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Indian Agriculture needs a Strategic Shift for Improving Fertilizer Response and Overcome Sluggish Foodgrain Production

Raj Gupta[1,*], DK Benbi[2], IP Abrol[1]

[1]Center for Advancement of Sustainable Agriculture (CASA), New Delhi

[2]Punjab Agricultural University, Ludhiana, Punjab

Corresponding author:

Raj Gupta, Center for Advancement of Sustainable Agriculture (CASA), New Delhi

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Abubaker Haroun Mohamed Adam, Department of Crop Science (Agronomy), College of Agriculture, Bahri University- Alkadaru- Khartoum -Sudan

Abstract

In India, loss of fertility through soil erosion is primarily a summer monsoons mediated phenomenon. Reversing the land degradation processes contribute to water availability, soil fertility maintenance, adapting to climate change and overall food security. Whereas kharif (monsoon/rainy season crop) foodgrain production largely depends on summer monsoons, the rabi season (post-rainy season/winter crop) rainfall is too little to exert a direct influence. In spite of larger acreage under kharif foodgrain crops, total fertiliser consumption during kharif and rabi seasons is comparable. Negative rainfall anomalies (deficit) adversely affected total fertiliser consumption and their use efficiency. Despite significant differences in fertiliser application rates, the response to applied fertiliser nutrients is almost similar in the two seasons. This implies that nutrient use efficiency (NUE) has a 'manageable' and an 'unmanageable' component wherein 4R practices are difficult to implement under unfavourable kharif weather conditions. Partial factor productivity of fertilizer nutrients (PFP_F) has continuously declined over decades mainly because of depletion of soil organic carbon, imbalanced use of nutrients and inability to maintain soil moisture supplies. These observations plus yield-gap analysis permitted us to conclude that past trends of declining NUE can only be reversed through a shift either in sustainable land management practices or enhancing the genetic yield potential/

biomass of crop cultivars or by combining both and making kharif crop planting independent of monsoons rains through direct dry seeding.

Introduction

For continued cultivation, adequate replenishment of nutrients is essential to avoid soil fertility depletions. In India, before independence, application of bulky organic manures and green manuring were the principal ways to maintain adequate soil fertility levels. In the transition period, farmers adopted integrated use of organics with some chemical fertilisers. Over the last four decades, Indian farmers have largely replaced organic manures with chemical fertilizers to improve soil fertility and land productivity. Most farmers have even discontinued the practices of green manuring and retaining or incorporating crop residues into soil. In the entire post-independence era, there has been a tendency to equate the use of organics only in terms of its nitrogen supplying capacity and meeting the loss of other nutrients. On this account, the role of organic matter in soils has largely remained unappreciated and such a narrow view on the role of organic matter has contributed to a fatigue in Indian agriculture. Ideally, the fertilizer research should aim to integrate and address the broader role of soil organic matter (SOM) in terms of (i) nutrient and water regulation, (ii) biological activity (iii) carbon sequestration, (iv) rainwater conservation coupled with *in situ* soil moisture storage and (v) improved agricultural production.

Although extensive use of chemical fertilizers in both rainfed and irrigated agriculture was set an early goal for enhancing agricultural production in the country, yet fertiliser consumption is not looking up [1]. For almost a decade, India has not been able to surpass the 28 million tonnes (MT) of NPK fertilizer nutrients [2] consumption achieved in 2010-11. Several researchers have recently published extensive reviews on 'better-bet fertiliser use' practices [3-9] reiterating the traditional views on nutrient management vis-à-vis yield gain. It occurs to us that a paradigm shift is inevitable as institutional deficit is not allowing a fuller understanding of the soil-water-crop management issues stagnating the consumption of chemical fertilisers in different agro-ecoregions, continuously declining crop-nutrient responses, and slowed down agricultural production under changing climate scenarios in the country. The objective of this paper is to address the issues: (a) Whether stagnating fertiliser consumption is a consequence of decreasing nutrient response or slowed growth rate in food-grain production, or a consequence of law of diminishing returns, (b) Why improved fertiliser management practices are not reflecting in nutrient response? (c) What strategic shifts are required for implementing the current thrust of the government to reduce the use of chemical fertiliser by half without adversely affecting food grain production in the country? In this paper, we bring out the need for a broader research perspective that should enable us to address the aforesaid issues based on an original analysis of the data on cropped area and food grains production available from Directorate of Economics & Statistics, Government of India [10] and NPK fertiliser consumption statistics [2] in kharif and rabi seasons. Long term average rainfall anomaly data provided by IMD [11] was used to relate it with NPK fertiliser consumption in kharif season. Our approach is based on the calculation of the partial factor productivity (PFP= Y/F), a long term indicator of the aggregate efficiency index of nutrients for cropping system.

Tipping Point of Indian Agriculture

In India, 72.4 and 54.2 million hectare (Mha) were devoted to food crops during kharif and rabi season, respectively in 2010-11. From a total area of 126.6 Mha, India annually produces about 281 million tonnes (MT) of food grains. Besides this, nearly 25.6 million hectares were devoted to horticultural crops in 2018-19 to produce 314.87 MT of fruits and vegetables. Compared with base year 1969-70, the current food and horticultural production has increased by about half a dozen folds. Much of the primary driving force contributing to agricultural growth during the aforesaid period relates to availability of modern higher yielding cultivars, expansion of irrigation, and increased use of fertilizer nutrients and agrochemicals, energy and agricultural machinery for timely completion of the farm operations [12]. A closer look at the available production data indicates that whereas area devoted to kharif food grain crops in India decreased from 78 to 69.5 Mha during last five decades (1965-2016), the acreage under rabi food grain crops has more than doubled, from 25 to 55.4 Mha in the same period (**Fig.1a**). Agricultural production and productivity during the rabi season exceeds the kharif season production even though the latter has more area under cultivation. Area and food grains production dynamics reveal that whereas yield gains mainly contributed to increase in kharif food grain production, both yield gains as well as expansion of harvested area contributed to increase in rabi food grain supplies. Though majority of the increase in rabi food grain supplies during 1966-1991 and 1992-2006 was due to yield gain (77% and 58%, respectively) on the existing land yet the expansion of harvested area accounted for half the increase in food grain production between 2007 and 2016. Higher growth rate in rabi food grains production (Table 1) is consistent with large irrigation support and development of the fertiliser responsive genotypes bred for irrigated environments [13]. Kharif food grain production did not perform as good as rabi season due to higher biotic pest pressure, monsoon season rainfall anomalies, declining water tables [14], reduced use of hybrid seeds and inability of the farmers to carry out timely farming operations.

It has been reported that deficit rainfall impacts food production more than the excess of it [15-16]. Several reports have pointed out that impact of deficit rainfall is as large at present as it was before 2000s, signifying that Indian agriculture continues to depend on monsoon rains in spite of commissioning of a large canal network and ground water development through tube-wells in the country [17-18]. Irrigated rice which contributes substantially to food basket from North Indian states, depend on this irrigation network during the kharif season. All the other kharif crops depend on rains and irrigation provisions seem to have little effect on kharif season production. In sharp contrast, rainfall during rabi season is too little to have significant influence on winter season food production. This implies that agriculture in rabi season is independent of rainfall and primarily depends on canal and ground water irrigation. Declining water tables in some of the agroclimatic regions of the country is just a pointer towards the 'slow down' in growth and unsustainability of agriculture in those regions.

Monsoon Rainfall Mediated Loss of Soil Fertility

Land degradation is a complex and an insidious phenomenon which begins to become obvious through (i) reduced crop yields despite usual application of inputs, (ii) increased runoff and soil erosion leading to declining soil fertility, (iii) reduced biomass production resulting from soil moisture shortages and C sequestration, (iv) reduced capacity of soils to moderate soil temperature, (v) declining water table, (vi) appearance of surface salt encrustations in high water areas, and (vii) surface sealing and temporary ponding after a rainfall event. In India, land degradation manifests itself through one or more of above mentioned symptomatic processes [19] is largely a monsoon-mediated phenomenon happening during the rainy season (June- September) each year. Poorly managed soils having no crop or residue cover become highly prone to land degradation under raindrop impact during the rainy season. The State of Indian Agriculture Report [20] points out that about 3 billion tonnes of soil gets eroded annually to the oceans. Consequently, soils annually lose nutrients worth more than $9 billion dollars ($3 per tonne of soil sediment [21-22]. Thus, Indian summer monsoons serve both a boon and a bane during rainy season, contributing to land degradation through loss of soil organic carbon (SOC) at elevated summer temperatures and loss of surface soil by beating action of summer monsoon rain

Table 1. Seasonal changes in growth rates of food grains during different time periods in India

Crop season	‡Growth Rates (MT Yr^{-1}) during the periods		Growth Rates during the periods (Present study)		
	1966-1990	1991-2006	1967-1991	1992-2007	2007-2016
Kharif	1.61	0.70	1.68	0.66	0.83
Rabi	1.97	0.40Ω	1.56	1.63	1.70
Total Food grains	***1950-1990**	***1996-2015**	**£2011-2015**		
(Kharif+Rabi)	2.7*-3.0£	1.2	1.8		

‡ Milesi et al. [48]

*Gadgil [18]

ΩLow values due to high base year production and short time span included several drought years, adversely affected rabi production.

£Reserve Bank of India database [64]

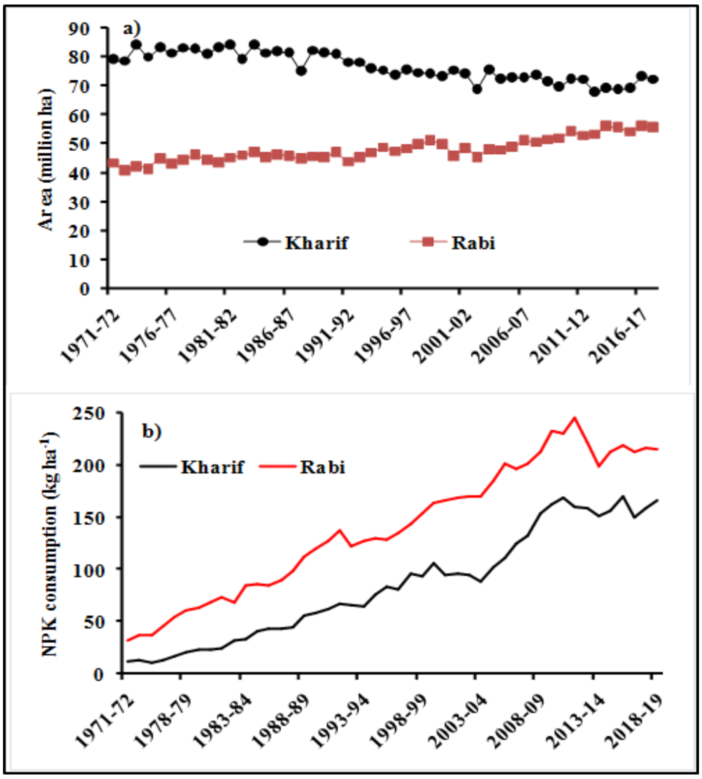

Figure 1. Dynamics of a) cropped area and b) NPK fertilizer consumption in kharif and rabi seasons in India.

drops. Therefore, reversing the processes contributing to land degradation are central to water availability, soil fertility, adapting to climate change and food security.

Nutrient Recovery/ Response is also Climate Dependent

In the semi-arid tropics, there appears a clear relationship among (a) adverse conditions in terms of available surface and ground water resources, (b) erratic rainfall leading to runoff and loss of top soil, (c) global warming and high potential evapotranspiration, (d) declining organic carbon contents and poor nutrient status of soils. The extent to which crop yields are limited in the tropics, depend on water and nutrients supplies. Response to fertilizer application is governed by the available soil moisture supplies. If there is not enough moisture in the soil to support plant growth, the increased input of external fertiliser nutrients is generally unwarranted. Soil moisture at wheat seeding alone accounts for 50% variation in crop yield [23]. Since plants absorb nutrients dissolved in soil water, the two must be considered together in any assessment of soil productivity and soil health.Significant positive interaction between applied N and water supply on water and nutrient use efficiency and yield of wheat has been reported earlier [24-25]. Fertilizer application must be combined with improved soil and water management practices, timely planting, optimum plant population, and pests, weeds, and disease management practices for realizing the full yield potential in irrigated crops and more particularly in the rainfed crops. Cassman et al [26] examined N fertilizer recovery for wheat in India and found that it averaged 18% and 49% respectively under poor and good weather conditions (Table 2). On the other hand, nitrogen recovery averaged 31% and 40%, respectively for irrigated rice grown by Asian farmers and crop grown under field specific management. These results point to the fact that fertiliser recovery has both a 'manageable part' that can be impacted by 4R practices and an unfavourable weather impacted 'non-manageable' part. Unfavourable weather conditions are hard to manage and improve and often do not allow timely farming operations. Unfavourable weather conditions may also exacerbate biotic and abiotic stresses leading to loss of crop yield and reduced fertiliser response.

Fertilizer use and Nutrient Use Efficiency (NUE)

Nutrients and water are the building blocks for plant biomass production through photosynthetic process. Presently, India is the world's third largest producer and user of fertilizer nutrients. Randhawa and Tandon [27] credited half the increase in agricultural production in India to use of fertilizers. Despite fertilizer use in significant amounts, nutrient removal by crops far exceeds the nutrient additions through fertilizers. Estimates suggest the NPK gap between removals and additions is negative, in range of 8 to 10 million tonnes [28-29]. Considering the amounts of nutrients depleted through horticultural and plantation crops, the estimated annual gap is likely to be higher. Crop production is influenced by fertilizer management as well as soil- and plant-water relationships. The NUE concept is used to evaluate the performance of different crop production systems. Sustainable nutrient management must increase both productivity and NUE. Therefore, management practices that improve NUE without any adverse effect on productivity are likely to be most valuable. Better bet fertilizer management practices such as 4R nutrient stewardship, must focus on application of the right nutrient source, at the right rate, in the right place and at the right time [30]. Mosier et al. [31] described four indices of nutrient efficiency, namely (i) Agronomic Efficiency (AE); (ii) Partial Factor Productivity (PFP_F); (iii) Recovery Efficiency (RE), and (iv) Agro-Physiological Efficiency (PE). NUE metrics and their appropriateness to different contexts has been discussed in earlier publications [32,33]. The short-term NUE of applied nutrients is better estimated using AE, RE and PE, but these indices require data that are not often available at a farm scale. Partial factor productivity ($PFP_F = Y/F$) is generally used to calculate units of crop yield (Y) per unit of nutrient applied (F), from annual fertilizer use and crop production statistics. It is a long term indicator of the efficiency of a cropping system calculated at the regional and national scale. Typically, the PFP [32-33] for N, P and K are in range of 40-90, 45-250 and 60-200, respectively. Higher values suggest that nutrient supply could be limiting productivity, whereas the lower values point towards less responsive soils or excessive and imbalanced application of nutrients. The PFP_F indicator does not consider inherent soil nutrient supplies and hence it does not reflect the true efficiency of fertilizer-derived nutrients.In spite of the limitations, the estimates of agricultural PFP_F provide a convenient way of summarizing the productivity performance of the aggregate crop sector and compare it against total land, and fertilizer resources employed in production [2].

Therefore, PFP_F expression is an aggregate efficiency index of nutrients and includes contributions to crop yield from (i) uptake of soil nutrients, (ii) fertilizer nutrient uptake, and (iii) the efficiency with which nutrients acquired by the plant are converted to grain yield. Thus, PFP_F is impacted, amongst other factors, by fertilizer management practices. For instance, the PFP for nitrogen (PFP_N) can be represented as (Eq. 1):

$$PFP_N = (Y_0 + \Delta Y_F)/N_F \qquad (1)$$

In the above expression, yield at a given fertilizer N level (N_F), represents the sum of yield without fertilizer N_0 (Y_0) plus the incremental yield gains due to fertilizer application (ΔY_F). The expression can be rewritten as (Eq. 2):

$$PFP_N = Y_0/N_F + \Delta Y_F/N_F \qquad (2)$$

Where $\Delta Y_F/N_F$ equals agronomic efficiency (AE) which is a product of RE and PE (or AE= RE*PE) in agronomic parlance. Therefore, $PFP_N = Y_0/N_F + RE*PE$. Since soils have an inherent capacity to supply nitrogen (N_S), the total supply of N from the soil and applied through fertiliser equals (N_s+N_F) and the term, $Y_0/N_F = Y_0/(N_s+N_f)$. Equation (2) can therefore, be written as (Eq. 3):

$$PFP_N = Y_0/(N_S+N_F)+\Delta Y_F/N_F \qquad (3)$$

From the term $Y_0/(N_S+N_F)$, it occurs that Y_0 depends on the physico-chemical and biological properties of the soils and the soil management factors determining the availability of nutrients including N in soil. A soil rich in organic carbon invariably will have more biotic activity, greater nutrient availability and better health. Fertilizer N application rates (N_F) in expression $Y_0/(N_S+N_F)$ influence both N_S and Y_0. Fertilizer N promotes plant growth and adds to SOM or builds-up residual N in soil to promote microbial activitycompared with a soil receiving no fertilizer. The net effect of application rates is linked to yield optima- lower levels build-up SOM and microbial biomass by promoting plant growth. Higher N application rates increase residual inorganic N to accelerate SOM losses through microbial actions [34-36]. Applied nitrogen, vis-à-vis balanced use of mineral fertilizers, generally enhances biomass, increases SOM and improves biological life [37-40]. If there are no additions of nutrients to replace those lost through crop off-take and other processes, the capacity of the soil to perform eco-functions decline. For healthy soils, soil organisms and SOC are critical [41]. We must endeavour to continuously replenish any loss of organic matter. For arresting and reversing the soil degradation processes, SOC together with soil microbes and soil moisture retention are critical for biomass production. These attributes enhance soil productivity, improve nutrient and water-use efficiency, reduce production costs, and significantly benefit the environment.

Global and Indian estimates of nitrogen use efficiency for cereals (maize, rice and wheat) indicate that it decreased with enhanced application rate and was lower in the Indian context than the global values (Table 3). A low nitrogen use efficiency points to the fact that nitrogen not taken up by the crop is vulnerable to losses through leaching, denitrification, volatilization or immobilized with SOM to be released at a later time. This calls for improvements in crop management practices, including water and pest and disease management. The nutrients such as P or K which are not as mobile in soil as N can easily get fixed or immobilized with the soil mineral matrix to become available later during the following crop season or so. All such situations impact the apparent use efficiency estimates. To account for contributions of added nutrients to succeeding crop, Dobermann et al. [42] advocated using efficiency of nutrient at the system level.

Fertilizer use Trends in Indian Agriculture

NPK fertilizer consumption in India has increased by a dozen times since 1969-70. Fertilizer consumption (28.122 MT) was highest in the year 2010-11, hovering around 25 MT between 2012 and 2017. In 2018-19, NPK consumption was 27.29 MT for all crops including the horticultural crops. Conservative estimates suggest that about 6% of the total NPKfertilizers are used in Indian horticulture sector [43]. NPK fertilizers are used primarily in food grain crops grown during the kharif and rabi seasons. As mentioned previously, the acreage of kharif season crops has decreased from 78 Mha to 69 Mha and that of rabi food crops increased from 25 to 55 Mha in the last five decades (Fig.1a). Changes in the acreage of kharif and rabi crops have altered the proportions of annual fertilizer nutrients consumed in the two seasons. Of the total NPK consumption of 18.069 MT in 1999-2000 (before the announcement of the National Agriculture Policy), 48.6 and 51.4 per cent of the total fertilizer nutrients were used during kharif and rabi seasons, respectively. Currently, the NPK fertilizer consumption is almost similar (~50% each) during the two seasons. However, the rates of fertilizer application during rabi season continue to be higher because of lower acreage in rabi season than the kharif season food crops (Fig 1b). It is worth mentioning that fertilizer application rates (Fg.1b) though significantly higher in rabi than the kharif season, yet the NUE is presently almost analogues in both the seasons (Fig. 2).This implies that uncertainty of the monsoons during the kharif season leads to obvious difficulties in implementing the 4R practices, despite the potential for improving NUE particularly at lower NPK application rates compared to rabi season. The PFP_F was high in years of low fertilizer application between 1970 and 1995. During the same period, the PFP_F was higher in kharif than the winter season rabi crops (Fig.2). The PFP_F remained nearly the same in both the seasons since 2000.

In order to visualize the effect of monsoon uncertainty on NUE, a relationship between fertilizer consumption during the kharif season and rainfall deviations from long term means was computed using available dataset of All India Summer Monsoon Rainfall index anomalies [11]for the period 1975 to 2018. Clearly, the relationship between amounts of monsoonal rains and fertilizer consumption is not very straight forward (Fig. 3). This is because large negative deviation from long term means (- rainfall anomalies; deficit rainfall) has the potential of making of kharif planting and fertilizer use quite uncertain. High negative rainfall anomalies often result in adverse soil moisture conditions and kharif crops vacating the fields late in the season. As a result, planting of rabi food grain crops is adversely affected during the winter season. Therefore, large negative rainfall anomalies resulting in abnormal weather conditions not only affect the total fertilizer consumption but also impacts NUE, reported earlier [26] (Table 2). Data presented in fig. 3 bring out that in above-normal rainfall season there is a general trend of increasing fertilizer consumption. Until 2000, increasing fertilizer consumption significantly influenced food grain production but the latter does not seem to influence fertilizer consumption through its influence on income of the farmers [44]. Stagnating fertilizer consumption in unfavorable weather conditions (negative rainfall anomalies since 2000) could also be due to agricultural productivity being impacted by unfavorable soil moisture regimes, inefficient irrigation systems, and loss of soil fertility through erosion with runoff water. It is for this reason, fertilizer nutrient consumption seems to have stagnated since 2011 when high rainfall anomalies were negative (deficit rainfall). Indian summer monsoons are known to be the primary water source during the kharif season, which continues to limit crop production. However, factors other than water availability seem to restrict agricultural growth in the rabi season for over the past four decades as winter rains are quite low. A general declining trend in the PFP of fertilizer nutrients over the past four decades brings out that Indian farmers are unable to concurrently manage adequate water and nutrient supplies required by the crops for high nutrient

Table 2. On-farm nitrogen fertilizer recovery efficiency in maize, rice and wheat

Crop	Region	Number of farms studied	Average N rate (kg ha^{-1})	N Recovery* (%)
Maize	North Central USA	56	103	37
Rice	Asian farmer practice	179	117	31
Rice	Asia- field specific management	179	112	40
Wheat	India- unfavourable weather	23	145	18
Wheat	India- favourable weather	21	123	49

Source: Cassman et al. [26]

*Recovery is the portion of applied N fertiliser taken up by the crops, calculated as the difference in total N uptake in above –ground biomass at physiological maturity between fertilized plots and an unfertilised control.

Table 3. Global and Indian estimates of nitrogen use efficiency in some cereal crops

Crop	Estimate	N rate$^{\Phi}$	AE$^{\Omega}$	PFP_f^{Ω}	RE‡	PE$^{¥}$
Maize	Global	123	24.2	72	65	36.7
Rice	Global	115	22.0	62.4	46	52.8
Rice	Indian	61-120	16.2	47.7	40.2	37.7
Wheat	Indian	121-180	13.1	37.8	31.3	40.4
Wheat	Global	112	18.1	44.5	57.0	28.9
Wheat	Indian	40-60	28.8	83.7	73.8	47.8
Wheat	Indian	61-120	20.1	50.2	57.7	42.8
Wheat	Indian	121-180	15.9	31.3	61.8	24.0

Units for different parameters: $^{\Phi}$kg N ha^{-1}; $^{\Omega}$kg grain·kg $nutrient^{-1}$ applied; ‡(%); $^{¥}$kg grain·(kg $nutrient)^{-1}$ absorbed by the crop

Sources: Global estimates from Ladha et al. [65] and Indian data from Prasad et al. [9]

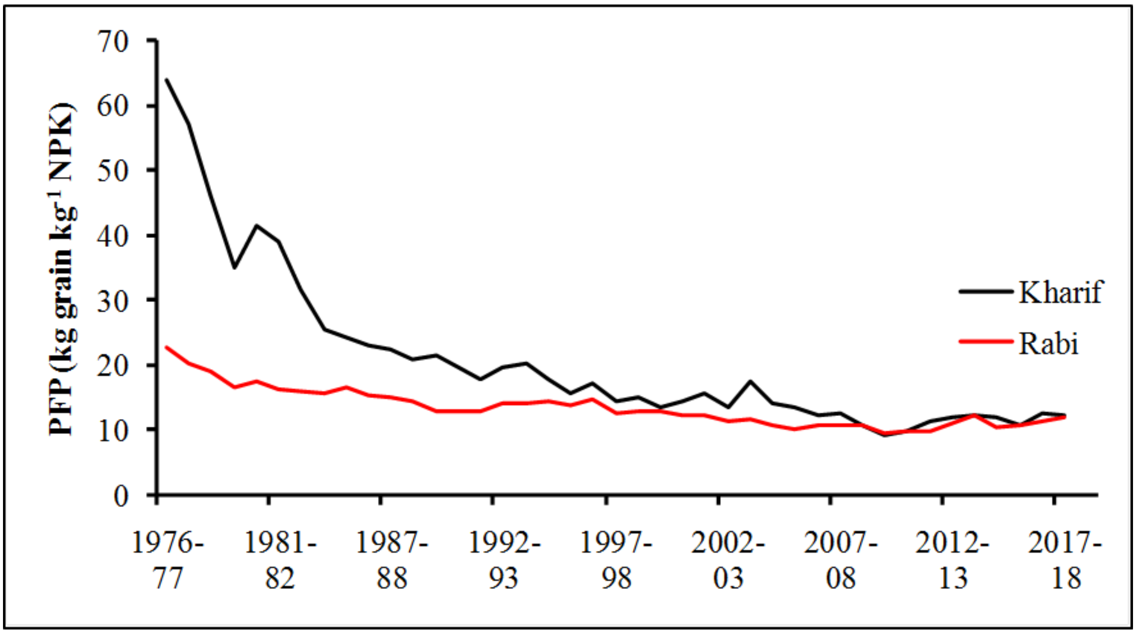

Figure 2. Partial factor productivity (PFP) of fertilizer nutrients (kg grains kg^{-1}NPK) used in kharif and rabi seasons for food grains production during 1975-2018.

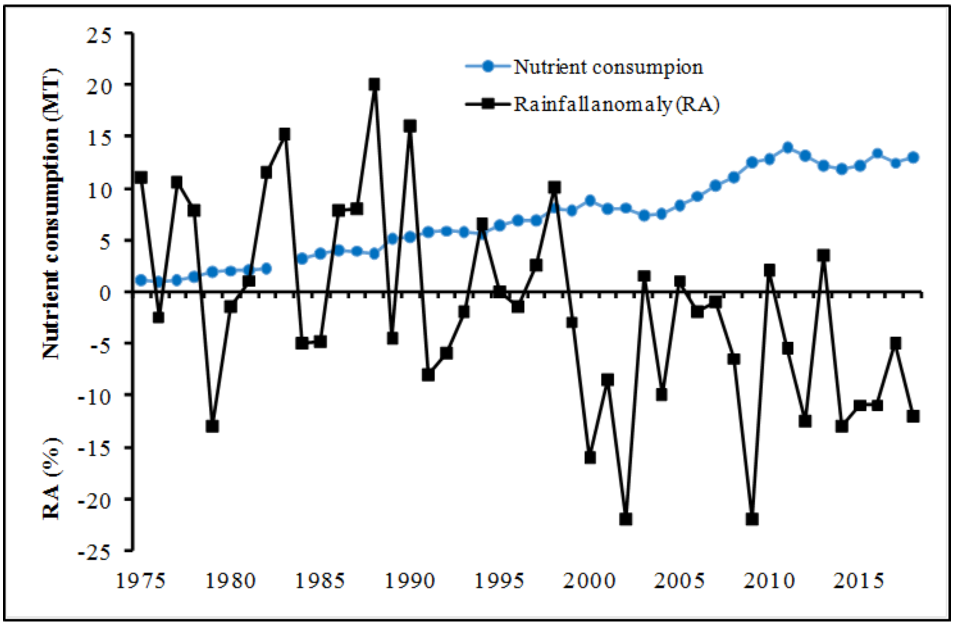

Figure 3. Dynamics of NPK nutrient consumption (MT) in kharif season and the rainfall anomaly (deviation from long-term mean)

use efficiency. Lassaletta et al. [45] also observed that nitrogen use efficiency of different cropping systems has been regularly decreasing over the past 50 years in India, China and Egypt. This suggests that crops cannot easily respond to increased fertilizer inputs without an improvement in fatigued agronomical practices [46]. In general, it has been observed that countries which use higher proportion of N inputs from symbiotic N_2 fixation and organic manures rather than from synthetic fertilizer have a better N use efficiency and lower environmental footprint. The reasons for declining PFP_F trends are mostly location specific but depletion of SOC has been suggested as a general cause in case of Inceptisol, Alfisol and Vertisol soils [47]. Sharp reductions in PFP_F in kharif season (Fig. 2) may also be because of climate change shocks as moisture deficits and rise in temperature have been reported to reduce kharif crop yields more [48-49] than the crops grown during the rabi season. Therefore the tipping point of Indian agriculture will continue to be how can we make sowing of kharif crops independent of the monsoon rains, improve PFP_F which in good measure also depends on the weakening of 'land degradation-food security- climate change' nexus of the summer monsoon rains.

Fertilizing to Bridge Yield Gaps

Maximum yield (under rainfed conditions) or potential yield (irrigated) at a given location is generally determined by solar radiation, temperature, and nutrient and water supplies to the crops. All these factors vary throughout the year, and therefore yield potential will depend not only on location but also on the crop-sowing and maturity dates.Half of the total yield gaps in rice-wheat systems of India have been attributed [50] to low fertility, late planting, soil moisture stresses, terminal heat, inappropriate cultivar choices and poor weed management.

Can High Yields and High NUE go together?

It is a common knowledge that yield increases are not linear with increase in single factor such as nitrogen. Mitscherlich [51] formulated the "law of declining yield improvement" which states that improvement in a growth factor increases the yield in proportion to the difference between maximum and the actual yield. It implies that the yield increases through nutrient additions but the difference between maximum and actual yield (Y_{max} - Y_{actual}) continues to become smaller and the efficiency of the specific fertilizer addition declines. A typical yield–nutrient response curve shown in fig 4 suggests that nutrient use efficiency is high at low yield levels and a small amount of nutrient application is likely to give large but diminishing yield response. When the crop yields are close to maximum, nutrient use efficiency is expected to be at its lowest. At maximum crop productivity, any effort to improve nutrient use efficiency further would warrant significant improvement in the production environment via sustainable land management (SLM) practices or via gains in genetic potential of the crop cultivars through appropriate breeding efforts or both. Breeding of wheat cultivars on conservation agriculture (CA) platforms for higher yields at Indian Agricultural Research Institute (IARI), New Delhi is a step in the this direction (Dr Rajbir Yadav. 2020 Personal Communication). New wheat cultivars (e.g. DBW 187, DBW 222), released recently by the Indian Wheat Improvement Program, suitable for early season planting in zero till situations harness benefits of conservation agriculture and enhanced genetic yield potential close to 10 Mg ha^{-1}.

It must be mentioned here that at low yield levels, crop cover will be less due to poor crop growth resulting from nutrient shortage. Reduced surface cover due to less vigorous crop growth results in decreased protection of soil from rainfall mediated soil erosion processes. On the upper end of the response curve, yields continue to improve, *albeit* at a slower rate.The extent of decline is best dictated by the better-bet crop and soil management practices (cultivar choices, zero-tillage, direct seeding, water management, residue management, 4R fertilizer management viz. right rate, right place, right time and right balance of chemical nutrients with organic manures and early seeding etc.) as well as climatic conditions. Mitscherlich's concept is extended by Baule to

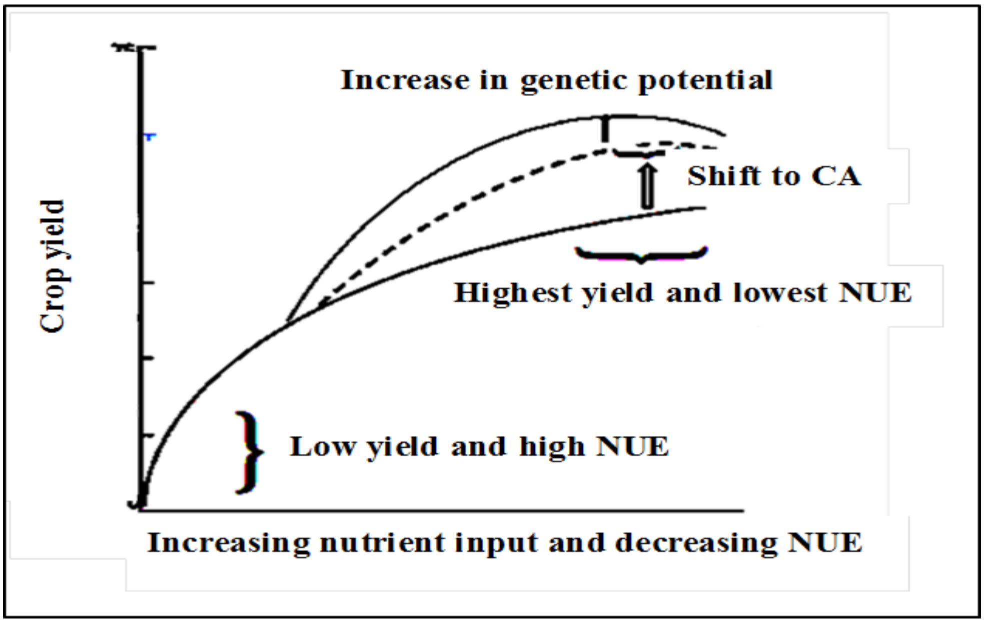

Figure 4. Schematic representation of the effects of shift to conservation agriculture (CA) and crop improvement oriented to sustainable land management practices on crop yield and nutrient use efficiency (NUE) (modified from Dibb [66])

Table 4. Soil mediated benefits of practicing conservation agriculture (CA)

	Resource Conserving Practices of CA			
Components of soils' productive capacity	No-Till/ Leveling	Mulching/ surface cover	Rotations/ Dry Seeding	Legumes
Physical	2	5	7	10
Chemical	-	-	9	12
Biological	3	6	8	11
Hydrological	1	4	13	-

1=Water infiltration, water percolation and moisture storage/ aquifer recharge, improves irrigation water application and use; 2= Stable and varied porosity; 3= Favors biological soil-layering;4=Buffers raindrop impact and diurnal temperature fluctuations in root zone; 5=Prevents soil-crusting and cracking; 6=Provide energy and nutrients for biota; 7= Augment channels and opens deep into soils; 8= enhance biodiversity in soils; 9=Beneficial root exudates promote biotic activity; 10= Favors development of optimum soil architecture (solids x spaces);11= Add N rich biomass; 12= Nitrogen fixation and nutrient mobilization; 13= Provide surface cover before rains and SWC. (Source: Adapted from Kassam).

simultaneous actions of two or more of growth limiting factors. The Baule rule states that the fractional yield of each individual factor must be multiplied to give total yield. Thus yield increases with additional Baule unit after the first, occurs only in a geometric fashion [52]. During the post Green Revolution era, intensive cultivation of cereal-cereal systems, excessive tillage, burning of crop residues, abandoning the use of organic manures and global warming has proved a big setback to efforts responsible for building SOC stocks which serve as an excellent store house of several micro- and secondary nutrients.As a consequence, beside NPK, presently many Indian soils suffer from multiple deficiencies [4] of several essential nutrients such as Zn, S, Mn, Fe, B, Ca and Mg. Multiplicity of simultaneous nutrient deficiencies drastically decreases crop response and nutrient use efficiency of major NPK fertilizer nutrients. Therefore, as we attain the achievable crop yields, close to potential yield, the nutrient use efficiency is likely to be at its lowest as depicted in fig. 4. The NAAS Report [8] had indicated that with available production technology, it is possible to increase rice and wheat production by 15–20 percent only. For a quantum jump we need a paradigm shift in our approach such as the one mentioned for wheat research above.

The performance of agriculture in the country can also be evaluated following the yield gap concept [53]. Yield gap defines the difference between the actual farmer's yield of a particular cultivar (Ya) and the potential yield (Ymax), which could be obtained in the same place in the absence of limitation by nutrient and water and any biotic pressure. Lassaletta et al. [45] applied the yield gap concept [53] and defined N limitation of a production system, using the dimensionless indicator [(Ymax-Ya)/Ymax] of the degree of N limitation, with all terms in the indicator expressed in protein-N. The yield gap expression [(Ymax-Ya)/Ymax] can simply be rewritten as (1- Ya/Ymax) to refer to unrealized yield gaps due to N nutrient limitations. When (Ya/Ymax equals >0.7, then the unrealized yield gaps (1- Ya/Ymax) due to nitrogen limitations is less than 0.3. For Indian agriculture, evidence[45] is that (1- Ya/Ymax) is less than 0.3, suggesting that there will be little or no expected yield benefits from simple increase of N fertilization without paradigm improvements in soil-water and crop management practices for cropping systems. Hence, Indian agriculture needs a paradigm shift in land management practices leading to sustainability of the agriculture during the Indian summer monsoon season.

Sustainable Land Management Practices for Improving Nutrient Efficiency

Decreasing productivity of the added nitrogen reflects loss in soil carbon and soil life disrupting paradigm of mechanical tillage which debilitates many important soil-mediated ecofunctions [54] including the improved crop performance [55]. The core resource conserving practices of CA can help in achieving a range of soil-mediated objectives listed in table 4 that improve the productive capacity of the soils. The enlisted outcomes from practicing CA can easily result in bridging the yield gaps and overcome stagnating yields [56] in some of the major crops in India, provided farmers combine efficient irrigation water management practices and conjunctive use of balanced fertilizers with quality seeds of well-adapted high yielding cultivars appropriate to different agro-ecozones.

Government Initiatives for Improving NUE

The low NUE observed for Indian agriculture systems appears to be related with excess dependence of farmers on synthetic fertilizers with little focus on N inputs derived from symbiotic N_2 fixation or other organic sources. When a significant proportion of the total arable lands in India are continuously devoted to production of rice, wheat, maize and sugarcane crops, the NUE is expected to be low. The logic warrants that area under cereal system must be reduced along with a paradigm shift in the way agriculture is currently practiced in the country. Ghosh[57] et al. [57] suggested that fertilizer nutrient re-allocation strategy from low responsive crops to more fertilizer responsive crops grown elsewhere can also be tried. Nutrient use efficiency, in general, and N use efficiency in particular is important for economic as well as environmental reasons. Worldwide, NUE for cereal production is as low as 33 per cent. The unaccounted 67 per cent is lost through leaching and gases polluting the environment and represents an annual loss of N fertilizer worth up to Rs. 72,000 crores [58,59]. Prasad [9, 60] reported that during the 1950–2008 period, fertilizer consumption in the country increased nearly 300 fold leading to a very low fertilizer use efficiency.

Government of India has taken several measures towards sustainable agriculture by giving greater importance to organic farming which promotes the use of organic manures and bio-fertilizers in agriculture. Reducing our dependence on the use of chemical fertilizers calls for (i) incorporating legumes in the cropping systems, (ii) promoting conjunctive use of organic and inorganic fertilizers (iii) relying on nutrient recycling through adoption of crops having different rooting systems, (iv) promoting beneficial symbiotic microbial associations, (v) deploying in-situ / ex-situ composting techniques to improve soil biotic activity, (vi) increasing biological N_2 fixation, (vii) green manuring, (viii) employing microbial inoculants to improve nutrient access in soils (arbuscular mycorrhiza and P solubilizing bacteria), (ix) using efficient fermented microbial formulations which are highly compatible with bio-enhancers which promote plant growth, yields, and healthy agro-ecosystems, and (x) promoting rational use of nutrients in cropping systems.

The other strategy requires promoting the adoption of production management systems (soil, water, crop and land management) that improve resource use efficiency and build soil organic carbon. The innovative production management systems should consider (i) tillage practices that reduce the rate of SOM decomposition, runoff and soil erosion, conserve soil moisture etc. to improve soil health (ii) inclusion of high biomass producing crops in cropping systems (iii) residue retention and recycling (iv) use of manures, (v) switch from monoculture to rotation cropping, (vi) annual to perennial crops, (vii) adoption of agroforestry systems and (viii) avoiding sudden land use change [61-62]. On the scales, it appears that to be able to move in the 'implied direction', it's even more important that we reorient our production management systems such that they begin to promote and enhance agroecosystems health under new realities of climate change. Production management system needs to promote adoption of soil, water, and crop management strategies that build SOC and improve resource-use efficiency together with enhanced production. Conservation agriculture, which is close to organic farming, is one such innovative approach to manage production systems. Conservation agriculture allows use of agrochemicals and its yield potential is hardly debatable, unlike organic farming.

Summary and Conclusions

Globally, researchers seem to be in general agreement that inclusion of M^3 research namely, soil Organic Matter, soil Microbes and soil Moisture retention, is critical in arresting and reversing soil degradation processes. M^3 soil attributes enhance soil productivity, improve nutrient and water use efficiency, reduce production costs and significantly benefit the environment. There is an urgent need to move away from the traditional tilled agriculture (having many conflicting and unsustainable practices) to CA production management system. Conservation agriculture has the targeted effect in reducing the use of synthetic fertilizers through slowed SOM decomposition, reduced soil erosion during rainy season through residue retention and brown manuring (green manure crop knocked down through herbicide to provide surface mulch) and avoidance of summer deep plowing. Conservation agriculture is more carbon efficient and sequesters more organic carbon which is central to continued delivery of soil eco-functions [63].

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Conflict of Interest

The authors declare no conflict of interest

Data availability

All data are included within the paper

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