



## Bio intensive Agronomy: A paradigm shift in agronomic research

R.L. YADAV\*, D.V. YADAV AND S.K. SHUKLA

Indian Institute of Sugarcane Research, P.O. Dilkusha, Lucknow, Uttar Pradesh 226 002

### ABSTRACT

The term paradigm shift was first introduced by Thomas Kuhn in his highly influential landmark book, *'The Structure of Scientific Revolutions'*. Kuhn's book shows how almost every significant breakthrough in scientific endeavor is first break with tradition, with old ways of thinking, with old paradigms. The word paradigm comes from the Greek. It was originally a scientific term, and is more commonly used today to mean model, theory, perception, assumption, or frame of reference. In more general sense, it's the way we see the world- not in terms of our visual sense of sight, but in terms of perceiving, understanding and interpreting. In pre green revolution period, the plant architecture of the cultivated cereal crops was long duration and tall. These plants were not responsive to input use i.e. with application of fertilizers and irrigation, they used to be lodged. Most of our agriculture was rainfed. Agronomic research therefore was revolving around increasing yield under this scenario available at that part of time. Simple fertilizer trial, tillage practices to conserve moisture and control weeds and mixed cropping were the main aspects of research. Farming was done for subsistence. Yields were sustained at low levels. Then, there was a breakthrough. Plant architecture was changed. Short duration dwarf varieties came into existence. Agronomic research also shifted from simple fertilizer trials to complex fertilizer experiments, mono- cropping to multiple cropping and scheduling irrigation. Use of herbicide increased to control weeds. With the expansion of irrigation, scheduling of irrigation became main focus and legumes went out of the cultivation and cereal- cereal cropping became predominant. Spread of rice- wheat cropping system in Indo-Gangetic Plain region is the glaring example of this. Due to this cereal-based crop rotation, natural resources started degrading and weeds developed resistance to herbicides. Factor productivity started declining. Presently these are our cultivation practices i.e. our convention, which is chemical based and input intensive, this we wish to change to bring bio-intensive agronomic practices, which will include massive use of biomanures, biofertilizers and biopesticides. The research on rhizospheric engineering and carbon sequestration has to be strengthened to improve the soil health and nutrient use efficiencies. Rhizospheric engineering refers to bringing changes in root architecture by modifying planting methods and crop geometry and also improving root zone soil profile through rhizodeposition. In irrigated ecosystem, where legumes could not be introduced due to their sensitivity to water, sugarcane is to be brought in the system, because several beneficial microorganisms are associated with its roots, which mobilizes soil materials. Also, large quantity of root mass of sugarcane upon decomposition adds substantial quantity of organic matter to the soil.

**Key words:** Farming systems, Crop production, Rhizospheric engineering, Soil Sustainability

The history of Indian agriculture can be broadly grouped into 3 periods. Before describing them, it is mentioned that during the colonial era, famines were frequent. The growth rate in food production during the 1900-1947 period was hardly 0.1%. Most of the important institutional developments in agriculture emanated from the recommendations of famine commissions. The great Bengal famine of 1942-43 provided the backdrop to India's independence. It is to the credit of independent India that famines of this kind have not been allowed to recur, although our population has grown from 350 million in 1947 to 1,100 million now.

India's food, nutritional, livelihood and economic security continues to be predicated by the performance of ag-

riculture sector and the situation is not likely to change in the near future. Even now, nearly 72% of our population lives in rural areas and about 58% are engaged in agriculture. The contribution of agriculture and allied sector to the GDP has fallen from 61 to 17.5% in the last 50 years. As of today, India supports 16.8% of the world's human and 11% of the livestock population on 4.2% of the world's water resources and 2.3% of the global land. Per caput availability of resources is about 4 to 6 times less as compared to the world average. Foreseeably, this will further decrease due to increasing demographic pressure and consequent land diversion for non-agricultural use, if by matching improvement, eroded and degraded land are not additionally brought to cultivation.

During 1950-51, the area under foodgrain cultivation was 97.32 m ha of which only 18% was irrigated, and the

productivity stood at 522 kg/ha and production around 51 m tonnes (mt). Population at that time was 361.1 m and growing at a modest rate of 1.25%, the population by 1961 touched 439.2 m at a growth rate of 1.96%, whereas foodgrain production increased to about 82 m t and the gap in the requirements had to be bridged through imports. Research and development initiative to attain self-reliance in food production was therefore considered essential. An all-round effort was made and the 'miracle seeds' of wheat and rice were introduced, improved and adopted to boost the production. Simultaneously, intensive efforts were made to strengthen agricultural research and education in the country and positive results ushered in 'Green Revolution'. Thus ended an era of foodgrain imports and the stigma of 'begging bowl' and 'ship to mouth' status was permanently shed off.

India, by adopting a path of science led growth of its agriculture reaped dividends in the form of a reasonably strong, self-reliant and resilient food security situation. The issues that call for priority attention include availability of water and its quality, soil health, managing climate change, diversification and enhancing input use efficiency. The present levels of efficiency of native resources (water, bio-energy, plant and animal residues), feeds and fodders and man-made inputs (fertilizers, pesticides, fossil energy) are unacceptably low. Furthermore, when resources and inputs are used inefficiently, both cost of cultivation and threat for biosphere pollution increase and production decreases. Efficiency-mediated improvement in productivity is the most viable option to raise production which would require much needed precision in agricultural operations based on innovative technologies and their large-scale adoption and translation into effective agricultural production, marketing and trade to ensure much needed enhancement in profitability.

The present cropping intensity of 137% has registered an increase of only 26% since 1950. Further, rainfed drylands constitute 65% of the total net sown area. Also there is an unprecedented degradation of land (107 m ha) and groundwater resource. Currently only 29% of the total precipitation is conserved, that too not optimally utilized. With the existing practices, water use efficiency seldom exceeds 40%. Use efficiency of nutrients ranges from 2 to 50%. We will have to adopt a holistic approach across different production systems with emphasis on integrated nutrient and pest management system.

Inter state variation in agricultural productivity has been further sharpened due to inequality in land-man ratio. Per caput agriculture income across states varied by about 41 % during early 1980's. The inequalities increased to the level of 47 % during second half of 1980's. Inter-state variation in per person NSDP agriculture further increased

to more than 51 % during the 1990's. There is clear evidence that since 1980-81, regional divergence in agricultural productivity and income have grown and the gap between underdeveloped and developed, and poor and rich states have continued to increase. This has happened despite special efforts made to reduce inter-state disparities by promoting level of agricultural development in underdeveloped states. There is a need to make more vigorous efforts on technological, institutional and infrastructural fronts to raise productivity and to accelerate growth rate not only of crop sector but also of livestock and other sub sectors of agriculture in under developed states.

### **Agricultural research and development**

#### *Phase I: Pre-green revolution period*

The 1960s was a decade of despair with regard to the world's ability to cope with the food-population balance, particularly in the tropics. The cultivated-land frontier was closing in most Asian countries, while population growth rates were accelerating, owing to rapidly declining mortality rates resulting from advancements in modern medicine and health care. International organizations and concerned professionals were busy organizing seminars and conferences to raise awareness regarding the ensuing food crisis and to mobilize global resources to tackle the problem on an emergency basis. In 'Time of Famines', published in 1967, the Paddock brothers (Paddock and Paddock, 1967) predicted, "Ten years from now, parts of the underdeveloped world will be suffering from famines. In 15 years, the famines will be catastrophic, and revolutions and social turmoil and economic upheavals will sweep areas of Asia, Africa and Latin America." Thanks to the widespread adoption of "Green Revolution" technology, large-scale famines and social and economic upheavals were averted (Table 1).

In this era, the major emphasis was on the development of infrastructure for scientific agriculture. The steps taken included the establishment of fertilizer and pesticide factories, construction of large multi-purpose irrigation-cum-power projects, organisation of community development and national extension programmes. During this period, the population started increasing by over 3 % year. The growth in food production was inadequate to meet the consumption needs of the growing population, and food imports became essential. Such food imports, largely under the 'PL 480' programme of the United States, touched a peak of 10 m t in 1966.

#### *Phase II: 1965-1985 green revolution phase*

The emphasis was on maximising the benefits of infrastructure created during Phase I, particularly in the areas

**Table1.** Status, research and development in agriculture during different periods

Period	Plant architecture	Agronomic paradigm	Agronomic research	Cultivation practices	Consequences
Pre-Green revolution	Long duration, tall	Rainfed and Natural farming.	Simple fertilizer trial, tillage for moisture conservation and weed control	Monocropping, mixed cropping, rainfed, bulky organic manures. Fallowing, summer ploughing, legumes in cropping system	Subsistence farming. Low level yields sustenance of crops.
Green Revolution	Short duration, dwarf, photo -and thermo -insensitive, lodging resistant, low source sink ratio.	Irrigated, chemical intensive farming.	Complex fertility trial, irrigation scheduling, multiple cropping, Integrated nutrient management.	Cereal based cropping system, Excessive use of fertilizers, pesticides and herbicides. Legumes out of cropping system.	Commercial farming, Unsustainable high yields, degradation of natural resources. Development of resistance herbicidal in weeds.
Post-Green Revolution	GM plant	Biointensive Irrigated	Rhizospheric engineering, carbon sequestration, residue recycling, identification of efficient strains of bioagents and plants, their application schedule, bioremediation, <i>In situ</i> organic farm waste recycling, conservation agriculture.	Subsoiling and enhanced use of bioagents	Corporate farming. Improvement in soil health. Mitigation of climate change effects

of irrigation and technology transfer. Major gaps in the strategies adopted during Phase I were filled, as for example the introduction of semi-dwarf high yielding varieties of wheat and rice, which could utilise sunlight, water, and nutrients more efficiently and yield 2-3 folds more than the strains included in the Intensive Agriculture District Programme (IADP) of the early 1960s.

All these steps led to a quantum jump in the productivity and production of crops such as wheat and rice, a phenomenon christened in 1968 as the Green Revolution. The green revolution generated a mood of self-confidence in our agricultural capability. The gains were consolidated during Sixth Five-Year Plan (1980-85) when for the first time agricultural growth rate exceeded the general economic growth rate. Also, the growth rate in food production exceeded that of the population. The Sixth Plan achievement illustrates the benefits arising from farmer-centred priorities in investment and in the overall agricultural production strategy.

#### *Phase III: 1985-2000 (post-green revolution phase)*

This phase was characterised by greater emphasis on the production of pulses and oilseeds as well as of vegetables, fruits, and milk. Technology Mission on Oilseed

(TMO) crops was launched which resulted in a rapid rise in oilseed production. The mission approach involves concurrent attention to conservation, cultivation, consumption and commerce. Rainfed areas and wastelands received greater attention and a Wasteland Development Board was set up. Wherever an end-to-end approach was introduced involving attention to all links in the production-consumption chain, progress was steady. This period ended with large grain reserves with the government. This period also saw a gradual decline in public investment in irrigation and infrastructure essential for agricultural progress. No wonder that the farmers, who keep others alive, are now forced to take their own lives and 40 % of them want to quit farming, if there is an alternative option.

The agricultural decline is taking place at a time when international prices of major foodgrains are going up steeply, partly owing to the use of grain for ethanol production. If agricultural production does not remain above the population growth rate and, if the public distribution system is starved of grain, there is every likelihood of our going back to the pre-independence situation of recurrent famines. The grain mountains have disappeared and we are today in the era of diminishing grain reserves, escalating prices, and persistence of widespread under-nutrition.

## Consequences

*Imbalanced production:* It has now been recognized that the green revolution, that helped us to make increase in our production, is not all that green. This is essentially because of the fact that the new technology demands an energy intensive farming, fuel to run machinery, fossil fuel based artificial fertilizers, diesel fuel or electricity to run irrigation pumps. The resource poor farmers of our country could not afford to go in for such costly inputs, with the result poor became poorer and rich became richer. Only prosperous and large farmers, who controlled more land and who had the financial resources, could adopt these new technologies. This is exemplified by the fact that these resourceful farmers, who accounted for less than 15 % of the area under food grains in India, contributed as much as 56 % of the increase in food grains production in the post green revolution period.

Another aspect of imbalance in Indian agriculture is the crop-wise disparities between food grains and non-food grains on one hand, and among different food grains themselves on the other. The increase realized in the food grain production was mainly due to the increase in the production of cereals, especially of wheat and rice. These two crops alone accounted for nearly 76 % in production of total foodgrains, 78 % of irrigated area, and 76 % of the area sown to high-yielding varieties on five cereals. As a result, the production and productivity of other crops have not been quite adequate. Again, the crops raised by the subsistence farmers were not paid adequate attention. Poor marketing facilities, non-availability of proper roads, and the size of land holdings of the resource - poor farmers further prevented them from adopting these new technologies. One of the major challenges facing the agricultural production in our country is the size of the land hold-

ings, which is becoming smaller and smaller due to increase in population and further division of land among family members. The high input technology, which demands larger holdings, thus does not become amenable to small farmers.

*Imbalanced fertilizer use:* Part of these inter-crop imbalances derive from regional imbalances. Imbalance in fertilizer use has been one of the major causes for the variation in production among different regions. Our fertilizer consumption ranges from as low as 2.1 kg/ha in Arunachal Pradesh and 3.9 kg/ha in Nagaland, to as high as 158.4 kg/ha (Punjab), 395.2 kg/ha (Delhi), and 494 kg/ha (Pondichery). Again, the consumption of N, P<sub>2</sub>O<sub>5</sub> and K<sub>2</sub>O has not been in the balanced proportions, which remains at 5.9:2.4:1 as of 2006-07, with nitrogen being consumed more than that of required as compared to phosphorus and potassium. Though many countries have taken advantage of the blended application of organics with inorganic fertilizers, utilization of organic manures is extremely low in India. All these factors contribute to the imbalanced production, both among inter-crops as well as among inter-regions (Tables 2, 3).

*Declining factor productivity and soil health:* In the last two decades, agricultural soils of the subtropical India have been intensively used for conventional crop production. Many producers have adopted organic amendment for sustainable crop growth, but use of inorganic fertilizers is predominant in the area. Excessive and continuous use of inorganic fertilizers is deteriorating soil quality and crop productivity (Dawe *et al.*, 2003). Increasing external subsidization destroyed the essential soil properties of resilient native soil fertility. Traditional farming systems appreciate sustainability on two counts, the irreversible

**Table 2.** All India N, P<sub>2</sub>O<sub>5</sub> and K<sub>2</sub>O consumption/unit gross cropped area (kg/ ha)

Phase	Year	Gross cropped area (m ha)	Consumption			
			N	P <sub>2</sub> O <sub>5</sub>	K <sub>2</sub> O	Total
Pre-Green Revolution	1951-52	133.234	0.44	0.05	-	0.49
	1956-57	149.492	0.82	0.11	0.10	1.03
	1961-62	156.209	1.60	0.39	0.18	2.17
Green Revolution	1966-67	157.350	4.68	1.58	0.73	6.99
	1971-72	165.186	10.88	3.38	1.82	16.08
	1976-77	167.334	14.68	3.79	1.91	20.38
	1981-82	176.750	23.02	7.48	3.83	34.33
	1986-87	176.405	32.40	11.78	4.82	49.01
Post-Green Revolution	1991-92	182.242	44.15	18.22	7.47	69.84
	1996-97	189.592	54.34	15.70	5.43	75.47
	2001-02	185.705	58.80	22.70	8.44	89.44
	2006-07(P)	190.911	72.15	29.04	12.23	113.42

Source: FAI (2006-07)

**Table 3.** Trends in gross nutrient removals by crops in India

Year	Food grain production (million tones)	Nutrient	Uptake (million tonnes)		
			Food grains	Others	Total
1986	150	N	4.4	1.5	5.9
		P <sub>2</sub> O <sub>5</sub>	1.7	0.9	2.6
		K <sub>2</sub> O	7.0	3.3	10.3
		Total	13.1	5.7	18.8
1995	192	N	5.6	1.9	7.5
		P <sub>2</sub> O <sub>5</sub>	2.2	1.2	3.4
		K <sub>2</sub> O	9.0	4.2	13.2
		Total	16.8	7.3	24.1
2000	200	N	5.8	2.0	7.8
		P <sub>2</sub> O <sub>5</sub>	2.2	1.3	3.5
		K <sub>2</sub> O	9.3	4.4	13.7
		Total	17.3	7.7	25.0
Future	225	N	6.6	2.2	8.8
		P <sub>2</sub> O <sub>5</sub>	2.6	1.4	4.0
		K <sub>2</sub> O	10.5	4.9	15.4
		Total	19.7	8.5	28.2

Source: FAI (2006-07)

and non-dissipative that requires dynamic closure of cycles, space-time differentiation and cooperative reciprocity. Hence increasing external subsidization that destroys native fertility and decreases resilience of the system is unfavourable to production. A debate on the subject, however, on “*inefficient use, overuse and abuse*” is relevant as it leads to economic loss to the nation and the farmer, including the adverse effects on the environment. Economic criteria used in modern market oriented agriculture, such as yield or gross margin are no longer deemed adequate for a global evaluation of agricultural practices, unless an assessment of their environmental impact is accounted for (Sen, 1981). Inappropriate product patterns and time and method of application as a mismatch to crop needs, account for half to two-thirds of the gap between actual and potential cereal grain yields. Much of the future food-grain increases must come only through management techniques in preference to input additions. Thus a judicious balance between soil inherent fertility (SOM) and the appropriate fertilizer level applied a balance between food and commercial crops and a balance between the 3 major nutrients: (NPK) would economically tap the untapped potentials. Environmental issues *viz.*, eutrophication of surface waters by phosphates and nitrates and nitrates in drinking waters cannot be ignored by the industry, though the industry is one among those responsible. It is thus a global problem of great importance for all. However, the Indian situation under bio-economic pressures requires a modification of organic agriculture, keeping the

**Table 4.** Intercropped grain legumes residue incorporation vis-à-vis biological properties of soil

Treatment	Soil Microbial Biomass Nitrogen (mg/kg/10 days)	
	Before <i>in-situ</i> incorporation	After <i>in-situ</i> incorporation
Sugarcane + cowpea	78.80	97.93
Sugarcane + green gram	78.06	83.37
Sugarcane + black gram	74.06	79.83
Sugarcane + <i>Sesbania</i> (green manure)	58.56	79.09

Source: Lal *et al.* (2002).

core objectives undisturbed, into eco-technologies –a blend of tradition and modernity (Tables 4, 5, 6). There is an unusual agreement of world opinion that efficient use of fertilizers can only be through integrated nutrient management, for which the current product patterns, use and application methods in India are an utter misfit. Revolutionary changes have to be made for the global prescription of ‘systematic and simultaneous account of the environmental aspects, the quality of the produce and profitability of the farmer’. The truth that profits supersede principles cannot be erased.

#### **Modern approach for an ever-green revolution**

The term ever-green revolution refers to an improvement in crop and animal productivity in perpetuity. In other words, an ever-Green Revolution implies a vertical growth in productivity in perpetuity. We have no scope for a horizontal expansion in area and we have no option except to produce more crop per drop of water and per plot of land. This will call for taking to eco-farming techniques, which are both ecologically sound, environmentally safe and economically efficient. We must achieve cost reduction without yield loss. This will be possible only through precision farming techniques rooted in the principles of ecology, economics and efficiency.

Our breeding programmes should emphasize on breeding crop varieties/ plant (GM plants), which would increase their natural ability to resist pests and diseases. The internal resources of agriculture, *viz.*, inherent soil fertility, rainfall and climatic patterns, dynamics of pest population and their natural enemies, must be taken into account while breeding crop varieties. This ‘maintenance research’ would help the subsistence farmers to maintain their yields.

Organic matter is considered a major binding agent that stabilizes soil aggregates (Tisdall and Oades 1982; Haynes *et al.*, 1991). Aggregate stability depends on the binding mechanisms of clay and organic matter, such as chemical

**Table 5.** Effect of different treatments on soil organic carbon (SOC) during crop growth and change at harvest (two seasons mean data)

Treatment	*Soil organic carbon (Mg/ha)			Difference (SOC at harvest - initial SOC)
	April	August	December (harvest)	
Trash mulch+T <sub>v</sub>	22.80 (1.44)**	28.00 (2.44)	20.83 (2.00)	5.08
Trash mulch-T <sub>v</sub>	19.81 (1.54)	24.25 (2.62)	18.88 (1.99)	3.13
Trash burn+T <sub>v</sub>	20.83 (1.13)	25.23 (1.55)	20.46 (1.22)	4.71
Trash burn-T <sub>v</sub>	17.58 (1.22)	21.31 (1.64)	18.17 (1.16)	2.42
Trash remove+T <sub>v</sub>	20.32 (1.23)	20.66 (2.14)	19.31 (1.92)	3.56
Trash remove -T <sub>v</sub>	16.94 (1.34)	16.60 (2.43)	17.27 (1.26)	1.52
CD (P = 0.05)				
Trash	0.56	0.69	0.58	
Trichoderma	0.45	0.54	0.45	
Trash x <i>Trichoderma</i>	0.76	0.81	0.88	

\*Initial soil organic carbon was 15.75 Mg/ha; T<sub>v</sub> : *Trichoderma viridi*

\*\*Figures in parenthesis are SMBC (%) of total soil organic carbon (SOC) content

Source: Yadav *et al.* (2009).

**Table 6.** Effect of various treatments on nutrient uptake, growth attributes and ratoon cane yield.

Treatment	Nutrient uptake (kg/ha)			Millable (000/ha) canes	Cane weight (g)	Ratoon yield (Mg/ha)	Sugar yield (Mg/ha)
	N	P	K				
N (Farmers practice)	152.2	17.95	166.5	92.7	818.8	62.3	7.06
NPK	164.0	21.54	199.3	100.0	885.7	71.5	8.07
Farmyard manure	155.9	22.05	191.4	100.4	898.0	65.2	7.28
Farmyard manure + <i>Trichoderma</i> + <i>Gluconacetobacter</i>	165.7	24.01	200.5	103.4	928.2	70.2	7.93
SEm ±	2.7	0.41	2.2	2.2	3.8	3.4	0.45
CD (P = 0.05)	7.8	1.20	6.4	6.4	11.5	6.9	1.30

Source: Shukla *et al.* (2008).

bonding of organic compounds and physical binding of particles by fungal hyphae and plant roots (Miller and Jastrow, 1990; Angers, 1998). Manure amendment is a management practice that can improve the nutrient status of the soil and increase soil organic carbon (SOC) levels (Rochette and Gregorich, 1998; Aoyama *et al.*, 1999a) observed an increase in SOM with addition of manure and consequently the formation of slaking resistant macro aggregates (0.25- 1 mm diameter). Aoyama *et al.* (1999b) concluded that manure application contributed to the accumulation of macro-aggregate protected C and N.

In general, incorporating plant residues in soil can affect soil microclimate and increase plant residue contact with soil. This will increase residue decomposition and organic matter transformation (Beare *et al.*, 1992; Paustian *et al.*, 1997). Trash mulching conserves soil moisture, controls weed growth, and improves SOC and availability of nutrients in ratoon crop. Mulching increased N uptake and apparent recovery of N (Gupta, 1989; Daisly *et al.*, 1988, Yadav *et al.*, 1994).

*Trichoderma* spp. are among the most commonly isolated soil fungi. Due to their ability to protect plants and

contain pathogen populations under different soil conditions, these fungi have been widely studied and commercially marketed as biopesticides, biofertilizers and soil amendments. *Trichoderma* spp. also produces numerous biologically active compounds, including cell wall degrading enzymes, and secondary metabolites (Vinale *et al.*, 2008). *Gluconacetobacter* is nitrogen-fixing bacterium specific to sugarcane and is present inside the plant tissue as an endophyte. Since sugarcane is grown in intensive cropping system in subtropical India, soils have become deficient in organic carbon and nitrogen.

Fertilizers, when applied in large doses, suppress the natural biological activity in the soil. The research programmes should, therefore, investigate opportunities to substitute the fertilizers by the farm-grown nutrient sources. The new revolution through biointensive agronomy needed for the future should take into account the “*principles of permanence*”, which not only emphasizes the minimum use of external inputs but also on accumulating and recycling of natural nutrients more effectively, protecting soils, and relying on genetic diversity. The future strategies should also emphasize on the *regen-*

*erative approach*, which aims at maximizing *biological contributions to agricultural productivity*. This approach works on the principles of recycling and conserving various nutrients in natural ecosystems by suitably adopting various farming practices *viz.*, sowing different crops together to tap the soil fertility to the maximum, rotating foodgrains with nitrogen-fixing legumes, and planting trees and shrubs which facilitates drawing of nutrients from deep soil layers to the surface. More emphasis should, therefore, be given to different farming systems, especially to agroforestry, legume-based crop rotations and intercropping systems and alley cropping. These cropping systems help in efficient conservation of soil moisture, effective recycling of nutrients and also in adding enough organic matter to the soil. These benefits that accumulate over time help to make farming on marginal lands more productive and profitable. These regenerative methods, though require careful farm management, are less costly than conventional approaches, and they also help farmers to reduce their vulnerability to crop failure and famine.

The challenge of our agricultural research, thus, lies in retaining the strengths of traditional agriculture so that the needs of the limited-resource farmers are met adequately. What we should do now? The green revolution of the 1960s was the result of synergy among technology, public policy and farmers' enthusiasm. The post-60th anniversary era in agriculture will depend upon our determination to implement Jawaharlal Nehru's exhortation, "*Everything else can wait, but not agriculture*" in both letter and spirit.

If farm ecology and economics go wrong, nothing else will go right in agriculture (Swaminathan, 2007). How can we resolve the crisis? The first and foremost priority should go to making the era of farmers' suicide history. Conservation of prime farmland for agriculture and soil health care and enhancement, issue of Soil-Health Cards indicating the organic matter and macro - and micronutrient status of the soil; Water harvesting, management and conjunctive use of surface, rain, ground and treated effluent water and safeguarding water quality; Low-risk and environmentally friendly green technologies (*viz.*, integrated pest and nutrient management) and the provision of the needed inputs at the right time and place and at affordable cost. These steps need to be taken and implemented in an integrated manner, so that we generate an ever-green revolution symphony. First, we must defend the gains already made in the green revolution areas of Punjab, Haryana, and western Uttar Pradesh. This heartland of the green revolution, or India's fertile crescent, is in a state of acute ecological and economic distress. Conservation farming and green agriculture should replace exploitative agriculture. Public policies promoting ecocides should be withdrawn and replaced with incentives for conservation

farming. This region will remain a major source of food grains for the public distribution system, and hence needs urgent attention. Secondly, we must extend the gains to additional areas like Bihar and the entire eastern India, which possess good soil and water resources, as well as to rainfed, hilly and coastal areas. A second fertile crescent can be created immediately in the region comprising Bihar, eastern Uttar Pradesh, Chhattisgarh, West Bengal and Assam, where the untapped production reservoir even with technologies on the shelf is high.

Farmer incentives are a central issue facing sustainable agriculture. Farmers grow crops or raise livestock to feed their families or to sell and earn a living in a market economy that is becoming increasingly global and competitive. Many studies indicate that fertilizer-use efficiency could be greatly increased by better matching nutrient inputs to crop demand in time and space. But essential investments in on-farm nutrient-management research and in extension activities that promote such practices have not yet occurred. Similar opportunities for a significant increase in fertilizer efficiency exist for small-scale intensive cropping systems. How, then, can society accomplish the dual objectives of improving yield levels and food stability and of preserving the quality and quantity of ecosystem services provided by the Earth's land and water resources? Clearly, appropriate incentives are needed. Thus, farmers will need to rely on a rapidly expanding base of biological and agronomic knowledge that is often specific to certain agro-ecosystems, regions, soil types and slopes. Making the right decisions at the farm level in input-use efficiency, human health and resource protection is becoming an increasingly knowledge-intensive task.

#### *Future research thrusts*

- In depth investigation on enhancing the fertilizer use efficiency in different cropping systems through appropriate application frequency of organic manures, crop residues, green manures and bio-manures.
- Identification of specific nutrient deficiencies under continuous sugarcane ratooning to rectify the emerging nutritional imbalances at various ratoon cycles.
- Development of microbial consortia based formulations with *Gluconacetobacter diazotrophicus* and other bio-agents with multifunctional activities.
- Inoculation of micro-propagated plantlets with their efficient isolates, to equip them with N-fixing ability and disease resistance mechanism.
- Development of Integrated Nutrient Management approach to supply secondary and micronutrients particularly S, Fe, Cu and Zn to correct their hidden hunger before visible symptoms appear in the crop.

- Search for new fertilizer management strategies in the context of modified planting techniques (ring/pit, deep trench, paired rows), irrigation methods (skip furrows, drip, fertigation), specific soils (waterlogged, saline-sodic, extremely sandy), crop environments (drought, frost, flood prone) and cropping systems (mono-cropping, intercropping, ratooning) with a view to improving nutrient use efficiency.
- Development of ideal fertilizer schedules (application dose, time and method) for specific group of new promising varieties viz., early and mid/late maturing to realize their potentiality under different agro-ecological niches.
- Development of technology package involving *in situ* chopping of stubble/trash, microbial inoculants capable of degrading cellulosic substances under low temperature conditions.

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