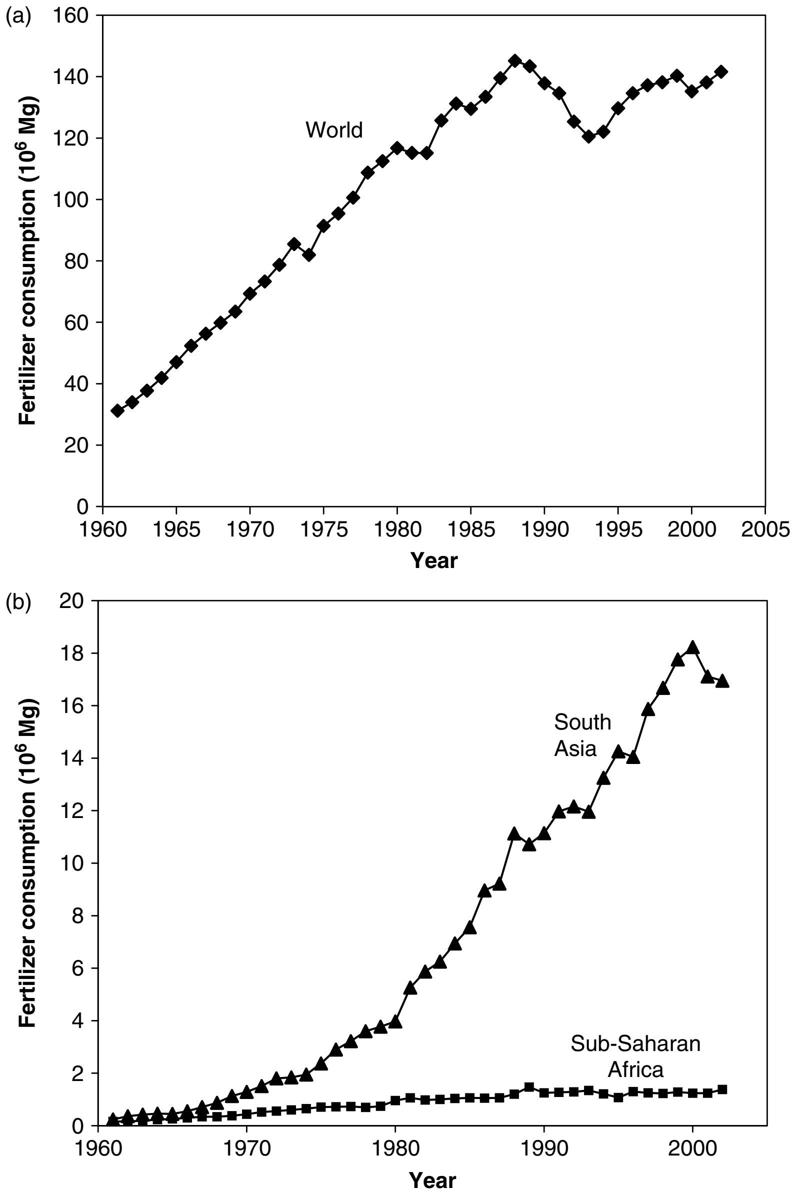

Figure 5. (a) World and (b) regional fertiliser consumption (redrawn from Refs 16 and 17).

Table 4. Changes in irrigated cropland area (Mha) in some countries between 1960 and 2003 (adapted from Ref. 7)

Country	1961	1965	1970	1975	1980	1985	1990	1995	2000	2003
China	30.4	33.6	38.1	42.8	45.5	44.6	48.0	49.9	54.6	54.6
Egypt	2.6	2.7	2.8	2.8	2.4	2.5	2.6	3.3	3.3	3.4
India	24.7	26.5	30.4	33.7	38.5	42.1	46.7	53.0	56.8	55.8
Iran	4.7	4.9	5.2	5.9	4.9	6.8	7.0	7.3	7.6	7.7
Pakistan	10.8	11.5	13.0	13.6	14.7	15.8	15.8	17.2	18.1	18.2
USA	14.0	15.2	16.0	16.7	20.6	19.8	20.9	21.8	22.5	22.4

indicate that there may be an additional 100 million food-insecure people by 2015, especially in SSA and South Asia. Lack of access to food due to poverty and lack of purchasing power are partly responsible for this food insecurity, and the problem is being exacerbated by agrarian stagnation in SSA. The latter is caused by the widespread use of extractive farming practices, non-adoption of recommended technologies and dismal investment in essential input such as fertilisers and irrigation. The data in Table 7 show little increase in irrigated land area in SSA during the second half of the 20th century. Whatever little increase in irrigated area that did occur in SSA between 1961 and 2003 was due to increases in three countries, Madagascar, Sudan and South Africa. There has been no progress in irrigation in any of the countries in the drought-prone West African Sahel. Similarly, the data in Fig. 5 show little increase in fertiliser consumption in SSA. Furthermore, allocation of water resources for agricultural production is facing strong competition from industrial and urban use, especially in developing countries with rapid urbanisation and industrial development (Fig. 8).

The widespread use of extractive farming, which perpetuates hunger and poverty, also exacerbates the problem of soil degradation (Table 8). The vicious cycle of low crop yield/low input/severe soil degradation/low crop yield cannot be broken without converting subsistence farming to commercial agriculture based on the adoption of recommended management practices (RMPs). When people are poverty-stricken and hungry, they pass on their miseries to the land. Soil degradation is a biophysical process but is driven by social, economic and political factors. Indeed, soil degradation hot spots of the world are also the regions plagued by poverty, malnutrition and political instability.[21] Anthropogenic activities responsible for severe soil degradation in Africa include deforestation, over-exploitation, overgrazing and extractive agricultural practices,[13] used by resource-poor farmers in a desperate attempt to make both ends meet.

Table 5. Average yield of cereals needed in developing countries[a] by 2025 and 2050 to meet required production with no increase in area (adapted from Ref. 19)

Parameter	Cereal grain yield (Mg ha^{-1})	Cereal production (10^6 Mg)
Present (2000)	2.64	1267
Required		
2025		
+35%[b]	3.60	1706
+62%[b]	4.40	2045
2050		
+58%[b]	4.30	1995
+121%[b]	6.00	2786

[a] Africa, Asia, South America and Asia (excluding Japan).
[b] Estimated increase above present (2000) level to account for increase in population and change in food habits.

Table 6. Hunger and malnutrition (millions of people) in developing countries (modified from Ref. 20)

Region	1970	1980	1990	Projected 2010
Sub-Saharan Africa	103	148	215	264
Near East and North Africa	48	27	37	53
South Asia	238	303	255	200
East and Southeast Asia	475	378	268	123
Latin America and the Caribbean	53	48	64	40
Total developing countries	917	904	839	680

SOIL MANAGEMENT AND AGRICULTURAL INTENSIFICATION IN SUB-SAHARAN AFRICA

Agrarian stagnation in Africa and in developing countries elsewhere is attributed to extractive farming

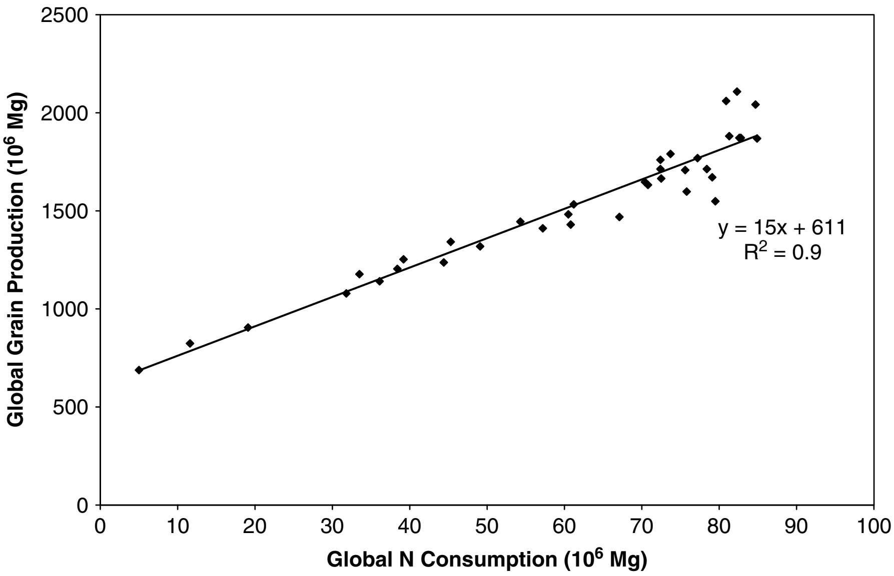

Figure 6. Relationship between global N fertiliser consumption and total grain production between 1950 and 2005 (data on N consumption from Refs 6, 7 and 16).

Table 7. Changes in irrigated land area (Mha) in 40 countries of sub-Saharan Africa (SSA) from 1960 to 2003 (recalculated from Ref. 7)

Country/region	1961	1965	1970	1975	1980	1985	1990	1995	2000	2003
SSA	3.450	3.690	3.997	4.353	4.849	5.308	5.781	6.442	6.903	7.023
Madagascar	0.300	0.330	0.330	0.465	0.645	0.826	1.000	1.087	1.086	1.086
Sudan	1.480	1.550	1.625	1.700	1.700	1.763	1.800	1.946	1.863	1.863
South Africa	0.808	0.890	1.000	1.017	1.128	1.128	1.200	1.355	1.498	1.498

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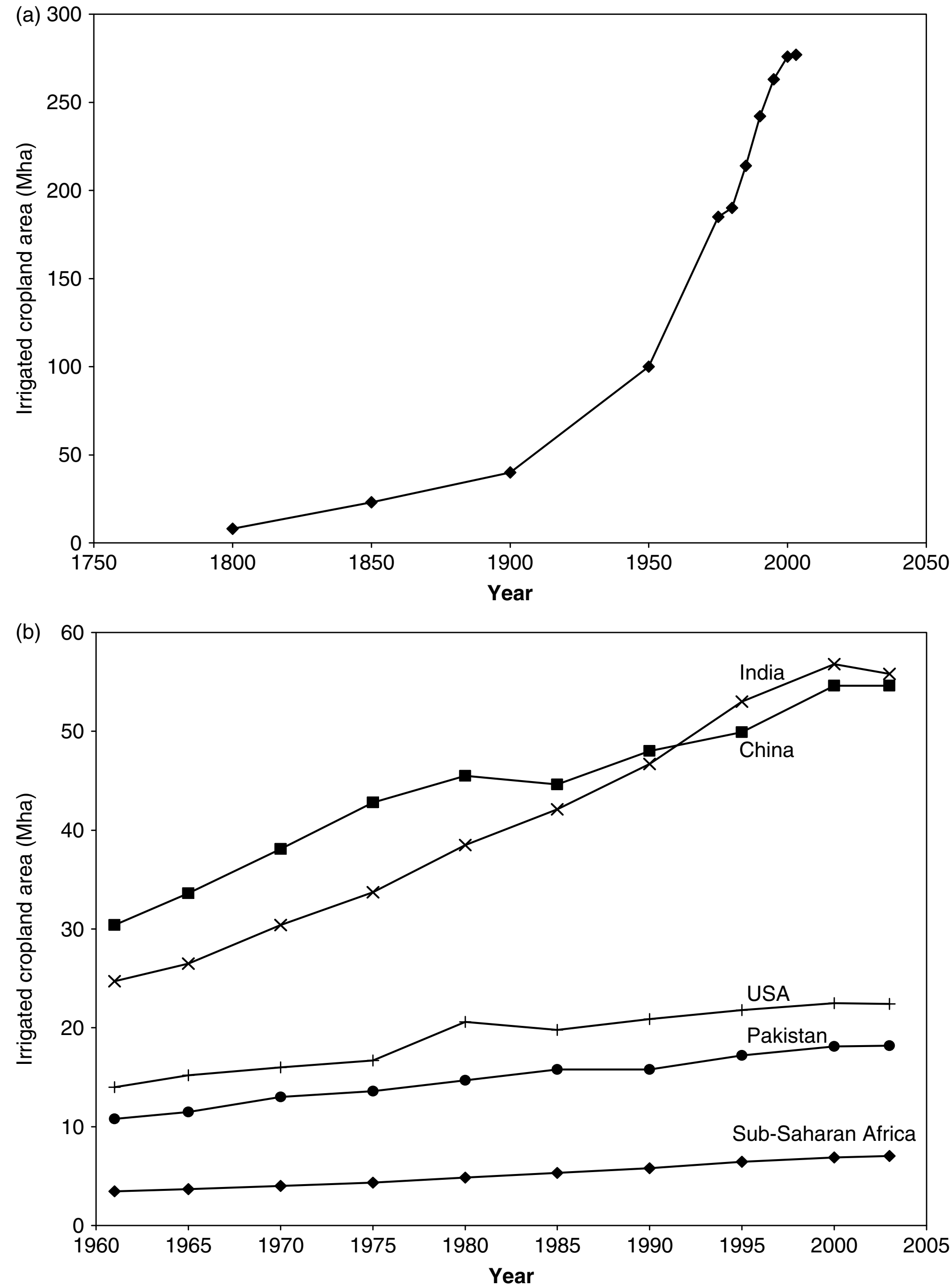

Figure 7. Temporal changes in irrigated crop land area: (a) world; (b) specific regions/countries (redrawn from Refs 7 and 18).

Table 8. Extent and severity of soil degradation in Africa (adapted from Ref. 13)

Degradation process	Area affected in Africa (Mha)	% of world total
Water erosion	227	20.7
Wind erosion	186	33.9
Chemical degradation	62	25.8
Physical degradation	19	22.9

practices used for millennia, severe soil degradation and non-adoption of RMPs. It is important to recognise that agricultural systems are sustainable only if the outputs of all components produced/harvested (e.g. N, P, K, Ca, Mg Zn, Cu) are adequately balanced by input to the system. It is the taking more out of the soil than what is put into it over a long period of time that has been responsible for severe nutrient deficit in SSA on the continental scale and has caused the severe problem of soil and environmental degradation. Whether the plant nutrients required to obtain the desired crop yields are supplied through input of organic amendments, inorganic fertilisers or some judicious combination of both is essentially a matter of logistics. Plants cannot differentiate the nutrients supplied through organic or inorganic sources. The practical issue is nutrient availability in sufficient quantity, in appropriate form and at the time needed for optimal growth and yield. Despite numerous benefits of using organic manures,

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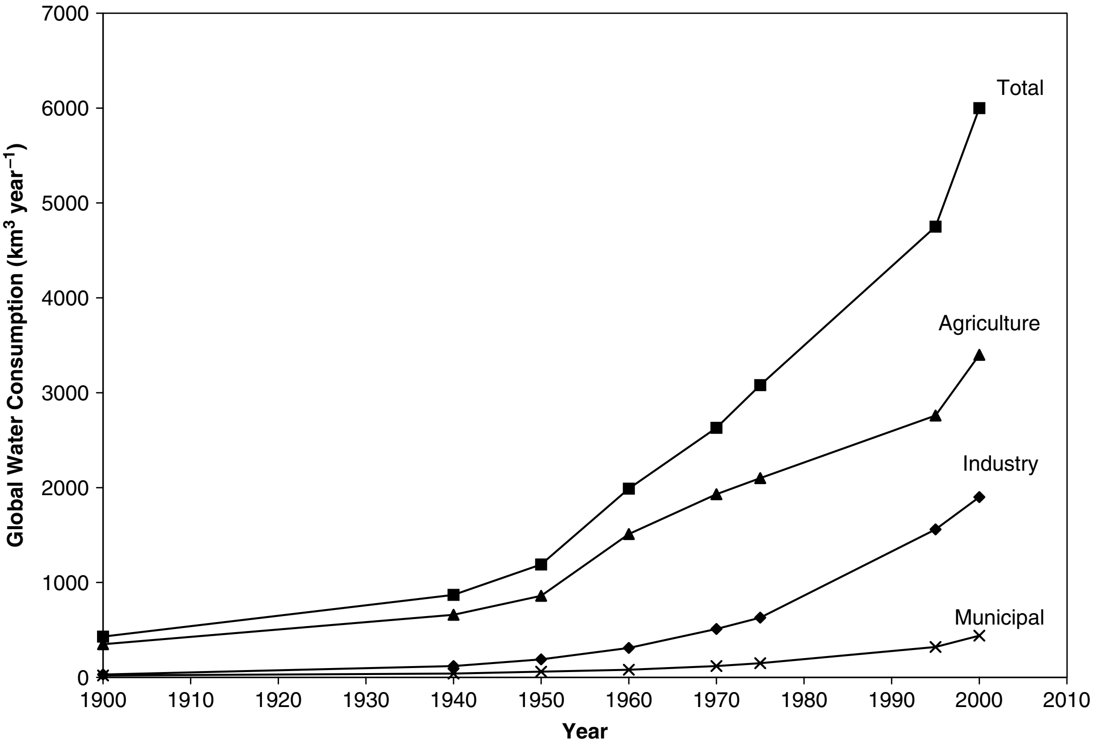

Figure 8. Trends in world water consumption during the 20th century (redrawn from Ref. 6).

there is no practical alternative to the judicious use of chemical fertilisers for feeding the present population of 6.5 billion and the future population of 10 billion.

The overall goal is to increase agronomic productivity through adoption of land-saving RMPs. The data in Table 9 show that the population-carrying capacity of the land is tremendously enhanced by adoption of intensive farming practices. The strategy is to (i) restore degraded soils and ecosystems, (ii) increase cropping intensity, (iii) replace low-yielding crops and cropping systems with high-yielding and improved genotypes and farming systems and (iv) increase use efficiency of fertiliser, irrigation and other input by decreasing losses through erosion, leaching and volatilisation. A generic package of RMPs may comprise the following: (i) convert plough tillage to conservation tillage or no-till; (ii) retain crop residues as mulch; (iii) include leguminous cover crops in the rotation cycle; (iv) maintain a positive nutrient balance through integrated nutrient management (INM) based on a judicious combination of biological nitrogen fixation (BNF), organic manures and chemical fertilisers; (v) adopt precision farming or soil/site-specific management; (vi) use sub-irrigation, drip irrigation and fertigation techniques complemented by appropriate water-harvesting measures; (vii) restore marginal/degraded soils for C sequestration and nature conservancy; (viii) adopt improved/complex cropping/farming systems involving genetically modified plants (e.g. *Bacillus thuringiensis* cotton, roundup-ready corn or soybeans) and agroforestry systems; (ix) integrate principles of watershed management within the improved farming system approach; (x) restore wetlands to improve water quality and control sedimentation. Potential risks to the environment (e.g. pollution/eutrophication of water, loss of biodiversity) must be recognised so that appropriate measures are put in place to minimise or alleviate them.

Soil and water resources of Africa and other regions with high and increasing population must be managed to feed the current and future human populations through adopting current RMPs and developing new ones that address soil-specific constraints. Enhancing crop yield on rain-fed soils remains a high priority, especially in SSA and South Asia. The effectiveness of soil management technologies can be greatly enhanced by growing improved genotypes through the use of biotechnology. Appropriate use of biotechnology can facilitate the development of new genotypes with high productive potential even under severe abiotic and biotic stresses.

Table 9. Carrying capacity of traditional and intensive farming systems (modified from Ref. 22)

Farming system	Population carrying capacity (people per ha)
Foraging/hunter-gatherers	1×10^{-3}–8×10^{-3}
Pastoralism	8×10^{-3}–3×10^{-2}
Shifting cultivation	1×10^{-1}–6×10^{-1}
Traditional farming	1×10^{0}–0.8×10^{1}
Intensive farming	6×10^{0}–2×10^{2}

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SOIL CARBON SEQUESTRATION AND GLOBAL FOOD SECURITY

Settled agriculture set in motion severe anthropogenic changes in terrestrial ecosystems through deforestation, biomass burning and soil cultivation.[22,23] These activities led to the depletion of the terrestrial C pool, especially the SOC pool, with an attendant release of CO_2 into the atmosphere. Ruddiman[24] hypothesised that the increase in atmospheric concentration of CO_2 began about 10 000 years ago with the onset of settled agriculture, an activity which may have averted an impending ice age.[25] Soil cultivation, i.e. tillage and related mechanical disturbance, accentuates the rate of mineralisation of soil organic matter (SOM). This process of oxidation/decomposition of SOM releases plant nutrients (e.g. N, P, K, Ca Mg, Zn, Cu) for uptake by crops and causes emission of CO_2 into the atmosphere. The magnitude and rate of emission are greater for tropical than temperate climates, for soils with high than low antecedent SOC pool, for light-textured than heavy-textured soils and for extractive/subsistence farming than commercial agriculture. The rate and magnitude of depletion are greater in any system where the input of biomass C is less than the losses of SOC pool caused by oxidation/mineralisation, erosion by water or wind, leaching of dissolved organic carbon (DOC) or illuviation with clay. Bellamy *et al.*[26] estimated that SOC loss from soils across England and Wales was at a mean rate of 0.6% $year^{-1}$ between 1978 and 2003. Lal[27] estimated that 78 ± 12 Pg C (1 Pg = 1 petagram = 10^{15} g = 1×10^9 t) has been emitted from world soils into the atmosphere, out of the total contribution from the terrestrial pool of 136 ± 55 Pg C.[28]

There are two important ramifications of the anthropogenically induced depletion of the SOC pool: (i) it leads to an increase in atmospheric concentration of CO_2 and the attendant greenhouse effect; (ii) depletion of the SOC pool has a severe adverse impact on soil quality. A soil severely depleted of its SOC pool is prone to decline in structural properties, leading to crusting, compaction, low infiltration rate, high water run-off, accelerated erosion, low plant-available water capacity and decline in agronomic/biomass yield. It also exacerbates leaching losses of plant nutrients by reducing the soil's capacity to retain and absorb plant nutrients. The widespread problem of soil and environmental degradation (water pollution), especially in SSA and South Asia,[13] is related to severe depletion of the SOC pool.

Most agricultural soils contain barely 25–50% of their antecedent SOC pool. Thus these soils have the capability of SOC pool enhancement through adoption of RMPs outlined in the previous section. Adoption of RMPs improves structural properties, reduces risks of crusting and compaction and sets in motion the overall restorative trends. Indeed, soils with higher SOC pool produce higher (agronomic biomass) crop yields up to a maximum level that differs among soils. An optimal level of SOC pool increases water and nutrient retention capacity, improves soil tilth and provides energy for microbial processes. The yield response to applied fertilisers also increases with increase in SOC pool or when used in conjunction with practices that restore the SOC pool. Increase in crop yield with increase in SOC pool is more for soils with a severely depleted SOC pool[29,30] and also occurs in soils under high-input commercial agriculture.[31,32] The critical limit for SOC concentration in most soils of the tropics is 1.1%,[33] below which an increase in SOC concentration would lead to a strong increase in crop yield. Most soils of SSA and South Asia have an SOC concentration of only 0.1–0.2%.

Results of several experiments conducted in temperate and tropical regions show an increase in agronomic yield by increasing the SOC pool in the root zone.[29] On the basis of a literature review, Lal[29] reported that an increase of 1 Mg C $ha^{-1}\,year^{-1}$ in the root zone through adoption of RMPs would increase grain yield by 100–300 kg $ha^{-1}\,year^{-1}$ for corn (*Zea mays* L.), 20–50 kg $ha^{-1}\,year^{-1}$ for soybeans (*Glycine max* L.), 20–70 kg $ha^{-1}\,year^{-1}$ for wheat (*Triticum aestivum* L.), 10–45 kg $ha^{-1}\,year^{-1}$ for rice (*Oryza sativa* L.) and 30–60 kg $ha^{-1}\,year^{-1}$ for beans (*Phaseolus vulgaris* L.). Despite numerous uncertainties due to vagaries in climate and differences in soil properties, extrapolation of these data shows that widespread adoption of RMPs on a global scale can increase food grain production by $(32 \pm 11) \times 10^6$ Mg $year^{-1}$. In addition, there will be an increase in the production of root crops such as cassava (*Manihot esculenta* L.), yam (*Dioscorea rotundata*), sweet potato (*Ipomea batata*) and taro (*Colocasia esculenta* L.) by $(7–11) \times 10^6$ Mg $year^{-1}$. Indeed, an 18 year experiment on a Nitisol in Kenya showed that the yield of corn and beans was 1.4 Mg $ha^{-1}\,year^{-1}$ without external input and 6.0 Mg $ha^{-1}\,year^{-1}$ when stover was retained and soil fertility was enhanced by applying fertilisers and manure. Adoption of RMPs also enhanced the SOC pool to 15 cm depth from 23.6 Mg ha^{-1} under control to 28.7 Mg ha^{-1} under RMPs at an average rate of 280 kg $ha^{-1}\,year^{-1}$.[34] Similarly, a long-term experiment on a Vertisol in Central India showed a quantum jump in food production through adoption of RMPs that improved the SOC pool and enhanced soil quality.[35] The package of RMPs consisted of soil and water conservation, water harvesting and recycling for supplemental irrigation, and INM along with legume-based rotations. The average grain yield with adoption of RMPs over a 24 year period was 4.7 Mg $ha^{-1}\,year^{-1}$, compared with 1 Mg $ha^{-1}\,year^{-1}$ with the conventional system. The rate of growth in agronomic productivity over the 24 year period was 77 kg $ha^{-1}\,year^{-1}$ and a carrying capacity of 18 persons per ha with RMPs, compared with 26 kg $ha^{-1}\,year^{-1}$ and a carrying capacity of 4 persons per ha with traditional management.[35] The importance of restoring soil fertility in order to enhance food production in Africa was also stressed by Sanchez[36] and Rosegrant and Cline.[37]

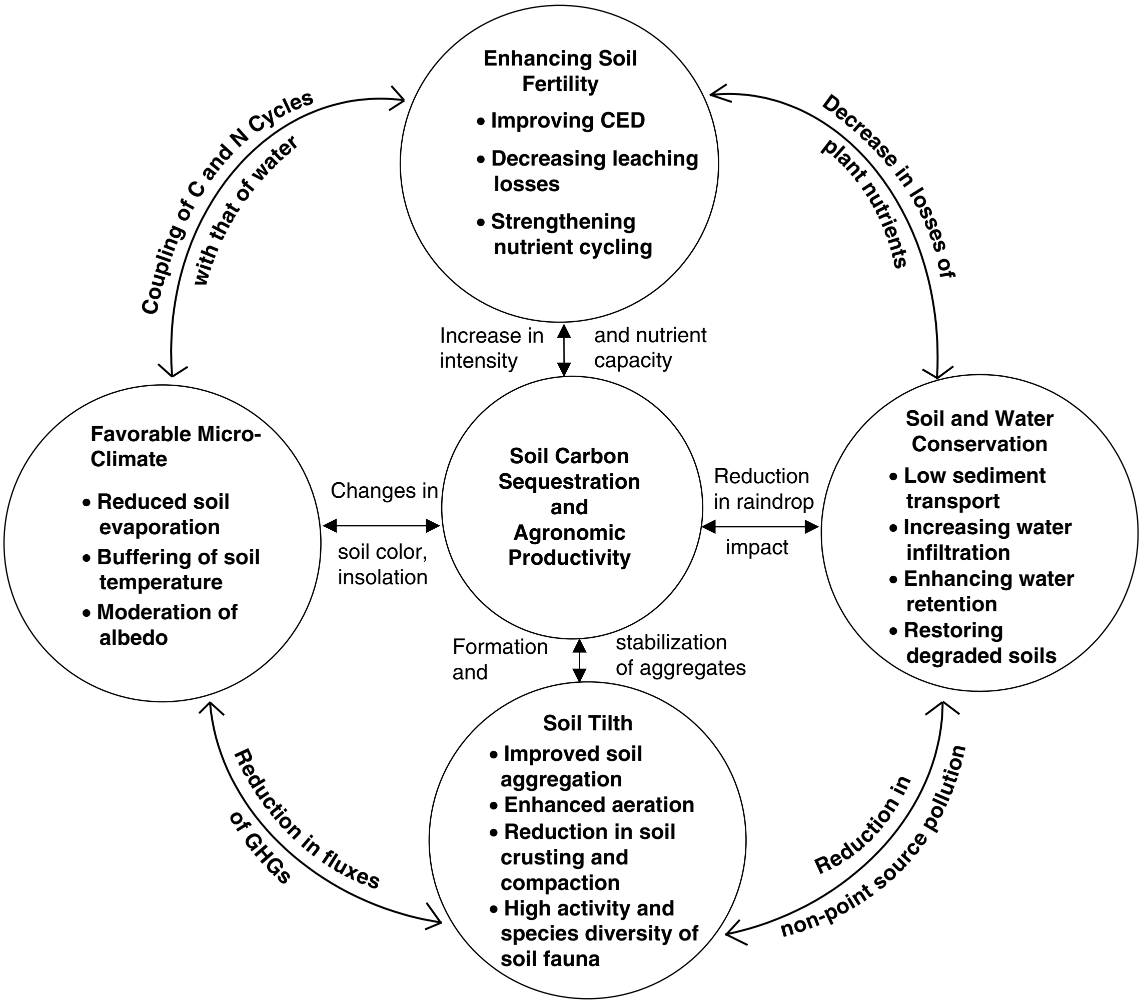

Figure 9. Processes leading to increase in agronomic productivity through soil organic carbon sequestration.

Thus restoring the quality of degraded soils through enhancement of the SOC pool by agricultural intensification and adoption of RMPs is a truly win–win or no-regrets strategy. It also has numerous ancillary benefits related to the enhancement of ecosystem services. Increase in agronomic productivity due to increase in SOC pool is related to improvement in soil quality with regards to soil fertility, soil structure and tilth, soil and water conservation and favourable micro-climate (Fig. 9). A strategy of enhancing the SOC pool can also be linked to production of biofuel through establishing energy/biofuel plantations (Fig. 10). Such plantations can be established on surplus, marginal or degraded lands. The objective of establishing biofuel plantations is twofold: (i) to produce lignocellulosic biomass so that large amounts of crop residues (e.g. of corn, wheat, sorghum, millet) produced globally[38] can be retained on agricultural soils as mulch for controlling erosion, conserving water, recycling nutrients and increasing the SOC pool; (ii) to restore agriculturally marginal and degraded soils through the ameliorative effect of short-rotation wood crops or warm season grasses (e.g. switchgrass), which produce a large amount of above-ground biomass and increase the SOC pool through biomass input from a deep and prolific root system. Establishing biofuel plantations is an important strategy for finding alternatives to fossil fuel. Irrespective of the climate debate, the SOC pool must be enhanced. Feeding a 6.5 billion population in 2006, 7 billion by 2010, 8 billion by 2025 and 10 billion by 2050 or beyond makes it essential that soil quality is restored and enhanced. With 850 million food-insecure people in the world and increasing, and the fear that the UN Millennium Goal of decreasing the food-insecure population by 50% by 2015 will not be met, there is an urgent need to enhance the SOC pool through agricultural intensification and adoption of RMPs. Narrowing the global food grain deficit of 13.2×10^6 Mg in 2000, and projected to be 23.3×10^6 Mg in 2010,[39] necessitates the widespread adoption of RMPs and restoration of degraded soils, especially in SSA and Asia. Agricultural intensification would also bridge the large yield gap between developed and developing countries.[40] Towards these goals, the importance of enhancing the SOC pool can hardly be overemphasised. SOC sequestration provides a handle to the vicious cycle of soil degradation/low productivity/more soil degradation that has plagued several regions in Africa, Asia and Central America.

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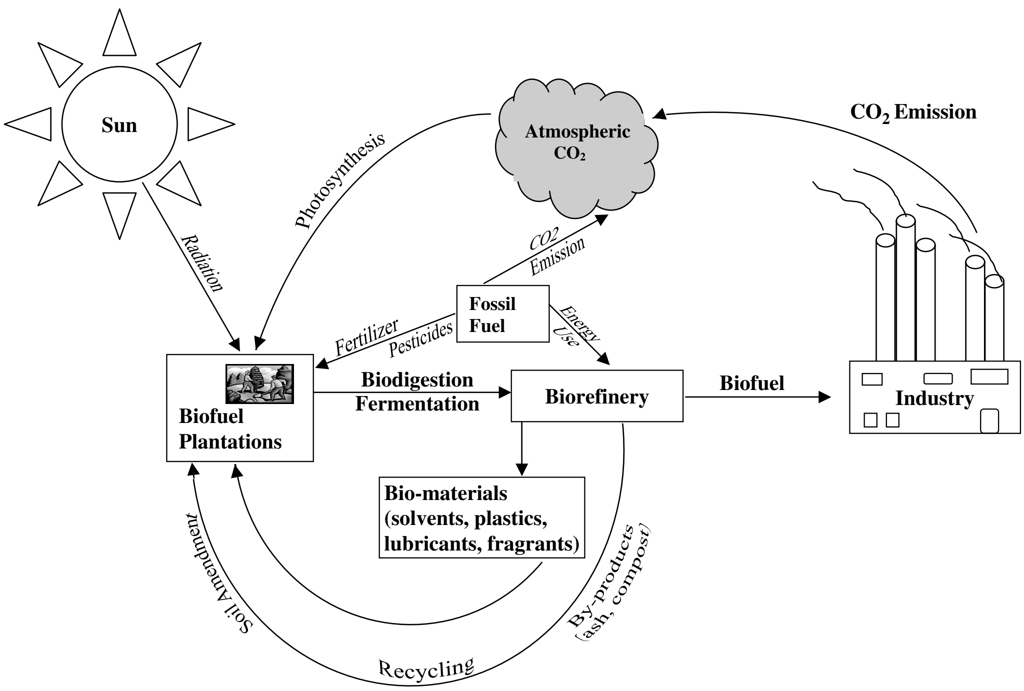

Figure 10. A carbon neutral strategy of biofuel production is feasible only if the energy input from fossil fuel for biofuel plantations (e.g. agricultural chemicals, irrigation) is less than energy output.

CONCLUSIONS

World grain production increased from 680×10^6 Mg in 1950 to 2060×10^6 Mg in 2000. This increase was attributed to increase in fertiliser use and irrigated cropland area. World grain production between 1950 and 2000 increased linearly with increase in N fertiliser consumption ($Y = 15X + 611$, $r = 0.96$, where Y is grain production and X is N fertiliser consumption in 10^6 Mg). Each 1×10^6 Mg of N fertiliser applied produced 15×10^6 Mg of grain. There was also a drastic increase in irrigated cropland area from 100 Mha in 1950 to 275 Mha in 2000. Despite these impressive gains, food production must be increased by an additional 35–62% between 2000 and 2025 and by 58–121% between 2000 and 2050 to meet the needs of growing population and possible change in food habits. Furthermore, future increase in food grains (and roots and tubers) must come from increase in use efficiencies of fertilisers, irrigation and other energy-based input, because the potential for increasing the area under cropland or irrigation is low. Food demand for the world population of 10 billion can only be met through agricultural improvement. The latter implies cultivating best soils with best management practices to produce the optimal sustainable yield. While enhancing agronomic productivity, agricultural intensification must also be a part of the solution to environmental problems.

The ultimate strategy of agricultural intensification means adopting RMPs where extractive farming practices are widely observed, enhancing the SOC pool through use of residue mulch and manures where biosolids are traditionally removed for fodder and household fuel, using integrated nutrient management practices to achieve positive nutrient balances where negative nutrient balances have occurred on a continental scale for decades, and rewarding farmers and land managers appropriately so that they adopt soil restorative practices where mining of soil C and nutrients has caused havoc to natural resources and the environment.

Increasing the SOC pool by 1 Mg ha^{-1} in the root zone can increase global food production by 32×10^6 Mg year^{-1} of grains and 9×10^6 Mg year^{-1} of roots and tubers while reducing the net rate of CO_2 emission into the atmosphere and improving the quality of natural waters. It is in this context that agricultural intensification, on existing croplands and saving marginal lands and other ecologically sensitive eco-regions for nature conservancy, is a truly win–win and no-regrets strategy.

For feeding the projected world population of 10 billion by the end of the 21st century, soil resources cannot be taken for granted. Soils must be used, improved and restored by increasing the SOC pool through C sequestration and by adopting the motto 'in soil we trust'.

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