



Invited Article

Soils and India's Food Security

R. LAL

Carbon Management and Sequestration Center, The Ohio State University, Columbus, OH 43210, USA

Abstract: Indian agriculture is on the cross roads. Yields of major food crops have stagnated or declined since 2000. Thus, Indian agriculture is facing a triple challenge of: (i) doubling the food production by 2030 compared with 2005, (ii) restoring degraded soils and improving quality of surface and ground waters, and (iii) alleviating rural poverty by value addition and diverting population to other professions (*e.g.*, agro-based industries). Yields of principal crops in India are 2 to 4 times less than those in the industrialized economies. In addition to biophysical (soil, water, climate) factors, there are also serious human dimension issues which need to be addressed to enhance and sustain agronomic production. While building upon the conventional technologies (*e.g.*, conservation tillage, mulch farming, use of plastic mulch, drip sub-soil irrigation, aerobic rice, positive nutrient budget), it is also important to use modern innovations based on nanotechnology, biotechnology and information technology. Zeolites-based amendments have an application in nutrient and moisture conservation. The critical issue is of enhancing the use efficiency of inputs (*e.g.*, fertilizer, irrigation water, energy) by reducing losses. The strategy is to improve agronomic yield per unit land area, time and the off-farm inputs of nutrients, energy, water, and labour. With its vast soil and water resources and a range of climates, India has the capacity to be the world's bread basket by mobilizing farming community, making soil science relevant to societal needs, and improving accountability and governance.

Key words: Sustainable agriculture, trading carbon credits, soil quality, food security

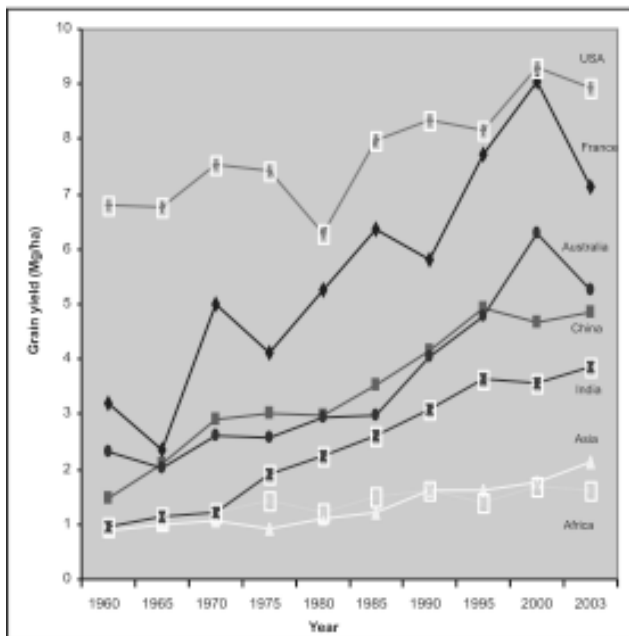
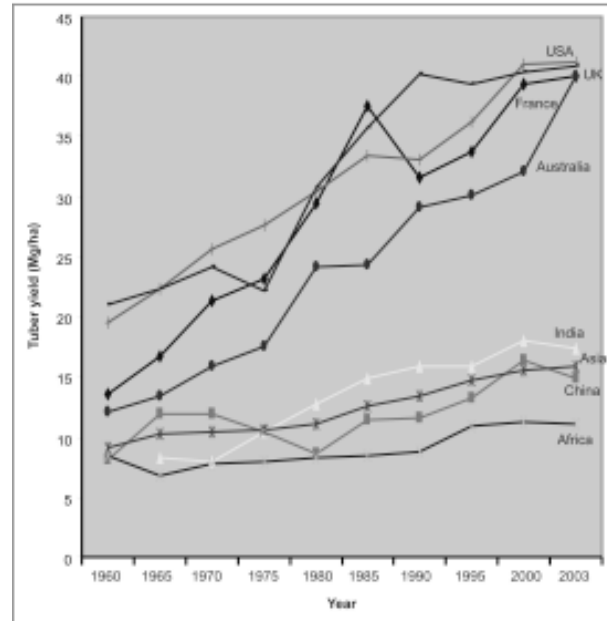
Agronomic production in India between 1960 and 2002 increased by a factor of 2.5 for rice, 6.4 for wheat, and 2.5 for all food grains (Table 1). Impressive as it seems, there is no cause for complacency. India's soil resources for crop production are second only to those of the U.S. With a wide range of climates, hard working and entrepreneurial farmers, and cadre of innovative young researchers, India has the capacity to feed the world. Alas, the reality of recent wheat importation and stagnating production warrant a critical appraisal of what has gone wrong. Yet the demand for food is going to be even more for the coming few decades. For example, India's population of 1.1 billion in 2007 is expected to reach 1.59 billion by 2050. With the need to increase food grain production from 206 million tonnes (Mt) in 2001 to 301 Mt with low food demand, 338 Mt with medium food demand and 423 Mt with high food demand by 2025 (Sekhon 1997; USDA 2004), the future of food insecurity is a growing concern of scientists, planners and policy makers. Among more than 850 million food-insecure people around the world

(Borlaug 2007), India is a home to more than 200 million or about 20% of the total population of the country (Elder 2006). The number of food-insecure people is progressively increasing. Prasad (2005) estimated that by 2020 India will need 294 Mt of food grains, or 82 Mt more than what was produced in 2002. This involves producing 29 Mt more rice, 31 Mt more wheat, 7 Mt more coarse grains and 15 Mt more pulses. Prasad argued that the yield of these crops will have to be increased by 22-41% in cereals and 110% in pulses over those in 2001-2002. However, FAO (2000-2007) show stagnation or decline in yields and total production of several food crops in India (Figs. 1-8). The situation is especially grave with regards to production of pulses, oil seeds and wheat. The production of pulses was 13.2 Mt in 2002 and the need by 2020 is projected to be 28 Mt.

The severity of the problem of the agrarian stagnation is further exacerbated by: (i) the rising energy and environmental costs of agricultural intensification, (ii) change in climate with the attendant adverse impact on the amount and variability in monsoons,

Table 1. Temporal changes in agricultural production and crop yields in India between 1960 and 2002 (Recalculated from Jain 2005)

Year	Total Production (Mt)			Grain yield (kg ha ⁻¹)		
	Rice	Wheat	All food grains	Rice	Wheat	All food grains
1960	36.7	11.7	83.3	1000	850	700
1970	43.7	24.2	108.4	1120	1300	850
1980	55.0	35.0	130.0	1350	1600	1020
1990	74.2	54.2	175.0	1720	2300	1380
1997	85.5	85.8	190.9	1900	2550	1550
2000	85.0	75.2	196.7	1920	2750	1620
2002	90.0	75.2	211.8	2100	2820	1720

**Fig. 1.** Temporal changes in corn grain yield (Redrawn from FAO Production Yearbooks)**Fig. 2.** Temporal changes in potato tuber yield (Redrawn from FAO Production Yearbooks)

(iii) severe problem of soil degradation, and (iv) drought stress accentuated by the increase in food production brought about by contamination and pollution of surface and ground waters. While the increase in food production through the Green Revolution of the 1960s and 1970s was based on growing input-responsive varieties planted on irrigated soils with intensive input of fertilizers and pesticides, the next quantum jump must come from using innovative technologies for sustainable management of soils based on cutting edge of scientific advances of the 21st century. Therefore, the objective of this chapter is to describe the factors responsible for yield decline and agrarian stagnation in India, discuss the role of modern innovations and of the synergism with recommended practices on improving soil productivity, enhancing use efficiency of inputs, and maintaining a positive trend in productivity over time.

Rationale for Agricultural Intensification in India

There are several compelling reasons for agricultural intensification in India: increase in population, changes in dietary habits associated with increase in income, severe soil degradation, decline in per capita land area, decline in per capita availability of renewable fresh water aggravated by the excessive withdrawal of ground water, and the need for alleviation of poverty among rural population.

Increase in population in developing countries in general and in India in particular, is a concern that must be addressed with all its ramifications. Years to double the population decrease exponentially with increase in the rate of population growth. The years to double the population are 693 for the rate (%/yr) of 0.1, 139 for 0.5, 70 for 1.0, 47 for 1.5, 35 for 2.0, 28 for 2.5, 25 for 2.8, 23 for 3.0, 20 for 3.5 and only 18 for 4.0 (Hardin 1969). Although India's popu-

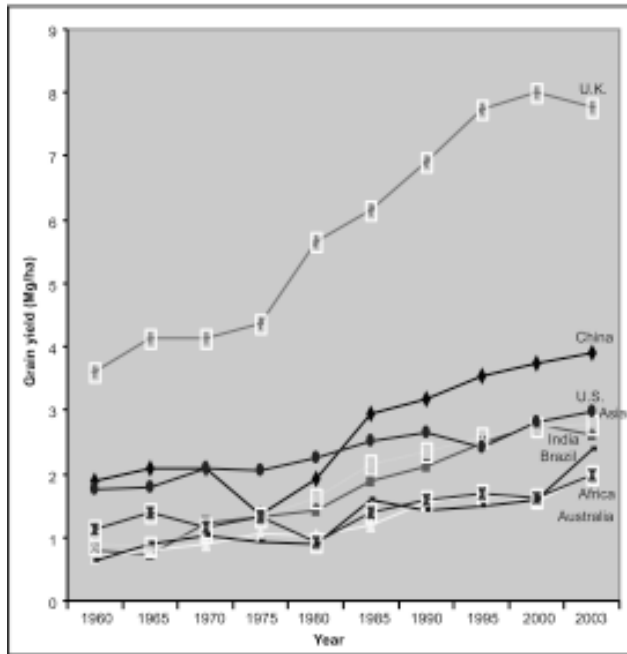


Fig. 3. Temporal changes in wheat grain yield (Redrawn from FAO Production Yearbooks)

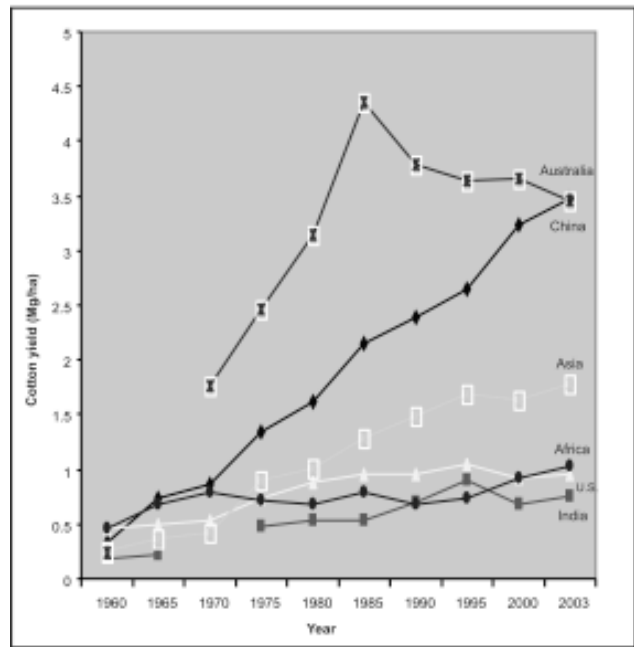


Fig. 5. Temporal changes in cotton lint yield (Redrawn from FAO Production Yearbooks)

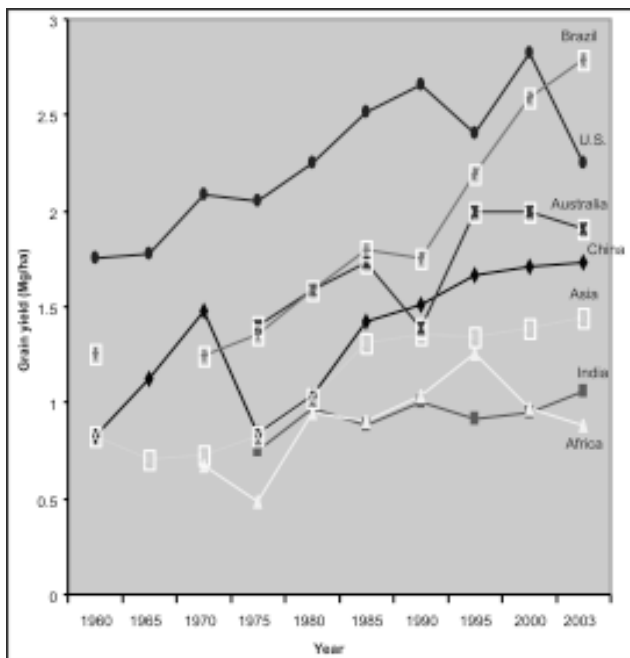


Fig. 4. Temporal changes in soybean grain yield (Redrawn from FAO Production Yearbooks)

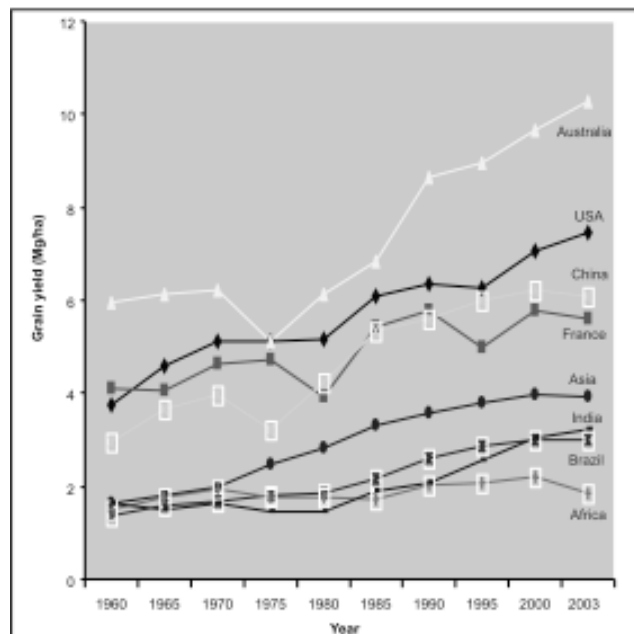


Fig. 6. Temporal changes in rice grain yield (Redrawn from FAO Production Yearbooks)

lation growth has been progressively declining to a present rate of 1.7%/yr, the projected population (billion) is estimated at 1.18 by 2010, 1.32 by 2020, 1.45 by 2030, 1.53 by 2040, and 1.59 by 2050. With progressive increase in GDP at 8% or more per year, there is a strong likelihood of change in dietary habits from predominantly plant-based vegetarian diet to a

progressive shift to animal-based diet (*e.g.*, poultry, fish, lamb etc). These dynamics necessitate a drastic increase in agronomic production over the next 2 to 4 decades (by 2025 and 2050).

Increase in population leads to decrease in farm size on the one hand and reduction in per capita arable land area on the other. The per capita land area

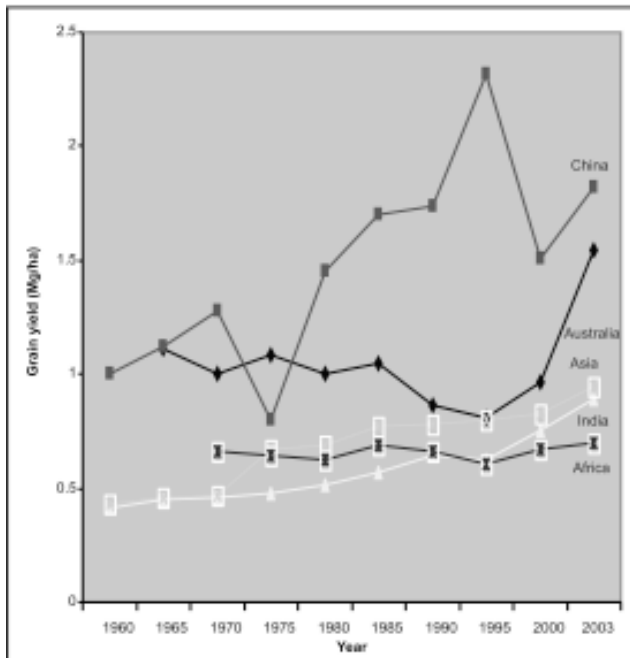


Fig. 7. Temporal changes in millet grain yield (Redrawn from FAO Production Yearbooks)

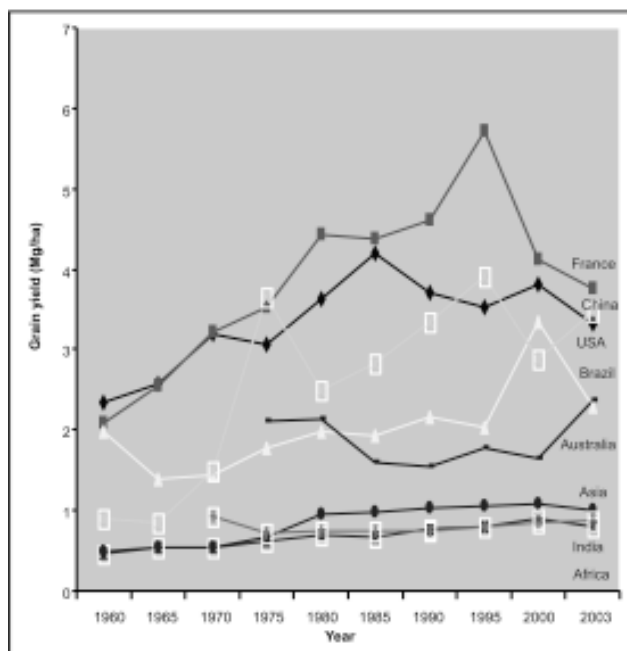


Fig. 8. Temporal changes in sorghum grain yield (Redrawn from FAO Production Yearbooks)

(ha) of India was 0.15 in 2000 and 0.147 in 2005. It is projected to be 0.136 in 2010, 0.121 in 2020, 0.110 in 2030, 0.105 in 2040 and 0.100 in 2050 (Engelman and Le Roy 1995). These projections are based on a dubious assumption that there will be no additional conversion of farm land to industrial/urban and other land uses or to degradation by erosion,

salinization, elemental imbalance etc. Yet, soil degradation in India remains to be a serious issue, especially that caused by accelerated erosion by water and wind and by salinization (FAO 1994). Similar to the trends in per capita land area, there is also a problem of water shortage (Engelman and Le Roy 1993). The latter is likely to be exacerbated because of the ever-increasing competition from urban and industrial uses, and increase in the vagaries of rainfall because of the projected climate change.

Irrigation has been a major factor in enhancing agronomic production in India since 1960s. The irrigated land area increased from about 34 Mha in 1975 to about 60 Mha in 2007 (FAO 2007). While there is a potential to double the land area under irrigation, both by surface and ground water utilization, the urgent necessity is in saving the water resources by reducing losses and increasing water use efficiency. Flooded rice culture requires 5000 litres of water to produce 1 kg of rice, leading to rapid depletion of the ground water. Similar to soil, the progressive decline in availability of per capita fresh water resources is also being exacerbated by pollution, contamination and eutrophication. Population (million) already affected by water scarcity in India is estimated at 221 compared with 133 in Pakistan, 489 in China, 17 in Mexico, 22 in Algeria and 16 in the U.S. (New York Times, 28 Sept., 2007). In India, the ground water depletion has accelerated with the proliferation of electric pumps for irrigation.

The problem of water depletion and soil degradation will be exacerbated in the developing countries of South Asia including India. The projected increase in temperature and increase in rainfall variability will accelerate soil degradation by erosion and depletion of soil organic matter (SOM) reserves. Under the projected climate change and increase in soil degradation, there would be a progressive decline in the use efficiency of off-farm input (*e.g.*, nutrients, irrigation, soil amendments, energy). Of the 400 million ha-m of rain water annually received in India, only 37.5% or 150 million ha-m presently infiltrates into the soil. The projected increase in temperature would accentuate losses due to evaporation and decrease even further the proportion of rain water utilized by crops (*e.g.*, the green water). The already low water use efficiency would decline even further. In view of these issues, there is an urgent need to revisit the concept of agricultural sustainability and the relevant strategies for enhancing food production in India.

Trends in Grain Yields

Trends in grain yield of food crops in India and other countries of the world are shown by the data in

Table 2. Comparative yields (t ha⁻¹) of vegetables in India (Adapted from Pain 2007)

Year	India	China	World
1990	10.2	17.7	14.9
1995	10.2	18.8	15.5
2000	13.1	18.9	16.6
2002	12.5	19.6	16.9
2003	12.9	19.2	16.8

figs. 1 to 8. The yields of corn (Fig. 1), potato (Fig. 2), wheat (Fig. 3), soybean (fig. 4), cotton (Fig. 5), rice (Fig. 6), millet (Fig. 7), and sorghum (Fig. 8) are amongst the lowest in the world. Yields per hectare of these crops in countries with commercial farming are as much as 3 times higher in corn, 2-2.5 times higher in potato, 3-4 times higher in wheat, 2 times higher in soybeans, 6-8 times higher in cotton lint, 3 times higher in rice, 2 times higher in millet, and 5-6 times higher in sorghum (Figs. 1-8). Crop yields are lower in India not only in comparison with developed countries (U.S., Canada, Europe, Australia, Japan), but also with reference to those in China, South East Asia, and South America. In fact, yields of rainfed (dry farming) crops in India are only marginally better than those in Sub-Saharan Africa. The concern of low yields is further enhanced by the stagnating production even in irrigated agriculture. Similar to food grains (Table 1), the yields of vegetables in India are about 50% lower than those of the world average, and 60-100% lower than those of China (Table 2). These low yields are also reflected in low annual growth rate in agricultural sector in India (Table 3). Agricultural growth was -7% in 2002-2003, and only 0.7% in 2004-2005. Yet, India's economy, now a trillion US \$, grew at 9.4% during 2006-2007. It is the agricultural sector which is lagging behind, and is adversely affecting the standard

Table 3. The average annual growth rate in agricultural sector in India (Adapted from Pain 2007)

Year	Annual growth in agriculture and allied sectors (%/yr)
1985-1990	3.2
1990-1992	1.3
1992-1997	4.7
1997-2002	2.1
2002-2003	-6.9
2003-2004	10.4
2004-2005	0.7

of living of the rural population. The economic gap is widening between the urban and the rural population in India.

Such a poor performance in agricultural sector in general and crop production in particular cannot be explained entirely on the basis of biophysical factors (e.g., soil, water and climate). The entire question of sustainability and of the use of unconventional and modern technology based on the cutting edge of science need to be objectively assessed. How can the immediate need of increasing aggregate availability of all food be increased from 280 Mt in 2002 to 317 Mt in 2008, 345 Mt in 2013, (Table 4) and by 50% more by 2025?

Revisiting Sustainable Agriculture in India

Since 1980s, the literature is replete with debate on sustainable agriculture. In the context of India, which is similar to other developing countries of South Asia and Sub-Saharan Africa, the challenge is how to increase food production by 50 to 100% over the next 20 years without jeopardizing the soil and water resources which are already under great stress. While the demand for food (cereals, pulses, cooking oil) is increasing, the productivity per hectare or unit input

Table 4. Recent trends in food production (MT/yr) in India (Adapted from USDA 2004)

Year	Grain production	Root production (Grain equivalent)	Commercial inputs (Grains)	Food aid (Grain equivalent)	Total availability of all food
1994	170.8	6.2	0	0.4	244.7
1995	174.9	6.1	0	0.4	249.7
1996	177.8	6.4	0.4	0.4	255.9
1997	182.8	7.8	1.3	0.3	261.3
1998	184.0	6.4	1.6	0.3	260.5
1999	191.0	7.9	1.4	0.3	267.4
2000	192.9	8.2	0	0.3	263.0
2001	197.4	7.6	0	0.2	278.8
2002	173.2	8.1	0.04	0.3	281.3
2003	189.5	8.3	0.3	-	279.5
<i>Projection</i>					
2008	216.3	9.0	0.3	-	316.5
2013	238.3	9.9	0.4	-	344.5

is decreasing and the risks of degradation of natural resources (soil and water) are increasing. There is a serious problem of nutrient mining because of extractive farming practices. For each tonne of cereal grains harvested, amount of major nutrients removed from the soils is 20-30 kg N, 4-8 kg P and 18-40 kg K (Conklin Jr. and Stilwell 2007). The negative nutrient budget is exacerbated by removal of crop residues and animal dung for other purposes. It is estimated that in India 20-70 Mt of crop residues and 36-108 Mt of animal dung are used as house-hold fuel rather than as soil amendment (Venkataraman *et al.* 2005) with severe adverse impacts on climate and the environment (Ramanathan *et al.* 2001). Consequently, agricultural soils of India have an annual nutrient ($N + P_2O_5 + K_2O$) deficit of about 5 Mt (Prasad 2005) due to continuous mining of soil fertility. In addition to macro-nutrients, there is also a widespread deficiency of secondary (S) and micro-nutrients (Zn, Cu, Mo, B). Yet, an objective assessment of the issue of yield decline in rice-wheat system (Ladha *et al.* 2003) and rainfed crops requires a visionary and a pragmatic approach (Vittal 2004).

Principles of ecological agriculture (Magdoff 2007) and sustainability need to be applied to improving agriculture in India. The goal is to shift from seed-based technology to soil and water management (Jain 2005). Sustainable agriculture, a positive trend

in production per unit input of off-farm resource, has at least 6 criteria (Fig. 9). One, the basic necessity of food, feed, fiber and fuel must be met for the present and future population. In this context, the biofuel is a modern fuel rather than the traditional crop residues and animal dung. It is important to find viable alternatives to the widespread use of traditional biofuel (especially animal dung). It has numerous adverse health and environmental issues (Venkataraman *et al.* 2005). Rather than using dung as traditional fuel, it can be used to generate methane-based electricity at village level. The residues (cellulose, lignin) can be composted and after fortification with N and P, used as soil amendment. Two, farm income must be enhanced and the poverty trap broken. This implies value addition of farm produce through processing and creation of a strong bioeconomy. The surplus food in rural areas must not be allowed to rot (grains, vegetables and fruits) while the poor starve (Waldman 2002; Thurow and Solomon 2004). Three, there is a strong need for creation of agro-industry in the rural areas so that a large proportion of rural population can be diverted away from the subsistence farming. This diversion would lead to an increase in the farm size and accrue benefits of the economy of scale. Four, sustainable farming systems must restore degraded soils and reverse the degradative trends. Five, increase in agricultural pro-

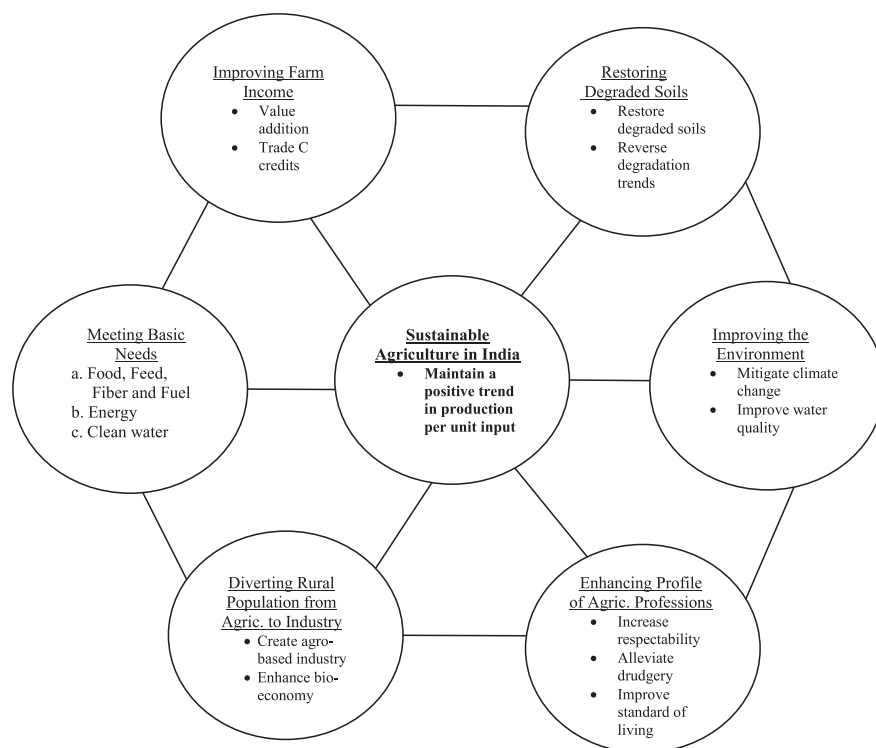


Fig. 9. Principles of sustainable agriculture in India and else where in the developing countries

duction must also be compatible with improving the environment, especially reducing emission of greenhouse gasses (CO_2 , CH_4 , N_2O) and improving water quality. Reducing non-point source pollution by transport of agricultural chemicals into natural water is an important criterion of sustainability. Six, the standard of living of rural masses must be improved, and the profile and respectability of the farming profession restored. There is no single prescriptive solution to achieve these goals. The strategies or combination of strategies would differ among soils, ecoregions, and social and ethnic conditions. While organic farming has a niche, especially an economic niche, it may not be the solution for land scarce countries such as those in South Asia (Badgley *et al.* 2007). New technology, such as no-till farming and conservation agriculture (Gupta and Sayre 2007), must be assessed in terms of these criteria and other constraints (Lal 2007a).

Modern Technology

The objective of developing modern technology is to save land, water and all energy-based input by decreasing losses and enhancing the use efficiency. The strategy is to deliver water and nutrients directly to plant roots at the time required and at the rate needed. It is also important to purify and reuse waste water (urban water) for irrigation (Lal 2007b). Natural zeolites can be used for purifying water (Pond and Mumpton 1984) and as soil conditioners. Flood irrigation must be replaced by drip sub-irrigation and other water-saving techniques. There is also a potential to enhance crop yields by sowing crops in more innovative spatial patterns, such as in clumps rather than in rows (Bandaru *et al.* 2006). Using innovative methods of enhancing soil fertility is yet another strong possibility (Benbi *et al.* 2007) and worthy of serious consideration. Water saving can also be achieved by growing aerobic rather than flooded rice, through development of appropriate varieties (Peng *et al.* 2006).

Nanotechnology has numerous applications in Soil Science, which must be harnessed (Fig. 10). This involves use of nanofertilizers, nano-delivery system, and use of new analytical techniques to study physical infra-structure of micro-aggregates at 10-50 nm scale. Biosensing with synthetic nanopores can have numerous applications. Synthetic sensors use molecular recognition events in nanopores for selective detection of proteins, nucleotides and other organic molecules (Martin and Siwy 2007). Use of zeolites has important application as soil amendment in enhancing use efficiency of water and nutrients (Allen

et al. 1995; Bhattacharyya *et al.* 2006; Mukhopadhyay 2005; Pal *et al.* 2006). These are the emerging technologies and are at the forefront for developing synthetic nanopore sensors. Economic and reliable methods are now available for preparing synthetic nanopores. Similarly, biotechnology has numerous applications to addressing soil-relevant stresses. The genetically modified (GM) plants can be grown to tolerate numerous biotic and abiotic stresses. Some plants can generate stress signals through emitting biomolecules which can be detected by remote sensing techniques, and targeted treatment implemented prior to any strong adverse impact on productivity. Use of nano-membranes, which can discriminate between H_2O and CO_2 molecules, can be used to minimize transpiration without hindering the uptake of CO_2 .

Advances in information technology (IT) has numerous applications to sustainable management of natural resources. The use of nanosensors dropped in remote areas can transmit information on soil properties, moisture and temperature regimes, and the edaphic environments. The IT can enhance connectivity, networking, improve linkages with markets, and provide the decision support systems to make sound decisions (Fig. 10).

Farming Carbon

There is a strong link between soil quality and soil organic carbon (SOC) concentration. The SOC concentration in soils of India is severely depleted, and is below the critical limits for soil and ecosystem functions. Because soils of India have lower SOC pool than their capacity as determined by the climate and ecological factors, there is a large sink capacity for atmospheric CO_2 . The sink capacity can be filled through conversion to a restorative land use and adoption of RMPs on agricultural soils.

Carbon sequestered in soil and trees is a marketable commodity. Trading C credits, through generating another income stream, offers an opportunity (Tucker 2001; Persson and Azar 2005) to adopt new technology and invest in restoration of soil and environment. Commodification of the soil/biotic C, to effectively use C sink capacity of terrestrial biosphere, would depend on involving industry (Johnson and Heinen 2004), and operationalization of the Clean Development Mechanism (CDM) of the Kyoto Protocol (Schlamadinger and Marland 1998; Tucker 2001; Diakoulaki and Giorgion 2007). Development of C market provides economic incentives (Persson *et al.* 2005). While farmers/land managers in developed countries can trade C through organization such as

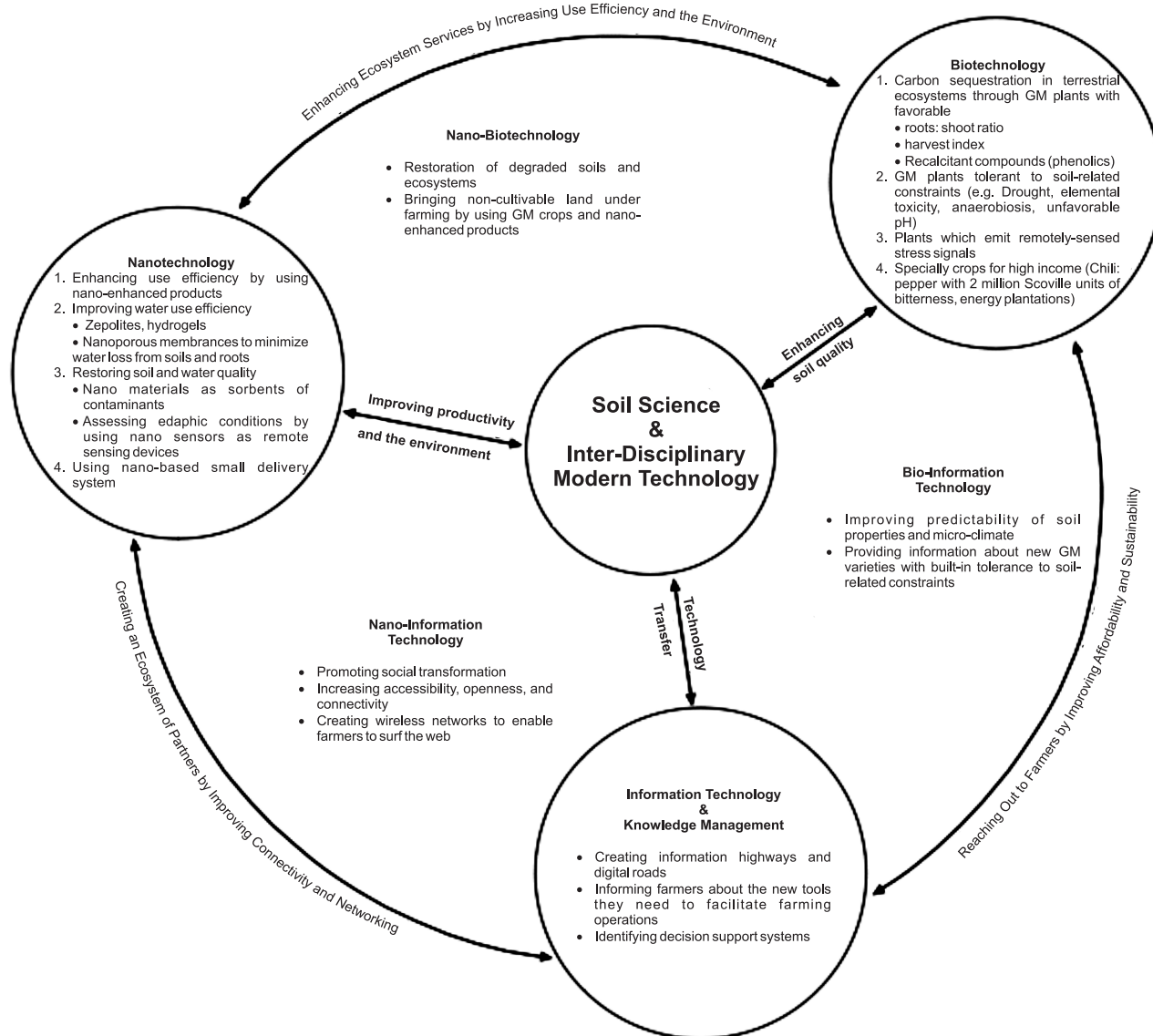


Fig. 10. Using modern technology to address soil-related issues of the 21st century (Adapted from Lal 2007b)

Chicago Climate Exchange and European Exchange, those in developing countries have also an option to do so through international organizations (World Bank 2003).

Conclusion

Despite vast soil resources, a wide range of climates, innovative farmers with “can do” attitude, and availability of high-calibre research and extension support services, agronomic production in India is either declining or stagnant. The regressive trend is attributed to decline in quality of soil and water resources attributed to extractive farming practices, and low use efficiency of fertilizer and water. In addition to conventional improved technology (e.g., conservation tillage, positive nutrient balance, drip-

subirrigation, manuring etc), there is a vast potential to use modern innovations including nanotechnology, biotechnology, information technology and synergism among these. Trading credits of C sequestered in soils and biota offers an opportunity to effectively utilize terrestrial sink capacity and create another income source to promote adoption of innovative technology.

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