Indian Journal of Agronomy **65** (2): 131—143 (June 2020)

Review Paper

Sustainability concern in Indian agriculture: needs science-led innovation and structural reforms

P.K. GHOSH[1], C.P. NATH[2], K.K. HAZRA[3], PRABHAT KUMAR[4], ANUP DAS[5] AND K.G. MANDAL[6]

National Agricultural Higher Education Project, Krishi Anusandhan Bhavan II, Pusa, New Delhi 110 012

Received: June 2018; Revised accepted: June 2020

ABSTRACT

Agriculture in India is facing several challenges which together are manifested into the sustainability issues. The broad contours of the agricultural production system in the country have been defined by the need to achieve food security which calls for close attention to rice–wheat (*Triticum aestivum* L.) cropping system of the Indo-Gangetic Plains (IGP) whose sustainability is under threat. Degradation of natural resources, severe biotic and abiotic stresses specially drought, floods, pest infestations with accompanying impacts on biodiversity and agricultural productivity are the major constraints to agricultural development. Further, climate change has gained significant global attention over the past decade due to concerns of deleterious long-term impacts on agriculture, water supply, human welfare, regional and political stability. All the related issues need to be addressed on priority, with particular emphasis on soil-carbon through a holistic approach. As the strategy brings focus on income of farmers, the agricultural technology needs to move from "Production oriented-Green Revolution" to "Farmer's Income oriented-Revolution" and environmentally sustainable farming. Therefore, for long-term sustainability in agriculture, 4 pillars/ components (good agricultural practices, climate-change mitigation and adaptation, diversification of high-value crops and biodiversity management) needs to be addressed properly, more importantly good agricultural practices (GAP). The GAPs are based on the principles of risk prevention, risk analysis, sustainable agriculture, and integrated crop management (ICM), which are of utmost importance in present time. The GAPs for agricultural sustainability are reduced tillage, conservation agriculture, resource-conservation technologies (RCTs), erosion-control measures, diversified cropping system, micro-irrigation, balanced fertilization, manuring, watershed management, organic farming, and integrated farming systems etc. Now that the vision is to impart income security to the farmers of the country, diversification of the system across all the sub-sectors of agriculture assumes importance which is, indeed a de-risking mechanism capable of negotiating both endogenous and exogenous risks associated with the system. The effective and efficient management of agro-biodiversity is also essential through management of genebanks, science-led innovations; livelihood, food and nutrition security though crop diversification, use of lesser-known crops and wild relatives in crop improvement; dealing appropriately with quarantine, bio-safety and bio-security.

Key words: Agro-biodiviersity, Carbon sequestration, Climate change, Conservation agriculture, Good agricultural practices, Government policy, Land degradation, Resource-conservation technologies

Sustainability concerns

The major challenges encountered by the Indian agriculture are due to agro-climatic/ environmental, social and economic dimensions. Green Revolution has changed the traditional pattern of cropping which was important for efficiency, productivity and sustainability of agro-ecosystems. In the decade of 2000, even with the best possible efforts, sustainability is in question in many production systems. It is unfortunate that ever since Independence, especially after 1960's, the emphasis in Indian agriculture has been more on exploitation of natural resources of land and water and less on improving, restoring, reclaiming and enhancing their productivity and sustainability (Ladha *et al*., 2003). Degradation of natural resources has direct consequences not only on productivity but also on the ability of the farm to withstand biotic and abiotic stresses. Pres-

[1]**Corresponding authors Email**: pkgiipr@gmail.com; [2]cpnath4@gmail.com
[1,4]National Coordinator, NAHEP, Krishi Anusandhan Bhawan II, New Delhi 110 012; [3]Scientist (Agronomy), ICAR-Indian Institute of Pulses Research, Kanpur, Uttar Pradsh 208 024; [5]Principal Scientist and Head, ICAR-Research Complex for NEH Region, Umiam, Meghalaya 793 103; [6]ICAR-Indian Institute of Water Management, Bhubaneswar, Odisha 751 023

ently, critical challenges are to feed the escalating human population under increasingly declining soil quality and changing climatic conditions. Moreover, natural resources, viz. land and water, are under severe pressure in India. It supports 18% of the human and 15% of livestock population of the world on only 2.2% of the world geographical area, 4.2% of freshwater resources, 1% of forest area and 0.5% of pasture land; where only 46% of the land is cultivable. The per capita availability of forest supplementing livelihood in India is only 0.08 ha against the world average of 0.8 ha. In addition, productive farmlands in India are under constant threat from various forms of land degradation and loss of productivity (Nath *et al*., 2017a). The utilizable surface water resource is estimated to reduce by 7% due to deforestation and soil erosion, while the loss due to water pollution is put up at 20% (IEG, 2000). Loss of soil organic carbon (SOC) and fertility, soil erosion, dwindling biodiversity, desertification, pesticide pollution, emerging pest resistance, pressing climate change, and rising food prices etc. are the major consequences of degradation of natural resources (Srivastava *et al*., 2016).

Considering the increasing population and limited availability of natural resources, agricultural productivity needs to continuously increase to meet the growing demand for food, fibre, and fuel. It is therefore, imperative to adopt a perspective plan that takes care of sustainability and anticipated impact of climate. Such systems aim to produce food that is both nutritious and without products that might harm human health. In this review article, various agents of degradation of natural resources, viz. land degradation, deterioration of soil health, water scarcity, soil-water-air pollution, deforestation, climate change, loss of biodiversity, their consequences on food security and sustainability as well as strategies to adopt for future sustainability are discussed in details.

Multiple concerns of agricultural sustainability

Land degradation

A large chunk of lands in India suffers from varying degrees and types of degradation stemming mainly from unstable use and inappropriate management practices. In India, the estimates of land degradation by different agencies vary widely from about 53 million ha to 188 million ha, which is attributed mainly to different approaches and methodologies adopted in defining degraded lands and/or differentiating criteria used. These data sets have now been harmonized to obtain a value of degraded land of 120.7 million ha. The analysis of changes in land-use pattern reveals that barren and uncultivable land has been reduced by about 54%, fallow land other than current fallow by 38.5%, while the current fallow has gone up by about 33%. However, since 1980–81, the area under current fallow is almost stable at around 4.8% of the reporting area (Sharma and Bhushan, 2001). The availability of per capita net sown area has reduced from 0.33 ha in 1951 to 0.14 ha in 2001 and is expected to decline further to 0.09 ha by 2050. A minimum economic holding size of 2 ha of un-irrigated land and 1 ha of irrigated land has been suggested in India for sustaining a family of 5 or 6 persons.

The land degradation has both on-site and off-site effects. On-site effects include lowering of productive capacity causing either reduced outputs or need for increased inputs. Off-site effects of water erosion occur because of the deterioration in water quality, river sedimentation, biodiversity loss, and natural calamities. The irrigated agriculture, especially through canal systems, has resulted in land degradation at many places due to the twin problems of waterlogging and salinization. It is estimated that nearly 8.4 m ha of the irrigated lands are affected by soil salinity and alkalinity, of which about 5.5 m ha is waterlogged (IDNP, 2002). A decline in soil productivity, particularly of organic C and nitrogen (N), deterioration in soil physical characteristics, and decreasing water availability are identified as the causes of this slowdown in productivity. About 29.4 m ha of our soils are experiencing decline in fertility with a net negative balance of 8–10 nutrients per annum, which is likely to increase in future. The current estimated average depletion per ha is about 16 kg N, 11 kg P_2O_5 and 42 kg K_2O. Besides, continuous mining of secondary and micro-nutrients has depleted nutrient reserves of soil. With negative nutrient balance, the deficiencies may become more widespread and acute, leading to further decline in fertilizer-use efficiency (Bhatia *et al*., 2004). It is evaluated that 5,334 mt of soil is lost yearly which works out to 16.35 t/ha, of which 29% is lost forever to the ocean, 10% gets deposited in ocean, and the rest 61% is dislodged starting with one place then onto the next or re-circulated. Pesticides and heavy metals diminish soil respiration, microbial activity, soil chemical action, restrain significant soil procedures; for example, ammonification and nitrification, decrease earthworm dominance, and smother algal activity. These possibly unsafe substances may accumulate in soil and cause long-term consequences for yield and quality, and may harm soil micro flora. Through food and feed, they may likewise get into human and domesticated animals and cause health hazard, if accumulation exceeds acceptable levels.

Water and its availability

The utilizable surface-water resource is estimated to reduce by 7% due to deforestation and soil erosion, while the loss due to water pollution is put at 20% (IEG, 2000). Hence, there is an urgent need to preserve and maintain the water quality of surface and ground water resources for production and other purposes. It is estimated that by 2050 about 22% of the geographical area and 17% of the population would be under absolute water scarcity (< 500 m^3/capita/year). Paradigm changes would be required in water resources development and management to avert such worst scenario. The average annual precipitation over India including snowfall of about 1,160 mm, which corresponds to about 4,000 billion cubic meters (BCM) of water. Of this, about 1,869 BCM is the annual runoff that appears as average annual potential flow in rivers. Because of various constraints in harnessing water from river flows, only about 1,122 BCM of the potential runoff of 1,869 BCM, is considered utilizable, which corresponds to a per capita availability in 2005 of only 1,023 BCM (Sharma and Bhushan, 2001). The problem of the falling groundwater table in central Punjab, where rice is a predominant crop, is because of the overdraft of water. A holistic strategy is required to overcome the water crisis, which includes crop diversification, delayed transplanting of rice, and adoption of water-saving agronomic practices etc.

Depletion of soil organic carbon

In most Indian soils, soil organic carbon (SOC) content is low but it is also dynamic in nature. Farming practices affect both quantity and quality of organic matter. In India, nearly 3.7 m ha is deteriorated due to depletion of SOC. These areas are widely distributed across the country, ranging from cultivated areas of subtropical belt to the areas under shifting cultivation. Especially in high-intensive cultivated areas of rice–wheat cropping system (RWCS) in IGPs, this problem of soil-health fatigue has been already observed in number of case studies. In the major rice–wheat regions of north-western India, SOC has decreased from 0.5% in 1960s to present level of 0.2% (Table 1) (Bhattacharyya *et al*., 2013). The removal or *in-situ* burning of crop residues, no or least addition of organic manures, and intensive cultivation are major reasons for depletion of SOC. Conservation efficient measures are required to arrest the degradation process and to restore productivity of degraded soils, so that more food could be produced to provide livelihood and environmental security to the increasing Indian population.

The carbon (C) stores in arid and semi-arid lands show a high temporal and spatial variability, some parts acting as C sources and others as C sinks. A decline in SOC content is a common phenomenon when land use changes from natural vegetation to cropping, reasons being reduction in C inputs, increased rate of decomposition due to mechanical disturbance of the soil, higher soil temperatures due to exposure of the soil surface, more frequent wetting and drying cycles and increased loss of surface soil rich in organic matter through erosion. Lal (2003) estimated that,

Table 1. Soil organic carbon content in 0–30 cm soil depth in different agro-climatic zone of India

Agro-climatic zones (ACZ)	Soil organic carbon (%) in 0–30 cm
Western Himalaya Zone (ACZ 1)	0.67
Eastern Himalaya Zone (ACZ 2)	1.88
Lower Gangetic Plains (ACZ 3)	0.47
Middle Gangetic Plains (ACZ 4)	0.18
Upper Gangetic Plains (ACZ 5)	0.78
Trans Gangetic Plains (ACZ 6)	0.27
Eastern plateau and hills regions (ACZ 7)	0.42
Central plateau and hills regions (ACZ 8)	0.52
Western plateau and hills regions (ACZ 9)	0.49
Southern plateau and hills regions (ACZ 10)	1.22
East coast and plains and hills (ACZ 11)	1.15
West coast plains and ghat regions (ACZ 12)	1.77
Gujarat plains and hills (ACZ 13)	0.63
Western dry (ACZ 14)	0.20
Island (ACZ 15)	6.14

Source: Bhattacharyya *et al*. (2013)

India has potential of 7 to 10 Tg C/year through restoration of degraded soils, 5 to 7 Tg C/year through control of erosion, 6 to 7 Tg C/year through good agricultural practices.

Deforestation

As per the India State of Forest Report 2015, 24.1% (21.3% under forest cover and 2.8% under tree cover) of the total geographical area in the country is under forest/tree cover as against the target of 33%. Human activity has always modified the natural ecosystems in such a way that environment becomes more favourable for non-agricultural activities. Apart from diversion of forest area to non-forest activities like industries, infrastructure development and human habitation, unrestricted exploitation of timber as well as other wood products for commercial purposes, and slash and burn method of cultivation are major causes of forest degradation. The social consequences of deforestation are many. Due to deforestation, watersheds that once provided drinking water and irrigation water have now become unreliable due to extreme fluctuations in water flow (FSI, 2005). Another serious consequence of deforestation is the loss of biodiversity, i.e. the extinction of thousands of species and varieties of plants and animals. Global warming is another consequence of deforestation. Around 80% of India's annual rainfall comes from the Indian summer monsoon, spanning from June to September.

Loss of biodiversity

Agro-biodiversity is the backbone of a nation's food security and the basis of economic development as a whole. Over the years this diversity in India is under pressure due to the massive commercialization of agriculture leading to almost extinction of traditional farming systems. The top-down approach agricultural research has contributed to an over-reliability on relatively few plant varieties.The rapid and large-scale global extinction of species also caused loss of biodiversity. In the 20th century, it happened thousand times higher than the average rate during the preceding 65 million years. However, over-exploitation, habitat destruction, pollution and species extinction are major causes of bio-diversity loss in India. Other factors include fires, which adversely affect regeneration in some cases. Agricultural biodiversity is at risk from climate change (IPCC, 2007). Indian farmers grew more than 30,000 different varieties of rice before Green Revolution. Unfortunately, this enormous diversity has reduced over years during post-Green Revolution period. There has been a loss of several thousand rice varieties. Species and communities at particular and possibly critical risk include those with limited climatic ranges, limited dispersal ability and those with specialized habitat requirements (Upadhyay *et al*., 2008).

Climate change

Climate change is the most dominant environmental concerns to the decision-makers and planners. The carbon dioxide (CO_2) has the least global warming potential among major GHGs but due to its much higher concentration in the atmosphere, it is the major contributor towards global warming and climate change. Agriculture sector in India contributes 28% of the total GHGs emissions. The global average contributions from agriculture are only 13.5% (IPCC, 2007). The per capita release of GHG emission is 1.02 tonnes/year in India, whereas developed countries like the USA release 20.0 tonnes/year. To reduce the CO_2 concentration in atmosphere, C-sequestration has a critical role. Increasing soil C by 1 Pg through C sequestration is equivalent to reducing atmospheric CO_2 concentration by 0.47 ppm (Aggarwal *et al*., 2004).

The changes in temperature, precipitation, CO_2 concentration, changes in frequency of infestation by pests and diseases caused agriculture vulnerable (Mendelssohn, 2014). In the case of an annual crop, the duration between sowing and harvesting will shorten; crop may experience terminal heat stress. For example, the duration in harvest of a maize (*Zea mays* L.) crop could shorten between 1 and 4 weeks. The shortening of such a cycle could have an adverse effect on productivity. In India, impact of 1–2^{o}C increase in mean air temperature is expected to decrease rice yield by about 0.75 t/ha in efficient zones and 0.06 t/ha in coastal regions; and impact of 0.5^{o}C increase in winter temperature is projected to reduce wheat yields by 0.45 t/ha. Productivity loss of 4–6% in rice, 6% in wheat, 18% in maize, 2.5% in sorghum [*Sorghum bicolor* (L.) Moench], 2% in Indian mustard [*Brassica juncea* (L.) Czernj.] and 2.5% in potato (*Solanum tuberosum* L.) are projected (Naresh Kumar *et al*., 2012). The diversity and dominance of weeds and pests are likely to increase with climate change. Global warming is expected to have profound effects on Indian horticultural sector. Climate change alters the seed dormancy and germination of horticultural crops (Aggarwal *et al*., 2004). Higher temperature restricts the seed germination and also detrimental to the fruit setting in trees. In the case of thermo-sensitive crops like tea [*Camellia sinesis* (L.) Kuntze], coffee (*Coffea Arabica* L.), cardamom (*Electtaria cardamomum*), cocoa (*Theobroma cacao* L.), cashew (*Anacardium occidentale* L.) and black pepper (*Piper nigrum* L.), the projected increase of 2–3°C in temperature may directly affect the cropped area and productivity. Adverse climate exhibited considerable amount of physiological and yield variation in plantation and spices crops. Temperature-induced ethylene is one of the detrimental effect on fruit trees.

Agro-ecological constraints

Challenges in irrigated areas

Irrigated system occupies a unique place in Indian agriculture achieving nutritional security and production sustainability. Around 46% of the cultivated area is under assured irrigation. Irrigated productions systems in the country are mainly cereal dominated. With advancement in irrigation facilities in northern India, wheat, rice and maize are predominately growing. Since last 2–3 decades, fast declining water-table and factor productivity in rice–wheat cropping system (RWCS) of IGP are the examples of over-exploitation of natural resources. There is a need for shifting of cropping systems and/or production practices in accordance to the resource availability, particularly with soil characterization and water availability (Das *et al*., 2013). More than 80% of the water available in the country is being used in agriculture, of which two-thirds is allocated to rice cultivation. Diversification of rice-based cropping systems is the need of the hour by adopting pigeonpea[*Cajanus cajan* (L.) Millsp.]–wheat, maize–wheat, and inclusion of pulses.

Challenges in rainfed agriculture

The rainfed agriculture is totally dependent on south-west monsoon and thus, it is synonymous with risk due to erratic monsoon. A decrease of rainfall amounting to one standard deviation from the mean value often leads to a complete loss of the crop. Dry spells of 2 to 4 weeks during critical crop-growing stages cause partial or complete crop failure. The evident climate shifts in rainfed areas will have larger implications for crop planning, water-resources assessment and prioritizing drought-proofing programmes. Rainfed crops are likely to be worst hit by climate change due to the limited options for coping with variability of rainfall and temperature. The potential impacts are likely to aggravate further on yield fluctuations and prices. Climatic risks like droughts and floods, and poor water and nutrient-retention capacity of soil and low soil organic matter impact rainfed agriculture highly vulnerable, requiring a different outlook and strategy. In this unique circumstance, it appears to be sound for general rural approach and in addition the policy framework to prioritize issues identified with flexibility to climate change and reinforces the natural resources to defeat different types of climatic vagaries, as a basic pre-requisite to accomplish ecosystem sustainability.

Constraints in coastal agriculture

Low productivity of coastal agriculture is attributed to its unfavourable agro-climatic conditions. Coastal soils encounter several abiotic stresses, viz. salinity, acidity and waterlogging. The estimate on the extent of acid sulphate soils in the coastal areas reveals that about 0.26 million ha area in Kerala and the Andaman and Nicobar group of Islands are occupied by this type of soil. The presence of acid sulphate soils has also been reported in the coastal areas of Sundarbans, West Bengal. Coastal soils exhibit a great deal of diversity due to difference in parent material, wide variation of climate, physiography, differentially active geomorphic processes, hydro-chemical characteristics of shallow underground water, and differential inundation by tidal marine/ lacustrine waters. Therefore, proper understanding about the nature, properties and prevailing constraints related to diverse group of coastal soils is necessary to adopt better management practices and improve the productivity and quality of such low-productive soils (Ray *et al*., 2014).

Ill-effect of shifting cultivation

Shifting cultivation in India is practiced by tribal people. About 2.0 million ha of forests are cleared every year by felling and burning the trees and shrubs. These clearings are cultivated under very crude and extravagant methods for 2–3 years and then abandoned when fertility dwindles or soil erosion makes it unfit or forests reappear. Rice, buckwheat, maize, millets, tobacco (*Nicotiana tabacum* L.), vegetables, tuber crops, banana (*Musa paradisciaca* L.) etc. are grown on the burnt over clearings. In a few years' time the soil becomes impoverished in the absence of manuring, and a new stretch of the forest is brought under the axe (Singh, 2015). In north-east India alone about 0.88 m ha area is under this method of cultivation. High soil and nutrient loss, biodiversity decline, greenhouse gas (GHG) emission etc. are some of the negative impacts of *jhum* farming. Improved *jhum* farming practices comprised adoption of location-specific soil and water-conservation practices, across the slope cultivation, inclusion of stress-tolerant high-yielding varieties, adoption of integrated nutrient-management practices with emphasis on biofertilizer, legumes etc. are some of the better options. Further, adoption of integrated farming system and tree-based agro forestry systems are two viable alternatives to shifting cultivation to improve livelihood of hill farmers and conserve natural resource base (Das *et al*., 2017).

Constraints in Rice-fallows ecosystem

Rice-fallows (~14 m ha) is monocrop rice-based production system of south Asia, which mainly concentrated in India, Nepal, Pakistan and Bangladesh (Subbarao *et al*., 2001). In India, around 11.7 m ha (30% of the areas under rice production) remains fallow in the subsequent winter season. Soil-moisture deficit, terminal drought of winter (*rabi*) crops and hard pan are the major factor in rice–fallows. Lentil (*Lens culinaris* Medikus), lathyrus (*Lathyrus* sp.) and chickpea (*Cicer arietinum* L.) are potential crops. Lentil and lathyrus are mostly grown in relay system (*utera* and *paira*) before harvesting of rice for effective utilization of residual soil moisture in parts of Bihar and West Bengal where productivity is vary (around 100–150 kg/ha). There is urgent need to identify location-specific varieties and develop package of practices for promotion of pulses and oilseed in rice–fallow areas in potential areas like North-East, West Bengal, Odisha, Chhattisgarh, Maharashtra, Madhya Pradesh, eastern Uttar Pradesh, Tamil Nadu, Telengana.

Strategies for achieving agricultural sustainability

Conservation agriculture and resource conservation technologies

Conservation agriculture (CA) has emerged as an alternative strategy to sustain agricultural production and is based on enhancing natural biological processes above and below the ground. It is endowed with 3 principles, viz. minimal soil disturbance, permanent soil cover, sensible crop rotation with legumes. The use of agro-chemical for controlling weeds and the use of machineries are the integral to the CA (Nath *et al*., 2015 and Susha *et al*., 2018). The improvement in crop productivity, SOM, and soil-moisture conservation are worldwide recognized (Ghosh *et al*., 2010, 2016 and Das *et al*., 2014). Also, continuous addition of crop residue leads to SOM enhancement. In the beginning, this is confined to the top layer of the soil, but with the advancement of time, this will extend to deeper soil layers. Organic matter plays an important role in the soil by improving fertilizer-use efficiency, water-holding capacity, soil aggregation, rooting environment and nutrient retention (Das *et al*., 2013). The CA reduces the soil erosion and improves water and air quality (Nath *et al*., 2017b). The soil biological activities, particularly soil enzymes, viz. dehydrogenase, urease, protease, phosphatase and β-glycosidase are enhanced under CA. Retaining and management of adequate amount of crop residues (at least 30%) under conservation agriculture is the key to realize long-term benefits and also to reverse the process of soil degradation. But most of the farmers in Haryana and Punjab burn the crop residues to get their fields well cleaned before sowing. Therefore, to replace residue burning, and to realize benefits of residue cover under CA, its efficient management through machinery modification is the need of time. Recently developed super-straw management system should be popularized among the farmers through suitable mechanism. Mulching with straw has favourable effect on the yield of maize, soybean [*Glycine max* (L.) Merr.] and sugarcane (*Sacharum officinarum*) crops (Ghosh *et al*., 2010). Field experiments on the rice–wheat cropping system show that incorporation of crop residues can increase soil organic C and total N contents (Bhattacharyya *et al*., 2015). Incorporation of crop residues increased organic C by 14–29% over residue removal treatments in 3–10 years of experiments. Residues increased the storage of organic C and N in soil, whereas their removal results in a substantial loss of organic C and N from the soil system (Malhi and Lemke, 2007).

Direct dry seeding of rice with subsequent aerobic soil conditions reduces overall water demand, saves labour, fuel and time, and gives similar yield to transplanted rice, if weeds are effectively controlled. The technology does not affect quality of rice and can be practiced in different ecologies such as upland, medium and lowland, deep water and irrigated areas. Soil health is maintained or improved, and fertilizer and water-use efficiencies increase. Therefore, it can be a feasible alternative to conventional puddled transplanted rice. In the context of CA, where soil is essentially biologically tilled, bed planting has significant role in enhancing the eco-friendly cultivation with higher productivity and profitability of various cropping systems. The important crop rotations, which virtually can directly go for permanent bed planting, are soybean–wheat, maize–wheat, pigeonpea–wheat, maize–vegetable–wheat, maize–toria (*Brassica campestris*)/ mustard–wheat, pigeonpea + mungbean [*Vigna radiata* (L.) R. Wilczek]/urdbean [*Vigna mungo* (L.) Hepper]/wheat etc. (Das *et al*., 2013).

4.2 Precision agriculture

Precision or site-specific crop management refers to a management system of production agriculture, using diverse technologies to enhance field productivity and protect the environment. Under precision agriculture, however, inputs are applied in each part of the field according to its unique set of conditions. Moreover, when to apply, how to apply, how much to apply, kind of inputs in relation to water, nutrient, pesticides etc., the residual effect of nutrient and crop residue and left-over water on the succeeding crop and their behaviour with the environment in time and space are studied critically, so that resource wastages may be reduced to minimum possible. Normally, farmers follow one uniform practice of application of water, nutrient and pesticides at their farm, while in this concept, the variation observed within the field itself is to be taken care of. Each field is to be visualized critically and to be assured with balanced supply of nutrients in desired amount in each nook and corner to achieve sustainable yield levels of different cropping systems.

Precision water management (more crop and income per drop of water)

A feasible strategy for realizing the potential of rainfed agriculture in rainfed districts is to harvest a small portion of available surplus runoff, which is very site/ agro-ecology specific and has to be quantified for storage in water-harvesting structures like farm pond and utilized for supplemental/ protective irrigation during critical crop-growth stages. Precision agriculture by way of micro-irrigation (drip and sprinkler); and sensor-drone-big data analytics-based technology is important. Micro-irrigation (MI) systems need to be provided as production enhancement and income-enhancement proposition rather than as a technology that merely saves water for farmers. Of course, the key is the integrated perspective where the MI systems are coupled with improved agronomic practices like fertigation and use of solar pumps. These techniques use precision technologies for efficient management of both water and nutrient precisely near the root zone of crop plant. The major advantages in terms of water application include 3 factors that directly enhance both conveyance and water-use efficiency, viz. (i) water is applied directly to the root zone of plants, (ii) water is applied at frequent intervals in precise quantities as per the crop-water requirement and (iii) water is applied through a low-pressure pipe net work. Such precision application of water results in lesser weeds and pests and greater pod retention, besides realization of efficiency in nutrient uptake due to fertigation (Praharaj *et al*., 2016).

Integrated nutrient management

To ensure adequate and balanced nutrient supply, integrated approach is an important option and involves more efficient use of chemical fertilizers in association with judicious combination of organic manures without detriment to soil fertility and improving crop productivity (Hazra *et al*., 2014). Integrated nutrient supply helps improve the physical, chemical and biological health of soil and avoids soil degradation and deterioration of water and environmental quality by promoting carbon sequestration and checking the losses of nutrients to water-bodies and atmosphere. The gradual depletion of one or more nutrients may have collective contribution to yield decline and stagnation in the IGP of Indian Sub-continent. Application of balanced NPK either alone or in combination of FYM maintained active and slow pools of C and N in surface 0–15 cm soil. This indicated that, organic pools of C associated nutrients particularly N may be maintained in rhizosphere zone and thereby sustaining soil quality and productivity (Manna *et al*., 2006).

Carbon sequestration

Soils are the largest carbon reservoir of the terrestrial carbon cycle. It is estimated that the buildup of each tonne of soil organic matter removes 3.7 t of CO_2 from the atmosphere. Promoting soil C sequestration is an effective strategy for reducing atmospheric CO_2 and improving soil quality. Increasing the soil C content means increasing the carbon input, decreasing output or a combination of the two through improved management. Carbon sequestration can also occur through a reduction in soil disturbance because more carbon is lost from tilled soils than from soils that are less disturbed (Das *et al*., 2013). Measures to increase carbon inputs to soil include preferential use of animal manure, crop residues, sewage sludge and compost on crop land instead of grassland, improved rotations with high carbon input to soil and in some cases fertilization, irrigation, livestock management to increase productivity. Soil tillage affects SOC through its influence on both aggrading and degrading processes. Seedbed preparation, based on mechanical soil manipulation, is a principal factor responsible for exacerbating soil processes that accentuate C mineralization and decomposition. Conservation tillage usually has a positive impact on activity and species diversity of soil fauna (e.g. earthworms and termites). Activity of soil fauna usually has beneficial effect on SOC because of mixing and deep placement. Burrowing activity of soil fauna facilitates translocation of SOC from surface to the subsoil. It is important to realize that low-input agricultural systems deplete SOC and accentuate risks of the greenhouse effect.

Agricultural practices with a profound positive effect on SOC content are cover crops, agroforestry and agro-pastoral systems, rotations with deep-rooted crops, and crop-residue management or mulching. Management practices such as application of fertilizer and manure play important role in soil C sequestration and thereby greenhouse gas mitigation (Ghosh *et al*., 2010). Plant root acts as a medium for transfer of atmospheric carbon into the soil in the form of carbon-containing compounds, viz. organic acid, phenolic acid, amino acid etc. Root lysis and root exudates contribute significant quantities of carbon deposited in subsurface soil. These deposits have potential for greater contribution for long-term carbon sequestration due to slow oxidation than surface soil. Pulses are known to play an important role in maintaining soil health and increases soil organic carbon though leaf drop and root biomass. It is very difficult to increase the soil organic matter content of the cultivated soil, unless legume or hay crops are included in the rotation or organic matter is added from external sources. Under current situation there is a stiff competition for organic matter from other sector as well. Simply inclusion of pulse crop itself acts as a component of integrated nutrient management and benefits arise out of this are very much comparable with the benefits obtained from any other organic manure. Therefore, pulse crop has dual benefits; besides being economically viable component of the system they also conserve our natural resources.

Universal soil health card scheme

The universal soil health card scheme (SHC), launched in 2014, is a very progressive and definitive step taken by the Government. It has laid a strong foundation for science-based soil-nutrient management. There is need to connect Soil Health Card Portal with Integrated Fertilizer Management System (I-FMS) of Department of Fertilisers, to ensure that SHC-based fertilizer is supplied to all the farmers. It is equally important to educate the farmers on use of the recommendations. The farmer should be enabled to receive electronic SHC (eSHC), anytime for any crop, based on the sample test already carried out. Encourage private sector infrastructure, in the nature of mini and major labs; mobile and static labs, capable of carrying out multiple tasks of SHC system; and also are capable of testing for comprehensive parameters (major, secondary and micro-nutrients; physio-chemical properties). Since a single service-based activity may not be financially viable, it may be considered to promote a single stop-service centre, which meets multiple needs of farming. For example, soil testing, assaying (for commodity quality testing), extension service, input sales, farm machinery etc. Farming as a Service (FAAS) is the concept that deserves promotion.

Diversification can be done through

Food crops: Food legumes/pulse crops endowed with the unique ability of biological nitrogen fixation (BNF), deep root-system, low water requirements, and capacity to withstand drought; hence, pulses can be a potential candidate for system diversification and for sustainable use of natural resources. Diversification with legumes not only provides food self-sufficiency but also contribute to nutritional adequacy (Singh *et al*., 2009). In North-Western IGP, short-duration pigeonpea are now being advocated in place of rice to curtail the demand for irrigation water and to tackle the negative impact of RWCS. The mungbean cultivation in summer fallows of irrigated cereal-based cropping system offers an immense scope to practice 'ecologically intensive' cropping system (Venkatesh *et al*., 2013). Growing of legume as green-manure [*Sesbania bispinosa* (Jacq.) Wight] helped to save 60 kg N for the succeeding paddy crop.

High-value crops: Horticultural crops play a unique role in India's economy by improving the income of the rural populace and provide enormous scope to small and marginal farmers with higher return per unit of land than any other staple crops. With a surge in the middle-and upper-income group in the population, demand for fresh fruits and vegetables is bound to increase several fold. In this context, in addition to more food, the young, rich and urban population would demand diversified nutritious and safe food of high quality and as a result of this, there will be pressure on supply of horticulture crops like fruits and vegetables. The potential of under-exploited segments of horticulture like dryland horticulture, temperate horticulture and floriculture have to be fully exploited to meet the ever-increasing demand and income of the farmers, employment generation if properly designed. There is scope for expanding the area under horticulture crops by 4 m ha and that with enhanced yields by 60%. This generates 8 million additional employment opportunities in horticulture.

Organic farming

Organic agriculture is recognized as an innovative farming system. It helps achieve multiple sustainability goals and will be of increasing importance in global food and ecosystem security (Reganold and Wachter, 2015). High demand for organic foods in Europe and North America has resulted in import of organic foods from large farms in less-developed countries (Willer and Lernoud, 2015). Organic agriculture relies on locations-specific varieties (resistant/ tolerant to pest and diseases), crop rotation, organic composts, green-manure, biological pest management and prohibits the use of synthetic fertilizers and pesticides, antibiotics, genetically modified organisms and growth hormones. Concerns about the un-sustainability of conventional agriculture, organic farming has the potential to produce quality food, enhance natural resource base and environment, increase income and contribute to the wellbeing of the farmers (Reaganold and Wachter, 2015; Hazra *et al*., 2018).

Integrated farming systems

Integrated farming system (IFS) is an entire complex of development, management and allocation of resources as well as decisions and activities, within an operational farm unit, or combinations of units, that result in agricultural production, processing and marketing of the products. The selection of enterprizes must be based on the cardinal principles of minimizing the competition and maximizing the complementarily between enterprizes. Some mention of sustainability of IFS models is given below:

- Model should be self-input generating, seeking minimum requirement of external resources from the market.
- IFS Model should able to generate year-round employment and income-perennial yield of income in contrast to seasonal nature of income.
- Waste of one component should be wealth for another component, meaning that complementarity should exist between/ among the various components.
- Model should be energy-efficient, economically viable and socially acceptable.
- IFS model should be capable of sustaining the farm family needs as per the Indian Council of Medical Research (ICMR) recommendations on nutrition.
- While designing the IFS Models, ecosystem services should take into consideration, model should effectively reduce the GHG emission, soil and nutrients erosion.

Currently, there is an imbalance between natural resources endowment and cropping patterns in rainfed areas. This calls for concerted efforts in efficient crop zoning/ crop colonies and/ or crop-alignment matching natural resources, rainfall and soil resources. Efficient crop zones have similar geographic setting in terms of soils, landforms, rainfall, temperature, length of growing period, irrigation potentials, suitable for a specific crops and cropping sequences and have the potentiality to respond similarly for similar kind of management practices (Ramamurthy *et al*., 2016).

Agro-forestry and agro-pastoral systems

Trees can be incorporated within a farming system by planting them on land which is not suitable for crop production. Thus, fragile ecosystem like hills, degraded lands can be brought under plantation of trees to improve soil quality and ecosystem services. Species recommended for agro-forestry in the area include: peripheral planting/ hedges row, silvi-pasture or fodder development, agri-horticulture/ orchard plantation, and horticulture. The value of forests and trees in sequestering carbon and reducing carbon dioxide emission to atmosphere is being recognized increasingly worldwide. Agro-forestry has importance as a

Table 2. The advantages of integrated farming system approach over arable farming

Sl. No.	Advantages	How?
1.	Increased food supply and nutritional security	Horticultural and vegetable crops can provide 2–3 times more calories than cereal crops on the same piece of land. Inclusion of bee keeping, fisheries, sericulture, mushroom cultivation under 2 or 3 tier system of integrated farming give substantial additional high energy food without affecting production of food grains.
2.	Recycling of farm residues	Proper collection and utilization of livestock excreta (both solid and liquid portion) and litters. This can save up to 50% of NPK require ments. Restoration of soil fertility through organic maturing, biomass recycling, use of legumes in cropping system etc.
3.	Use of marginal and wastelands	Combination of forestry, fishery, poultry, dairying, mushroom and bee keeping can be combined with crop rising and all these activities can be undertaken on marginal to wastelands too.
4.	Increased employment	There is 200 to 400% increase in gainful employment and additional income to farm families to increase their standard of living.
5.	Multiple use of resources	The appropriate mix of different enterprizes and utilization of products within the system results in multiple uses of resources thereby reduction in total cost of inputs leading to higher profitability.
6.	Risk reduction	The effect of climate variability on different crop/ animal/ fisheries enterprizes will be different.

C-sequestration strategy because of carbon-storage potential in its multiple plant species and soil as well as its applicability in agricultural lands and in reforestation. Proper design and management of agro-forestry systems can make them effective carbon sinks. Average carbon storage by agro-forestry systems has been estimated to be 9, 21, 50 and 63 Mg C/ha in semi-arid, sub-humid, humid and temperate regions (Montagnini and Nair, 2004).

Watershed management

A watershed is a defined geographic area through which water flows across the land and drains into a common point, whether a stream, river, lake or ocean. Watershed management is based on the principle of ridge to valley treatment, leading to effective and soil and water conservation, which are the basic resources for an agricultural system. For realizing the larger benefit of water approach, it would be useful to adopt "clustered approach" at large scales. The clustering by definition is a "geo-hydrological unit" comprising clusters of micro-watersheds as the new unit for planning and where assessment and intervention are planned on the on landscape level, with a focus on hydrological resources. The first and foremost step is to form clusters based on to "multi-tier" sequencing of watershed development, beginning with upper reaches or forests "where the water sources originate," followed by "the second tier" or intermediate slopes just above the cultivable lands and then the "third level" or plains/flat areas "where typically farmers cultivate." Watershed essentially is a people-centric initiative. Hence, the desired focus has to be on mobilization of the inhabitants to accept and own the watershed.

Contract farming

Contract farming involves carrying out of agricultural production on the basis of an agreement between the buyer and farm producers. Sometimes it involves the buyer specifying the quality required and the price, with the farmer agreeing to deliver at a future date. The farmer undertakes to supply agreed quantities of a crop or livestock product, based on the quality standards and delivery requirements of the purchaser. In return, the buyer, usually a company, agrees to buy the product, often at a price that is established in advance. Although contract farming must first and foremost be considered as a commercial proposition, it has also come to be viewed as an effective approach to help solving many of the market access and input-supply problems faced by small farmers. Effective linkages between companies and thousands of farmers often require the involvement of formal farmer associations or cooperatives or, at least, informal farmer groups.

Climate-change adaptation and mitigation

Adaptation is an anticipatory and planned process, managed through policies, technologies and developmental activities. Though mitigation strategies are important to reduce the drivers of climate change, it is adaptation strategies that are more essential to minimize its impacts. Hence adaptation strategies are more likely to save livelihoods and ensure food security than mitigation strategies (Ladha *et al.*, 2003). The adaptation options include (*i*) technological developments; (*ii*) government programmes and insurance products; (*iii*) farm-production practices; and (*iv*) farm financial management. Intercropping has a higher biological efficiency than sole cropping (usually at least 30%, if farmers adopt intercropping), because of several reasons, viz. better buffering against climatic extremes; more efficient use of resources (light, nutrients, water); and less problems with pests and diseases.

Biodiversity management

Biodiversity can be managed at ecosystem, species and gene levels. *In-situ* approach is appropriate at ecosystem, while *ex-situ* approach is adopted for study, conservation and exploitation purposes. Agro-biodiversity builds the foundation of sustainable agricultural development and is an essential natural resource to ensure current and future food and nutrition security. The effective and efficient management of agro-biodiversity is essential through management of genebanks, science-led innovations; livelihood, food and nutrition security though crop diversification, use of lesser-known crops and wild relatives in crop improvement; dealing appropriately with quarantine, bio-safety and bio-security. The conservation and use of genetic resources will remain essential for improving productivity in agriculture, sustaining human existence and well-being. Given that global food security depends significantly on production in more industrial agriculture, it is relevant to note the important contribution of agricultural biodiversity to global food production as well as to sustainable livelihoods. It is, therefore, inappropriate to promote large-scale abandonment of bio-diverse agriculture and to marginalize it in intensive industrial production systems. The demand for uniformity in the modern world is in a way legislative to low-cost natural management that the nature contains in its order and warrants its maintenance.

Recommendations and policy intervention

To tackle the adverse situations and arrest the deterioration of scared natural resources and biodiversity, and also to bring long-term sustainability of agricultural productivity (both crops and soil productivity), a holistic approach involving scientific intervention, participation of more number of stakeholders, policy, strengthening of on-going schemes of the Government is essentially required. Recommendations which could be used/ implemented for the solutions to real-field problems, which farmers of different regions are being faced time to time are furnished below:

- Prevent land degradation and bring erosion by water and wind within permissible limit for sustained productivity following appropriate technologies and conservation measures and also through strong research support.
- Use remote sensing and geographic information system-based decision-support systems with database on climate, soil, land use and crop yields for assessing, mapping, and monitoring land-use performance under given technological conditions.
- Grow food legumes/ pulses for self-sufficient in their N needs and contribute to the N economy of the entire cropping system by contributing fixed N to the soil pool and drawing little or none from soil reserves. However, follow effective integrated nutrient manage-

Table 4. Assessing new germplasm as sources of tolerance

Wheat	Terminal heat, water stress, rusts
Rice	Blight, blast, drought, submergence
Maize	Flooding, drought, Banded leaf and sheath blight
Pearl millet	Downy mildew, blast, drought, heat tolerance
Sorghum	Moulds, downy mildew, white fly, borers

Table 3. Suggested strategies for strengthening traditional rainfed farming systems.

Rainfall zone (mean annual rainfall)	Strengthening predominant traditional rainfed farming systems	Agro-ecology specific components along with efficient *in-situ* and *ex-situ* rainwater-management practices
< 500 mm	Livestock–crop based	Small ruminants, nutritious cereals/ millets
500–750 mm	Crop–horticulture–livestock based	Small/ large ruminants, predominant rained crops and dryland horticulture.
750–1,000 mm	Crop–horticulture–livestock–poultry based	Predominant rained crops, dryland horticulture, agri-horti systems, rainfed vegetable crops, small/ large ruminants, improved breeds of poultry.
> 1000 mm	Multiple enterprise based on multiple water use	Predominant rained crops, lowland rice with water-saving technologies, dryland horticulture, vegetable crops, other high-value crops, agri-horti systems, small/large ruminants, improved breeds of poultry, fish and other income-generating enterprises like seed production, apiary, mushroom cultivation etc.

ment (INM) with rhizobial bio-fertilizers coupled with supplemental inputs of essential elements (P, S, B, and Mo) to reach their growth and N-fixing potential in most agro-ecosystems.

- Conservation agriculture, soil-fertility mapping, smart city, crop residue, rice–fallows, agri-animal waste, neem-coated urea should be adopted. To capture organic carbon, increase cropping intensity by reducing the frequency of bare fallow to improve biomass production and soil C sequestration. In addition, increase cropping intensity to decrease the rate of decomposition of organic matter and rate of mineralization/ oxidation of soil organic carbon.
- In dryland systems, capture and conserve soil moisture, and make effective use of available moisture for crop production.
- Identify new niches of rice–fallow areas for irrigated pulses, particularly in eastern and north-eastern India, for increasing acreage and production of pulses in the country.
- Rice is consumed as staple food by more than half of the world's population. Puddling, a procedure of ploughing soil in standing water, expends a substantial amount of water. There is a danger that Asian rice producers will most likely have insufficient access to irrigation water in future. Therefore, adopt alternatives of rice-establishment techniques like unpuddled transplanted rice (UPTPR), zero tillage transplanted rice (ZTTPR), and zero tillage direct-seeded rice (ZTDSR) for mitigating climate change.
- Promote niche-based organic farming in crops, commodities and regions where the country has comparative advantage. To begin with, advocate organic farming for low-volume high-value crops, like spices, medicinal plants, besides fruits and vegetables along with Research and Development support.
- There is need to connect Soil Health Card Portal with Integrated Fertilizer Management System (I-FMS) of Department of Fertilisers, to ensure that SHC-based fertilizer is supplied to all the farmers.
- Prepare a district-level nutrient map to promote district-and-crop-specific customized fertilizers based on the soil health card data. Once nutrient mapping is completed for all districts, and crop-specific fertilizer prescription is made, this will not only economize fertilizer input but also enhance input-use efficiency and farm income.
- Parampragat Krishi Vikas Yojna, a new scheme was launched in 2015–16 to develop organic clusters and make available chemical-free inputs to farmers, improve soil health and leads to better-quality crops.
- Customized Fertilizers (CF), though introduced in 2008, are yet not popular. Small scale industries may be allowed to manufacture CFs for small zones like Taluk or District.
- A robust 'Seed Rolling Plan' should be ensured based on active partnership of Department of Agriculture, Cooperation and Farmers Welfare (DACFW)-ICAR-States, who, in turn, build a network with efficient seed producers, across both public and private sectors.

CONCLUSION

Sustainable intensification (SI) remains a foremost goal of Indian agriculture in the 21st century. Besides achieving increased crop production per unit area, SI intends to take care of natural resources, ecosystem services, declining soil productivity, and also the evident consequences of 'Green Revolution'. Degradation of natural resources remains the primary challenge to Indian Agriculture in the face of burgeoning population. Among other long-term flaws, this industrial agro-management leads to loss of soil organic carbon and fertility, causes soil erosion, dwindling biodiversity, desertification, pesticide pollution and emerging pest resistance, pressing climate change, rising food prices etc. These adverse effects pose serious threats to sustainability. Over-use of chemicals resulted into multiple ecological and environmental issues, which necessitates developing alternative less chemical intensive agriculture in order to ensure ecological sustainability. Immediate attention is warranted to conserve the natural resources, biodiversity, and mitigate extreme weather events to minimize the risk of crop failure for small and marginal farmers. Afforestation is of paramount importance to combat the gravest threat of climate change and to achieve ecosystem sustainability. The conservation agriculture, erosion control, diversified cropping system, balanced fertilization, etc are recommended management practices for C-sequestration. To impart income security to the farmers of the country, in addition to food and nutritional security, diversification across all the sub-sectors of agriculture assumes importance which is, indeed a de-risking mechanism and promotes resource-use efficiency, sustainable intensification, nutritional security and productive employment. The effective and efficient management of agro-biodiversity is also essential for long-term sustainability through management of genebanks, science-led innovations; livelihood, food and nutrition security though crop diversification, use of lesser-known crops and wild relatives in crop improvement.

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