Perspectives of soil fertility management with a focus on fertilizer use for crop productivity

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Agricultural development strategy for India in the 21st century must be through increasing productivity of the land under cultivation, with reduced costs of production and higher use efficiency of inputs with no harm to the environmental quality. The prime requisite is the promotion of health of the soil–plant–environment system to be free from economic exploitation under overuse and abuse of the inputs as if with impunity. To this end, a new strategy of promoting eco-technologies, a blend of traditional practice and modern advances (as agro-ecosystems) replaces existing methods to eliminate its grave consequences. This is the agro-ecosystem management, a prudent design for economic viability of the farmer and ecological sustainability of crop yields, that is elaborated and presented here.

THE planet earth is a gigantic ecosystem of an area of about 13.4 billion hectares. It is made up of 12 billion natural ecosystems of high biodiversity and 1.48 billion man-made ecosystems of crops designated as agro-ecosystems; their management is known as agro-ecology. Population growth and agricultural economic activity that represent linked responses across a broad range of environments and cultural context have ended up in the global spread of agro-ecosystems (AES) over the period from 1940 to date, as set out in Table 1.

Farming systems

With the industrial revolution, farming in the developed countries, specially in USA witnessed remarkable and incredible progress for high yields in a short time. The developed countries, after a short term had on hand anchoring evidence that energy-intensive and chemicalized farming (industrial agriculture) subverted ecology, disrupted environment, degraded soil productivity, mismanaged water resources; input use efficiency declined and agribusiness lost its sustainability. Unsustainable and unacceptable industrial agriculture was the result of (i) abandonment of ecological principles in food production, (ii) acceptance of cultural premise that placed humans as the rulers of the world and not therefore subject to the laws of nature. Both are untenable. This necessitated an early major shift to ecological agriculture. It is indeed a combined discipline of agricultural and natural sciences which is a solution to the food imbalances.

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Ecological agriculture

An ecosystem is an assemblage of organisms that interact or have the potential to interact with each other and with their physical environment. All ecosystems, whether they are untouched by man's activity or intensely managed, operate on the basis of natural laws.

AES are ecological systems but modified by man to produce food, fodder, fibre and raw materials for the industry. Conway[1] defines AES 'as a true cybernetic system whose goal is increased social value achieved through a variety of strategies that combine at different levels of productivity, stability sustainability and equitability'.

Many of the traditional farming systems, once regarded as primitive and archaic, are now being recognized as sophisticated and appropriate. Blended with modern agricultural advances they go under the name eco-technologies, and carry the following structural and functional elements:

(i) They combine high species numbers and structural diversity in time and space, through both vertical and horizontal organization of crops.
(ii) They exploit the full range of micro environments (which differ in soil, water, temperature, altitude, slope, fertility, etc.) within a field or a region.
(iii) They maintain closed cycles of materials and wastes through effective recycling practices and rely on the complexity of biological interdependencies, resulting in some degree of biological pest suppression.
(iv) They rely on local resources and human and animal energy, thereby using low levels of technology input.
(v) They rely on local varieties of crops and incorporate the use of wild plants and animals. Production is usually for local consumption. The level of income is low; thus the influence of non-economic factors on decision-making is substantial.

Table 1. Effect of AES spread over the period from 1940 to 2050 on population and foodgrain productivity

Year	1940	1960	1990	2000	2025	2050
Population (million)	2400	3000	5200	6000	8400	9920
Agricultural ecosystem area (ml/ha)	600	1320	1430	1480	1490	2080
Production of foodgrains (ml/t)	630	824	1430	1890	2350	3170
Agricultural area (per capita/ha)	0.25	0.44	0.27	0.24	0.17	0.10
Grain yield (tons/ha)	1.05	0.62	1.0	1.31	1.59	3.4
Per capita production (entitlement) (kg/year)	262	275	275	315	280	320

Data for 2050 as reported by World Bank Seminar, 1998.

Ecological services

The concept of agro-ecological zone first introduced by FAO is a step towards agro-ecological harmony and maximizing the efficiency of the system. It provides a basis to inform the policy makers about the yield potential of the ten major food crops important in the developing world and potential sustainability of the various cropping systems. For this reason change in the concept of commodity-oriented green revolution to farming systems-driven evergreen revolution, appears appropriate. The ecosystem science provides a framework which integrates the assimilative and supportive functional attributes of biological populations with their physical and chemical environments. Ecological services available to man are (1) control and moderate climate, (2) provide, renew air, water and soil, (3) recycle vital nutrients through chemical cycling, (4) provide renewable and non-renewable energy sources and non-renewable minerals, (5) furnish food, fibre, medicines, timber and paper, (6) pollinate crops, (7) absorb, dilute or detoxify many pollutants and toxic chemicals, (8) help control population of pests and disease organisms, (9) slow soil erosion and help prevent flooding, (10) provide bio-diversity of genes and species needed to adapt to environmental conditions through evolution and genetic engineering. There are as many supportive as assimilatory functions of the ecosystems and in balancing the two lies the crux of excellence. Currently, the idea of sustainability displaces the goal of growth, with no escape from the grim future of exhausted resources. One such is imbalance of carbon resulting in global warming, with which 185 nations are wrestling and the top culprit, USA, is unyielding.

Costanzo *et al.*[2] assessed the value of seventeen ecosystem services and flows for sixteen biomes at $ 33 trillion/year (see Table 2). By comparison, global GNP is now only $ 18 trillion/year. Food production services of crop land (1400 mha/year) is hardly $ 0.13 trillion/year (0.004% of the total ecosystem services). In short, global natural product is more valuable than global national product. Hence the need to conserve ecosystem services and flows under different agro-ecological conditions through precision farming practices can hardly be overemphasized. Even the basic truth that more input is needed for more output, does not hold. The experience of the 20th century teaches that unless technology and public policy are rooted to the principles of ecology, social and gender equity, employment generation and energy conservation development will not be environmentally and socially sustainable. Hence the immediate need is for a shift from an approach that has over-exploited and under-utilized our environments, to a strategy that derives full and sustainable benefit from our environments[3].

Table 2. Average annual global value of ecosystem services

Biome	Area (million/ha)	Total value ($/ha/year)	Total global flow value (trillion $/year)	Food production ($/ha/year)
Marine	36302	577	20949	93
Terrestrial	15323	804	12319	–
Forests	4855	969	4706	43
Grasslands	3898	232	906	67
Wetlands	330	14785	4879	256
Cropland	1400	92	128	54
Urban	332	–	–	–
Total for all 16 biomes	51625	–	33268	1386

(From ref. 2).

Native soil organic matter is made up of three fractions; (i) active microbial biomass, (ii) decomposable organic matter (microbial products of litter and root lignin) and (iii) recalcitrant. About 50% of the organic matter is protected under cultivation, but protection was reduced to 20% for the plough layer and 40% for the subsoil. In management of carbon and nitrogen cycles in nature through active intervention of soil micro-organisms that primarily derive their need from carbon of the soil organic matter, the three benefits derived are (i) reduction in cost of production, (ii) enhanced use efficiency of fertilizers added and (iii) enhanced quality of the environment. The constant interaction between atmospheric and terrestrial CO_2 permits the cycle, the conversion of inorganic carbon to organic (immobilization) and back to inorganic forms (mineralization.) Crop production security must first establish soil health care, plant production potential and environmental health – all integrated for economy and efficiency.

It has been formidable for sometime to define and measure the soil quality (health). Workers on the subject preferred to measure multiple characters that reflect the physical, chemical and biological properties that make up a healthy soil. These are, bulk density, structure, retention and release of water and nutrients, resistance to soil erosion, cation exchange capacity, nitrifying and nitrogen fixing capacity, all measured in the laboratory with simple equipment. Strangely, all these are influenced by the organic matter content of the soil. The soil has become a sink for carbon from the atmosphere. It is now realized in all quarters that replacement of inter-cropping and crop rotation by mono cultures ended up in yield fatigue from which recovery is through a recall of traditional practices, specially by the developed countries where emissions from fossil-fuel use have to be reduced at all costs.

Until soil fertility is restored, improvement in crop cultural practices and varieties will improve yield only marginally. It is primarily and essentially building soil carbon as SOM through the addition of organic manure and legumes in crop rotation and green manuring. Only then will supplementation with chemical fertilizers become relevant.

Soil productivity, that measures the output per unit of all inputs expressed as yield kg of grain per hectare or a return in terms of money, masks such effects as environmental health and soil quality in specific measurable terms, under input subsidization and controlled conditions of a glasshouse. Soil quality is defined as 'the ability of a soil to perform its three functions: as a primary input to crop production, to partition and regulate water flow and to act as an environmental filter. The concept of soil quality should be the principle guiding the recommendations for use of conservation practices and the targeting programmes and resources. A recent call for the development of 'soil health index' was stimulated by the perception that human health and welfare are associated with the quality and health of soils. Soil quality is determined by a set of many physical, chemical and biological properties (Table 3).

Soil fertility developments – Historical

Food has been considered primarily as a means to abolish hunger, ignoring its vital role in economic growth. Although 97% of all food comes from the soil, hardly 10% is reasonably free from all known constraints. But it remains unbelievable what King[5] recorded in his classical text, viz. how farmers in the Far East could maintain soil fertility and rice-grain productivity over forty centuries, despite such high population densities in China, Korea and Japan. He could grasp the intimate relationship between extensive recycling of a vast array of organic materials such as animal manure, crop residues and legumes in rotation with cereals as soil conditioners for maintenance of soil fertility. He asserted, that the absence of animals in any farming system makes the endeavour sterile.

Soil quality is determined by a set of many highly correlated physical, chemical and biological properties and is defined as 'the ability of a soil to perform its three primary functions: a primary input to crop production, to partition and regulate water flow, and to act as an environmental filter'. It is a function of many factors, including agro-climatic factors, hydro-geology and cropping and cultural practices[6].

(i) Technologically and economically relied as the medium for crop production by virtue of unique physical, chemical and biological properties functioning with integration to confer such essential properties as resilience and thixotropy among others.
(ii) Ability of the soil to sustain increased production depends on the way in which its properties are manipulated to sustain organic matter at its maximum. Under all soil-climate zones, it is the organic matter build-up that has not witnessed any change over a long period, as the efforts of the farmers to increase the organic matter content with many of traditional practices alone sustained yields of high quality as well.

The common thesis of the entire process asserted that the physical and chemical attributes of the soil regulate soil biological activity and interchanges of molecules and ions among the solid, liquid and gaseous phases which influence nutrient cycling, plant growth and decomposition of organic materials. The inorganic components of

Table 3. Soil health (quality) characterization

Soil property	Influence on productivity
Texture and structure	Positive influence on air–water relationship, drainage and erodability, aggregate stability.
Water-soluble salts (EC)	Index of salinity with specific effects on germination, growth and maturity.
Keen box data (density, porosity, MWHC, field capacity)	Determines the choice of tillage operations and measures to improve retention and release of water and nutrients.
Soil reaction (pH)	Guidance for reclamation measures to shift pH towards normal range of 6.8 to 7.5.
CEC of soil/roots	Regulation of retention and release of water and nutrients for higher crop productivity. Nutrients to be a blend of organic and inorganic.
Organic carbon (OC × 1.72 = organic matter)	Influences favourably all physical, chemical and biological properties. As a sink to CO_2 of the atmosphere, improves environmental quality with reduced global warming.
Assay of biological processes	Nitrifying power, nitrogen fixation and total bacterial count indicate a healthy soil to promote productivity.

MWHC, Maximum water holding capacity; CEC, Cation exchange capacity; EC, Electrical conductivity. (From ref. 4).

the soil play a major role retaining cations through ionic exchange and non-polar organic compounds and anions through sorption reactions. Essential parts of the global C, N, P and S and water cycles occur in the soil and soil organic matter is a major terrestrial pool for C, N, P and S; the cycling rate and availability of these elements is continually being altered by soil organisms in their constant search for food and energy sources. Indian soils (tropical climate) on an average contain only 0.05% nitrogen and 0.6% of organic carbon (1.03% of organic matter). Cultivated over a period of seven years continuously with grain crops, but with legume crop rotation, as much as 1.8% organic matter could be obtained. But for the temperate soils of Europe with and without crop rotation, organic matter registered as much as 4.0 and 2.8%, respectively. The influence of climate (tropical and temperate) and cropping patterns with and without crop rotation and over a time of zero to eight years may be clearly seen in Figure 1.

The native soil fertility in terms of organic matter content of temperate and tropical soils (natural ecosystems) stands at 2 : 1. With continuous grain cropping after seven years the ratio changes to 3 : 1. But under crop rotation and residue management, the ratio returns back to 2 : 1. Since nutrients can be supplied through fertilizers, the extent to which the natural fertility of a soil should be replaced is a question that has been of much interest since fertilizers first became widely available in the middle of the 19th century. Is there a natural fertility level and an associated critical organic matter content for a given site, below which problems of soil management and reduced yield become unacceptable. There is not yet a straight answer.

Soil fertility studies – Major landmarks

The soil is a resource (capital) for which there is no substitute. Fertilizers are not a substitute for part or whole of soil fertility. Crop production essentially relied upon traditional practices of soil, water and energy management with no adverse effects on the health of the plant soil and environment, except for sporadic natural calamities. In the studies over centuries on fertility status and variations from 1843 to 2000, six major landmarks (milestones) in our journey are recognized as under:

(1) Lawes and Gilbert – Start of long-term agro-ecosystem (LTAE) experiments at Rothamsted, UK, 1843; mineral nutrition theory of crops by Liebig; Jordan soil fertility at Pennsylvania and Ohio experiment station, 1882; field experiments of Illinois, 1876; permanent manurial experiments of India at Coimbatore, 1912.
(2) Soil as a living system – Biocycling of nutrients; organic matter decomposition C/N ratio of organic matter; compost preparation (Lipman, USA and B. Viswanath, India).
(3) Industrial agriculture – Development of water sources and fertilizer; cereal yield revolution; rapid replacement of traditional practices (industrial farming of the US).
(4) Regenerative agriculture of Rodale at Emass, 1947 (organic farming concepts); soil breeding concept of J. Hutchinson; use of fertilizers in India from 62,000 tons in 1952 reached about 18 million tons by 2000. First enunciation of four factors of integration, viz. nutrient level, water, variety and skill of the farmer in making use of fertility improvement, but with a sense of conservation of resources.
(5) Concept and indicators of soil health – Monitoring soil quality with measurable indicators.
(6) Concept of ecosystem and ecological services – Management of AES and gradual spread of alternative agriculture. Introduction of eco-technologies to relieve yield fatigue of the green revolution in India[7].

The aspects of study of LTAE are (i) crop production, (ii) nutrient cycling and (iii) environmental impacts on agriculture. They provide a resource for evaluating biological, bio-geochemical and environmental dimensions of agricultural sustainability. The changes in the role of LTAE over time relates to productivity (1840 to 1900) followed by sustainability (1920 to 1990) and environmental impact (1962 to 2000) to change in species adaptation from 1900 and finally culminating into unknown opportunities for the future from 2000 (ref. 8). It is necessary to compare tropical and temperate farming systems as they differ widely in nearly all recognized parameters governing agricultural production. Developing countries need such research centres. An international network to coordinate data collection might facilitate more precise prediction of agro-systems sustainability.

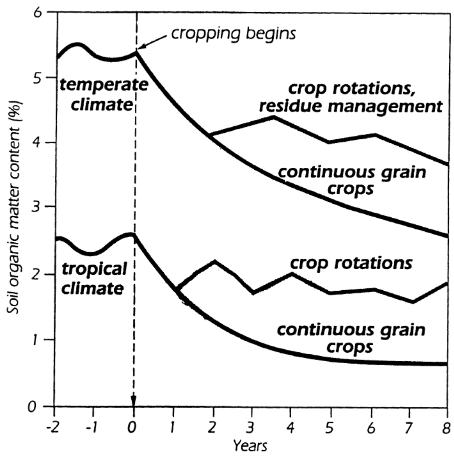

Figure 1. Decline of soil organic matter with crop cultivation (Courtesy: *Soil-Enriching the Earth*, MIT Press).

Monitoring soil fertility in the UK, India and USA

John Russel (1940) reviewed 97 years' results of the long-term experiments started by Lawes and Gilbert (1843) on wheat to study the merits of organic and mineral fertilizers on yield and quality. A summary of the report revealed (i) average yields are approximately the same for both, (ii) seasonal fluctuations in yield are smaller on the farmyard manure (FYM) plots than in mineral fertilizers alone, (iii) deterioration of yield with time is slightly lower with FYM plots than mineral fertilizer plots, and (iv) no significant differences were observed in the baking quality or nutritive value of wheat from the differently manured plots.

At the start of the experiment in 1843, issues like sustainability, environmental quality and species adaptation to impact of biotic and abiotic stresses were not envisioned. During the past six decades (1930 to 1990) some changes were made in the experiments and the data examined at 20–50-year intervals were to be of immense help to the revised objects being clarified.

Earliest work in India refers to classical investigations of McCarrison[9] which brought clear-cut evidence in three vital directions: (i) The yield of a pure strain of seed is capable of being influenced by soil conditions and treatment and third acquired character may continue perhaps to a less degree into the next generation. (ii) Grains grown with cattle manure possessed better nutritive value than the crops grown with chemical fertilizers or with no manure and those grown with chemical fertilizers were superior to those grown in soil without manure. (iii) The digestive coefficients of herbage varied with the nature of manuring – 74% for that grown with cattle manure, 70% for mineral fertilizer, 62% with no manure. By 1937, in his presidential address, at the 24th Indian Science Congress, Hyderabad, Viswanath[10] observed that if we neglect organic manure and fail to build up the humus content of the soil, we shall be doing four things; Firstly, we shall not be able to maintain the fertility of the soil. Secondly, we shall not be using artificial fertilizers to the best advantage. Thirdly, we shall be failing to keep up the inherent cropping power of our improved seed and run counter to the good work of the plant breeder. Fourthly, we shall be producing food deficient in nutritive value. The essence of all the four is an essential component of the eco-technological package. Such practice increased grain yields in Europe by 7% over mineral fertilizers alone.

The permanent manurial experiments (old and new series) at Coimbatore in 1912, established a judicious combination of organic and inorganic fertilizers recommended for increase in yield, improvement in quality of crops, and physical and chemical and microbiological properties of the soils[11]. As environmental health issues were a threat to energy-intensive agriculture, the change to alternative agriculture in USA for yields and sustainability, is the last landmark in soil fertility development. Carbon input (through all known inputs and practices) was shown to be critical for the long-term maintenance of both soil organic matter and soil fertility. Increased carbon sequestration in soil organic matter is a possible sink for excess CO_2 and therefore a means of ameliorating climate change. Modern techniques, carbon dating and isotope discrimination techniques facilitated to monitor the changes of organic N and carbon over time. For India, the strategy to make agriculture economical and efficient, with distributive justice for farmers and consumers, is the eco-technological approach. The technological empowerment of the resource poor is an integrated process, involving the identification of technologies that are environmentally compatible, economically viable and socially equitable; testing and adapting them to specific socio-economic conditions of the participants. Operationally, a mix of enterprises appropriate to the resource endowments of the area are identified and the resource poor are enabled to translate them into income and employment-generating activities.

As early as 1970, the US realized that all the earlier excellence of agriculture had come with erosion of precious but finite natural resources. The environmental problems of loss of biodiversity, increased pollution due to economic activity and dwindling yields of food crops convinced that agricultural developments as in the past cannot be relied upon for the future, unless some drastic changes in the utilization of natural resources and energy are made with no harm to environmental issues that are growing exponentially. Hence, the report of the National Academy of Sciences, USA[12] was compelling to change agriculture of the past on the basis of strengthening research base. That is exactly the alternative agriculture firmly based on enhancing productivity of land, labour, and rising the use efficiency of inputs with no harm to the environmental quality.

Lessons learnt – Reward without risks

In the achievement of unprecedented crop yields, many agricultural scientists overlooked the need for long-term sustainability and their obsession with short-term gains caused enormous environmental and social distress. The need for sustainable balance between the real human needs and the limitations of the earth assumed all importance.

Neglecting internal resources (legumes in crop rotation and biological nitrogen fixation) diminished their strength and vitality and disturbed the economy of grain production. Talent and technology of the developed world must work with the germplasm-holders of developing countries where biodiversity is shrinking fast. No technology could ever double the cultivated area expansion or overtake the rate of population growth. The idea that human technology of the MNC's in particular will substitute for the services provided by nature is based on utter ignorance of biophysical realities.

Mobile soil health service at the farmer's door

In the early nineties, a project of integrated advisory work at the farmer's field level, with the sole objective of raising soil quality for higher crop productivity was initiated in 1994 in the environs of Chennai. Extension officers were first offered an orientation programme followed by farmers' training in the village. The farmers were assured that over a period of time the soil productivity would be upgraded with the adoption of such cultural practices wherein the traditional blend with modern advances. No prejudice for the use of fertilizer of the right kind, level and method of application is essential. Soil samples will be drawn from chosen fields of farmers and they will be examined in the field and a few at the laboratory. Data were recorded on a specially designed form – the soil health card (see Box 1) given to each farmer, and periodically a dialogue with the farmer at his own field provided answers to all the questions raised. That would educate the farmers about the quality of the soil and how effectively it would act to raise productivity. The farmers' response and their keen desire to cooperate was more than expected, as farmers at the outset were assured that it is not a short-term magic, but a long-term struggle with rewarding results. After a couple of years, the farmers felt that the soil health card is a passport to be on the path of prosperity to raise productivity economically.

In the five decades of the past century, agriculture has not turned out as the farmers and technologists wished. When tradition is erased, greed replaced need, arrogance defied humility, tillers' profit usurped by those who harvest without sowing as a way of life without limits, both means and ends are unjust, then, agricultural production ran aground for poverty to balloon and wealth was concentrated in few hands while individual prosperity eclipsed community's overall living standards. Civil unrest, cold wars, crime and corruption are rampant and honesty sterilized – above all the absence of a stable government of reasonable interest in the poor of the rural areas is not in sight for decades to come. Finally any type of violence suffocates opportunities made available at heavy costs. Crop yields are known to swing between the technological thrusts and threats. A chronological sequence of scientific advances in crop improvement between pure line selection (1930) and current biotechnological efforts (2010) yield rise from 2.0 to 12.0 tons per hectare was projected by Kush[13]. The requirements to this end are enhancement of soil quality, upgradation of use efficiency of fertilizer, water and energy, reduction of losses from pest, disease and weed, including storage and distribution. Any attempt towards this end without total support of policy makers is as formidable as can be imagined. But the single source of stout optimism which was the ability of the nation in (1965–75) the early years of green revolution when the HYV technology was demonstrated right on the farmer's fields, resulting in yields on an average of 4.0 t/ha stood at only 1.8 by 2000. The reason that external subsidization was large enough to destroy social relationships and break nutrient cycles was dispensed to depend only on intensified external input. For the same reason the much praised and touted industrial agriculture of the developed world turned out to be unsustainable. In a study of three types of rice cultivation, pre-industrial, semi-industrial and fully industrial, their respective efficiencies were good, medium and very poor[14]. The remedy is to reduce chemicalization of agriculture, remove the subsidies for fertilizer, water and energy and set the goal as economic maximization of yield. The side effect of this would be improvement of environmental quality (Table 4).

By 2025, an estimated recovery of 25 ml/t is possible, it would add to the current harvest of 200 ml/t that meets the demand of the population of 1300 ml by 2025 and per capita entitlement of 480 g/per day.

Fertilizer science and business

The importance of fertilizer use for foodgrain production all over the world was accepted and executed with unprecedented success, with no opposition from any quarter for about fifty years of the past century. Manure and fertilizer are complementary but not competitive, and fertilizer is deemed not a substitute to manure, where manure is available. As organic farming is on the increase and as traditional practices have come back with vigour in the developed world, fertilizer usage suffered significantly. The food problem improved to cause no anxiety and the fertilizer response even to increased levels was too feeble, with no profit to the farmer. Nil or negative fertilizer use is no longer the trump card to determine production excellence. Even in countries like India and China, the concern relates to fall in use efficiency, problems arising from overuse, or under-use. Today's farming is no longer profitable to continue to invest and prosper as in the past with fertilizers. Some obvious experiences in India are illustrated below.

(1) The essentiality of mineral fertilizers for crop production in India was recognized as early as 1937, but with a caution that it must be blended with at least a third of organic manure to derive the synergetic benefits of efficiency and economy; but it was quietly ignored.

Table 4. Locked-up yield potential of foodgrain production (ml/t), 2000

Regional imbalance (N, S, E and W)	25 to 30
Soil healthcare and correction of agronomic deficiencies	50 to 55
Enhanced use efficiency of fertilizer, water and energy	35 to 45
Improvement of assured areas of irrigation	30 to 35
Better management of rainfed areas	30 to 40
Losses from pest, disease, weed and storage	50 to 55
Storage and distribution	15 to 25
Total	235 to 255

(From ref. 15).

Combinations of N, P and K with FYM or compost, could contribute 20% of the total production[16].

(2) Regarding fertilizer use, India's grave blunder in increasing the levels without being ensured of the use efficiency led to yield fatigue. In global ranking for fertilizer consumption India ranks third for nitrogen and phosphate, but in crop yields for rice and wheat ranks 14 and 16, respectively. Levels of fertilizer use in India by 1990 on a district basis need pruning and redistribution as set out in Table 5. The higher levels of the two categories, viz. above 200, and 200 to 150 may be deleted and the fertilizer so saved could be used in areas of assured rainfall to benefit from higher yields.

(3) Impressive land-saving benefits of the green revolution for USA, China and India, of 70, 150 and 75 ml/ha, respectively by 1992 (ref. 17) could not be sustained by 2000. For India in particular, the per capita grain area dropped from 0.21 ha (1950) to 0.1 ha (2000). Absence

Box 1. Soil health card

Name and address of the farmer | Survey No. | Farm area:

Rainfed/irrigated

1. Texture	Structure	EC (milli mhos)	pH	Depth

2. Colour	Bulk density/true density	WHC	Permeability (drainage) H M L

3. Organic carbon	Available P and K	Micro nutrients status

4. Acid/alkaline	Shallow depth	Water logging	Water Availability	Water Quality

5. Productivity (kg/ha)	High	Medium	Poor
Cereals			
Cotton			
Legumes			
Sugarcane			

6. Soil microflora–fauna	Nitrifying capacity	Earthworms	Algae

7. Rating	A (85–100)	B (60–85)	C (below 60)

Soil health, in terms of essential characteristics and nutrient status, is important for achieving food security. A. Sankaram explains the system of monitoring the soil quality and offers farmers a passport for guidance in soil and crop management. This is a maiden exercise in the country, initiated by the M.S. Swaminathan Research Foundation and actively put into field practice by the Government in Chingleput district. (Courtesy: *The Hindu*, 18 September 1994).

of suitable land for expansion and marginal lands to be brought under the plough being too expensive, since 2000 the strategy to raise productivity of land already under cultivation, as economically as possible with no harm to the environment on a sustainable basis is under promotion.

(4) According to experiments on nitrogen levels (75, 150 and 300 kg/N/ha) in wheat for nitrogen use efficiency, 75 N was higher than for 150 and 300 (Table 6)[18].

(5) Thus in 1981, the use efficiency for 75 N was 60 kg wheat for kg N and lowest 55 for the year 1960. Experiments at ICRISAT (Hyderabad) over a decade (1983–93), by returning the crop residues to the soil and addition of a small dose of fertilizer showed that crop yields climbed from 1.6 t/ha (1983) to 6.0 t/ha (1993), while fertilizer alone recorded only 1.2 t/ha (Report, ICRISAT, Hyderabad, 1997).

(6) Maximum fertilizer use efficiency would be achieved by optimal utilization of indigenous (soil) nitrogen supply and applied fertilizer under proper crop management. Studies reported based on research at five locations, (Vietnam, Thailand, Indonesia, the Philippines and India) indicate that the use efficiency of fertilizer N added would be influenced by the inherent soil fertility. For this reason traditional practices that enhance inherent soil fertility such as crop rotation, legumes as inter crops, green manuring and compost application assume importance in agronomy[19].

Product patterns

If the need for too many varieties of rice was a hindrance for growth in 1965, the myriad of complex fertilizers, NPK, with nearly 50% of inert filler (concealed adulteration) is the enemy to productivity of grains since 1975 for India. To promote the complexes as 'suitable' for all crops grown all over India is unscientific and subsidization carries no justification.

As nitrogen is required from tillering to flowering, two splits of the fertilizer N is more responsive to production than a single dose prior to planting. But phosphate must be applied prior to planting in one dose, as the nutrient is needed at the start and it has the ability to spread over the needed areas. Potash may be applied at any stage prior to flowering. For this reason, single-nutrient materials are more favoured. Hence a complex of the three nutrients NPK is neither economical nor efficient. This is justified as experiments recorded reveal that: (i) Rice yields of Punjab over 96–97 were as low as 3.4 t/ha, while during 1965 (complexes were absent) the use of single nutrients gave 4.32 t/ha (ref. 20). (ii) In national demonstrations by ICAR, (1975 to 85) on the farmer's field, rice harvests ranged from 4.5 t/ha as the minimum and 5.2 t/ha as the maximum[21]. (iii) In 1985 at the Andhra Pradesh Agricultural University, Hyderabad, with the use of single-nutrient fertilizers, urea super granules, single super phosphate and muriate of potash for only 56 kg/N level, the rice yield was 5.2 t/ha. At 112 kg level, the yield moved up to only 5.68 t/ha with use efficiency of 25 (Table 7). Doubling the level of N gave only 0.48 tonnes. This underlines the fact that overuse carries no pay-off. Despite experimental evidence, the results were discarded and totally unscientific and unwarranted NPK complexes were promoted[22].

In the last few years, the yield fatigue and absence of response to higher levels of fertilizers clearly justify that unless product pattern, choice of level, time and method of application are altered on the basis of results of field experiments, fertilizer use would add to production costs and environmental degradation, with farmers and consumers as the victims.

In rice culture, the results of studies by the International Network on soil fertility where 22 countries and 50 scientists collaborated recommended: (i) Sulphur-coated urea (SCU) and urea super granules (USG) through deep placement out-performed the best split application of

Table 5. Classification of districts according to NPK consumption (kg/ha)

Range	> 200	200–150	150–100	100–50	75–50	50–75	Total number
As on 1995	6	26	53	85	–	95	265 (as per FAI)
According to need	–	–	48	120 (100 to 75)	100	80	348

Fertilizer Statistics 1995–96, FAI, New Delhi.

Table 6. Levels of N and use efficiency on traditional and improved varieties of wheat

Level N/kg ha	1950	1960	1962	1966	1970	1973	1979	1981	1985
75	45	58	60	62	63	63	63	70	70
150	25	35	35	36	36	28	35	37	36
300	10	17	18	18	18	18	20	20	20

Data for each year denote use efficiency as kg wheat per kg N (ref. 18). Data for 1950 refer to old variety and for the rest, improved varieties.

prilled urea (PU) at 24 centers in seven countries. (ii) To produce one ton of extra rice per hectare, from the use of SCU or SGU, 50% and 48% less urea is required, respectively, over the PU. (iii) Rainfed rice yield required 57% less and 62% less for SCU and SGU, respectively than PU. (iv) Ammonia volatilization was higher with urea broadcast than deep placement[23].

Integrated nutrient management

Published literature on the merits of integrated nutrient management repeated with emphasis since 1980 to date with no one to doubt its merits. It is an endeavour to blend ecology and economy in a cost–benefit framework. It takes systematic and simultaneous account of the environmental aspects, the quality of the produce and the profitability of the farm[24]. The Indian situation presented[22] is more than convincing that to practice integrated nutrient management is more than impossible as long as the complex NPK is worshipped in India. That India should abandon blanket recommendations for crops individually and a systems approach for the entire cropping system is repeatedly underlined, but the response was poor. The current experience of steep drop in use efficiency and yield fatigue is the result of misuse and abuse of the fertilizer, as elaborated: (i) the product patterns, blend with organics levels of use, time and method of application are an utter mismatch to soil–crop–climate complex of different regions and cropping patterns. The data presented in Table 8 of the widely different characteristics of the three major nutrients as a complex cannot guarantee release of each nutrient according to crop needs. (ii) All the factors of production act in a complex interconnected manner for symbiosis and synergetic benefits. For this reason a single input however excellent it might be, is ineffective. The interaction of twelve factors with seven inputs and the benefits derived are presented in Table 9, that underline the supreme influence of cooperation between industry and agriculture, and the government policies that influence the efforts of the farmer and the industry. A holistic approach in association with nature is necessary, where the intensity of all practices lies within the carrying capacity. To regain traditional practices is a problem and to blend with recent advances is neither free nor fair, under patent rights which Third World farmers (increasing in numbers and decreasing in size) can ill-afford.

Table 7. Fertilizer use efficiency in relation to level, product pattern time and method of application of urea super granules (rice, 1986)

Treatment	N level (kg/ha)	Rice yield (kg/ha)	Response (kg/grain/kg N)
Urea all basal	56	4667	15.7
Urea all basal	112	5449	14.6
Urea in three splits	56	5217	25.5
Urea in three splits	112	5687	17.0

Soil fertility studies 1986 under the aegis of IFFCO at APAU, Hyderabad.

Approach and practices for the 21st century

For the chronology of soil fertility studies, the 21st century represents the seventh milestone – soil productivity through ecosystem management. That is the integrated approach to achieve the health of soil–plant–environment on a sustainable basis. This is not only distinct from the green revolution, physico-chemical paradigm, but also from organic agriculture', in that it does not accept petrochemically-driven inputs but emphasizes on the efficiency of their minimum use. The green revolution failed as the strategy that high output needs high input was extended beyond reasonable limits despite loss in use efficiency, to end up with loss in yields and profits.

Table 8. Some properties of major plant nutrients

Property	Nitrogen (N)	Phosphate (P)	Potash (K)
Energy required to manufacture, transport and apply 1 kg (ml Joules)	60 to 80	10 to 20	5 to 10
Dry matter productivity as grams per gram of nutrient absorbed	Rice 40 Potato 47	Rice 205 Potato 320	Rice 44 Potato 33
Nutrient removal (kg/t) rough rice	Rice 65	Rice 67	Rice 11
Nutrient in the grain (% of the absorbed nutrient)	Wheat 61	Wheat 70	Wheat 9
Residual value	Nil	Two successive crops	Low
Luxury consumption	Yes	No	Poor
Function	Vegetative growth	Root development and seed formation	Translocating photosynthate
Time of need	From 21 days growth to flowering	Largely in the early stages	Flowering to seed formation
Final residue	Grain and straw	Largely in seeds	90% in straw
Harvest index (%)	75	60	90

(From ref. 25).

Increasing external subsidization destroyed the essential soil properties of resilient native soil fertility. Traditional farming systems appreciate sustainability on two counts: the irreversible 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.

Disputes on the use of fertilizers to world agriculture and India and China in particular, are untenable. 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[27]. 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 three major nutrients (NPK) would economically tap the untapped potentials. Environmental issues such as 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 core objectives undisturbed, into eco-technologies – a blend of tradition and modernity. 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. Over entire Europe, integrated nutrient management is deemed a real alternative for European agriculture, compared to conventional high input systems and organic low input farming[27]. Without integrated nutrient management and absence of traditional practice (crop rotation, mixed and intercropping and cropping patterns) soil fertility improvement on a sustainable basis is a calamity and the failure of all genetic and breeding efforts is a reality. The conversion of conventional to sustainable agriculture carries three components (i) increase efficiency, (ii) substitute synthetic nitrogen fertilizers to organic sources, pesticides by biological control agents, mould board plow to zero or feeble tillage, (iii) redesign for external inputs substitution to internal management approaches for farming to be ecologically and economically diverse and more self-reliant. A full treatise on this aspect may be seen in the review by MacRae *et al.*[28]. Management of crop residues as a reliable source of promoting soil fertility and importance of green manuring for development of SOM have been presented[29]. It would be appropriate to mention here that a caveat of signi-

Table 9. Influence of factors on crop productivity

Factor	Land	Plant	Water	Fertilizer	Energy	Plant protection	Economy
Land reclamation for alkalinity, acidity and salinity	+	+					+
Crop rotation, inter, mixed cropping systems	+	+				+	+
Crop residues, rural and urban composts, bio solids	+			+		+	+
Minimum or no tillage, soil drainage	+	+	+		+		+
Blend of organic manure and inorganic fertilizer	+			+			+
Annual repair for dams, desilting irrigation channels	+		+	+			+
Wind, solar, hydro and bio (human and animal) energy		+			+		+
Advance preparation for climate change				+	+	+	+
Breeding technologies for yield promotion LAI, HI and hybrid vigour, C3 and C4 photosynthesis	+	+			+	+	+
Research programme with farmer's participation	+	+	+	+	+	+	+
Harmony between industry and agriculture for development	+	+	+	+	+	+	+
Govt. policy perceptions in favour of farmer, industry, people	+	+	+	+	+	+	+

+, Positive effect; LAI, leaf area index; HI, harvest index.

ficance about the fertilizer technology itself was on record as early 1977 and to quote 'Without major improvements in fertilizer tailored specifically to tropical and subtropical conditions and technology better (suited) adapted to conditions in the developing country, it is doubtful whether the Third World will achieve the goals and benefits it has set for itself under the Lima declaration'[30]. India ignored this to its peril. Though late, it would be better if this is taken into account in product patterns, levels, and time and method of application that would save the fertilizer use and enhance the crop yields which otherwise would remain the same.

India needs more sustainability for agriculture, not just more fertilizers, or total organic approaches, but a blend of both. Other techniques include water harvesting, zero tillage, legume crop rotation, compost, mulches and crop livestock systems. Crop production security must first establish soil–plant–environment health. With bio-economic pressures (population and economic activity), demands placed on the earth's natural resources and ecological services are growing exponentially. Both developed and developing countries are suffering, the former for food safety and obesity and the latter for food out of economic reach. In our endeavour to follow that response to fertilizer would be linear at all levels, we lost much of our productivity of the green revolution.

The AES is increasingly pressurized from bio-economic activity over the recent years. A change in the management of the ecosystem (1970 to 90) is the green revolution of Asia in general, especially in India and China. Yet the fatigue of the green revolution for crop yields and environmental problems is the result of utter disregard to ecological principles and total abuse of inputs management. Towards the end of the century, a change from conventional to eco technological is under active promotion. In short, it is based on the care of the 'soil–plant–environment health' presented in this paper.

In monitoring the impacts of these practices, a variety of biological, physical, chemical, landscape and economic measures are being used as indicators of environmental change. Of the twenty-one indicators identified by Meyer *et al.*[31] only six were selected as most important. Soil organic matter is the most critical, which was extensively presented by Smith *et al.*[32] and needs further study. It adequately supports the current endeavour to search for all the traditional practices, to be the basic foundation of agricultural practices to build and maintain soil organic matter at desired levels. Even if it were to be universally adopted and assiduously practiced, no single approach or technology can make a decisive difference. The principles of AES management, relate to technologies that are economically viable, ecologically sound, environmentally compatible and socially equitable. A devotional practice of these would ensure income and employment by generating production methodology to confer the much-needed purchasing capacity to landless poor of the rural areas. However an achievement lies entirely with the policy-makers in the process of reconciliation of issues involved in the functioning of demography, development and democracy, where crop production management decisions are in the company of farmers and not within the closed doors without the farmers, as in the past.

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