Journal of Soil Science and Plant Nutrition (2022) 22:1832–1845
https://doi.org/10.1007/s42729-022-00775-2

ORIGINAL PAPER

Nutrient Budget in Indian Agriculture During 1970–2018: Assessing Inputs and Outputs of Nitrogen, Phosphorus, and Potassium

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Received: 3 September 2021 / Accepted: 12 January 2022 / Published online: 25 January 2022

Abstract

Chemical fertilizer has contributed significantly in increasing food grain production in India. However, there are emerging concerns of environmental pollution at local scale, climate change at global scale, and sustainability of chemical fertilizer-dependent agriculture. Budgeting of nutrient is a valuable tool in assessing the nutrient use efficiency, nutrient mining, and environmental pollution. We constructed a field level top-down nutrient budget for food grain production in India since the onset of the Green Revolution in the country, i.e., 1970 to 2018, using equation-based empirical methods. Total nutrient input to Indian agriculture was 666.4 million tons (Mt) of N, 189.1 Mt of P, and 244.8 Mt of K during 1970–2018. Chemical fertilizer contributed 68.1% of N, 91.3% of P, and 28.8% of K towards the inputs. Nutrient budget for the last 48 years showed that there was positive balance of N (12.2 Mt), accumulation of P (11.7 Mt) but negative balance for K (157.9 Mt). Further, with the business-as-usual scenario, there would be positive balance of 276.2 Mt N, accumulation of 20.9 Mt P, and negative balance of 202 Mt K from Indian agriculture soils by 2050. The nutrient budget provides valuable information on the present status and balance of nutrient use and the trends with time, which will be helpful for reorienting the fertilizer use policies for sustainable agriculture.

Keywords Fertilizer · Manure · Nutrient inputs · Nutrient outputs · Nutrient use efficiency

1 Introduction

The Green Revolution in India during the 1960s occurred mainly because of the use of high-yielding varieties of the field crops, development of irrigation facilities, and use of chemical fertilizer. With the Green Revolution, the food grain production in the country increased by about 170%, i.e., from 105 million tons (Mt) in 1970 to 284 Mt in 2018 (Fig. 1a) (FAOSTAT 2021). Correspondingly, per capita food production also increased from 189.7 in 1970 to 209.6 kg in 2018 (Fig. 1a). Consumption of nitrogen (N) and potassium (K) fertilizer increased by about 12 times, and phosphorus (P) fertilizer by 13 times in the country during the period (FAI 2020) with a strong correlation between fertilizer use and food grain production (Fig. 1b).

Application of nutrients is crucial for sustainable management of soil health. Indian soils with low organic C content (less than 0.5%) and poor nutrient supplying capacity need to be supplemented with external sources of nutrients to harvest high yield. India's present food grain production mostly relies on the intensive agricultural practices with considerable use of fertilizer and pesticides. Indiscriminate use of chemical fertilizers has become a global concern that could accelerate environmental pollution, degrade natural resource base, and increase health hazards (Evans et al. 2019). Despite considerable developments in fertilizer use research, the recovery efficiency of applied fertilizer is low, i.e., 30–40, 20–25, and 40–50% for N, P, and K, respectively (Chien et al. 2009; Pathak et al. 2019). The main loss pathways are (1) leaching, predominantly of nitrate and potassium but also of nitrite, ammonium, and soluble organic N; (2) denitrification, resulting in emissions of nitrous oxide (N_2O) and dinitrogen (N_2); (3) volatilization of ammonia into the atmosphere; and (4) erosion of mostly K and P and to some extent N (Fagodiya et al. 2017; Goulding et al. 2021; Pathak et al. 2019; Thomson et al. 2012). Globally,

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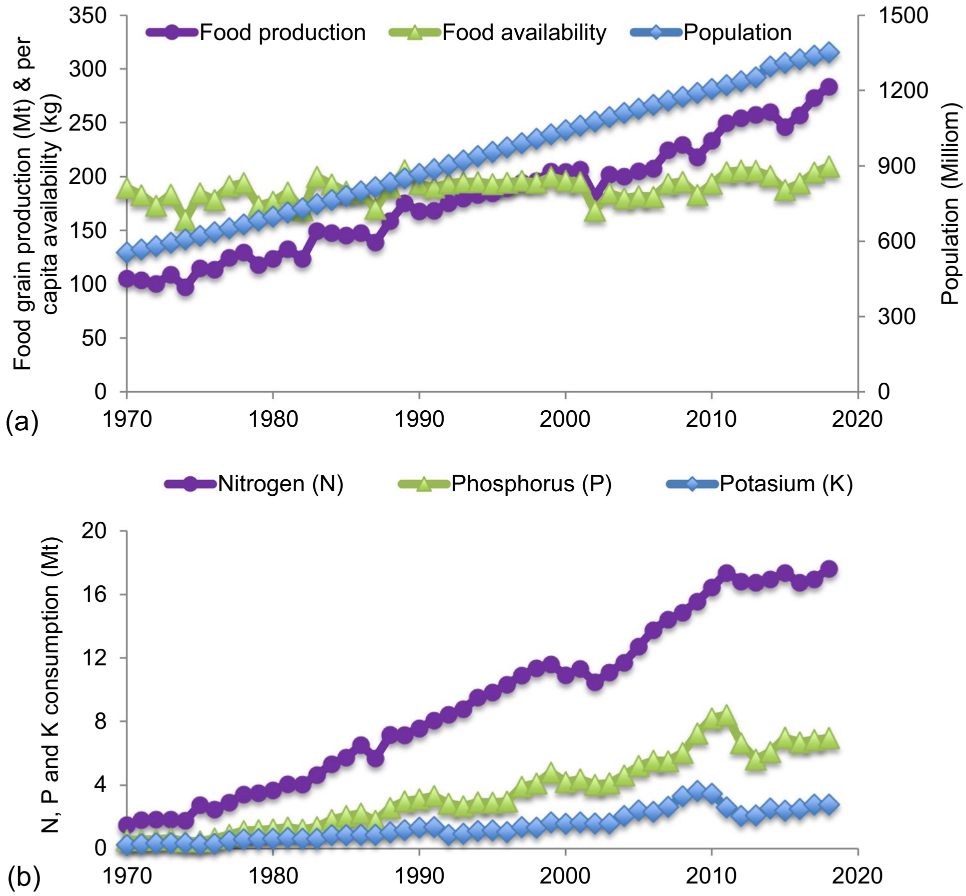

Fig. 1 **a** Production of food grain, population growth, and per capita availability of food grain and **b** consumption of N, P, and K fertilizer in India during 1970–2018

about 33% of the fertilizer N used in agriculture contributes to the transient effects on the agro-ecosystems, and the remaining 67% is converted back to atmosphere as N_2 (Ladha et al. 2016).

The Government of India spent 6.3 billion US$ in 2018–2019 on subsidy for urea fertilizer alone, which increased to 7.4 billion US$ in 2019–2020 and to 12.8 billion US$ in 2020–2021 (MoF 2021). During 2018, the fertilizer consumption in India was 17.63 Mt of N, 6.97 Mt of P, and 2.78 Mt of K, which was 16.22%, 17.14%, and 7.15% of global fertilizer consumption (FAOSTAT 2021). Since 1961, the N, P, and K fertilizers consumption in India increased by 71, 115, and 99 times (FAOSTAT 2021). The increased consumption of fertilizers, particularly N fertilizer, enhances crop production, lowers the partial factor productivity (PFP) and N use efficiency (NUE), and enhances the gaseous emissions causing atmospheric pollution with ammonia (NH_3) and global warming with nitrous oxide (N_2O). The N_2O emissions from Indian agricultural fields were estimated to be 61 Tg CO_2e during 2004 (Bhatia et al. 2004). The 100-year global warming impacts of N added to Indian agricultural soils increased from 41.50 Mt CO_2e in 1961 to 217.31 Mt CO_2e in 2014 (Fagodiya et al. 2020).

Consumption of N and P fertilizers in the country has risen sharply but use of K fertilizer remains very low resulting in an imbalanced nutrient use. Therefore, there is a need for a reliable assessment of different sources and sinks of N, P, and K to optimize the nutrient use and to reduce the pollution impacts. Nutrient budgeting of an agro-ecosystem could be a powerful tool for assessing the fate of different nutrients (Pathak et al. 2010; Swaney et al. 2015). The nutrient budgeting in major watershed of the country was estimated by Swaney et al. (2015). Pathak et al. (2010) assessed the N, P, and K budgets in different states of the country for the year 2000–2001. In the current analysis, a long-term field level nutrient budget, i.e., 1970–2018, for Indian agriculture was estimated. The objectives of the present study were to evaluate the long-term (1970–2018) nutrient budget; identify the major sources, sinks, and losses of nutrients in Indian agriculture; predict the N, P, and K budgets up to 2050 with the business-as-usual scenario; and suggest options for enhancing use efficiency and loss of nutrients.

2 Materials and Methods

2.1 Calculation of N, P, and K Budgets

Annual N, P, and K budgets (Mg $year^{-1}$) were calculated using Eqs. (1), (2), and (3), respectively.

$$\text{N budget} = \sum(\text{N input}) - \sum(\text{N output} + \text{N loss}) \quad (1)$$

$$\text{P budget} = \sum(\text{P input}) - \text{P output} \quad (2)$$

$$\text{K budget} = \sum(\text{K input}) - \sum(\text{K output} + \text{K loss}) \quad (3)$$

Here, removals of applied (input) N, P, and K nutrient by crops were considered as nutrient output and the fraction of input N and K which was not taken up by crops and subjected to loss by means is considered as nutrient loss from the soil system.

2.2 Inputs of N, P, and K

To calculate the total inputs of N, the following Eq. (4) was used.

$$\text{N input}\left(\text{Mg year}^{-1}\right) = N_{IN} + N_{AM} + N_{CM} + N_{GM} + N_{LG} + N_{NL} + N_{CR} + N_{SN} + N_{RN} + N_{IR} \quad (4)$$

where N_{IN}, N_{AM}, N_{CM}, N_{GM}, N_{LG}, N_{NL}, N_{CR}, N_{SN}, N_{RN}, and N_{IR} are the inputs of N with inorganic fertilizer, animal manure, compost, green manure, leguminous fixation, non-leguminous fixation, crop residues, seed, rain, and irrigation, respectively.

The data for inorganic fertilizer N were obtained from the FAOSTAT (2021). The N input through atmospheric deposition was estimated by extrapolation of results of Liu et al. (2010). Contributions of seed for N inputs were on the basis of seed rate of different crops and their N content. Contribution of irrigation water in N addition was calculated based on Pathak et al. (2010).

The contribution of manure was calculated based on FAOSTAT data of manure N applied to soil and its N content (Table 1). It was considered that some of the manure is lost during the collection, used as construction material, and also burnt as domestic fuel. Only the remaining amount of animal manure is applied to agricultural soil. The N input in Indian agriculture due to use of animal manure (N_{AM}) was calculated using the following Eq. (5).

Table 1 Contents of N, P, and K in manure and compost. The values are the averages obtained from a comprehensive review of published literature (FAI 2015–2020; Ladha et al. 2016; Pathak et al. 2010; Subrian et al. 2000)

Source	Nutrient content (%)		
	N	P	K
Manure (bovine)	1.00	0.15	0.45
Manure (goat and sheep)	1.87	0.35	1.00
Compost (urban)	1.50	0.40	1.20
Compost (rural)	0.60	0.20	1.42

$$N_{AM} = \sum\nolimits_T \left(N_T x N_{ex(T)}\right) x\left[1 - \left(AM_{CL} + AM_{FL} + AM_{CN}\right)\right] \quad (5)$$

where T represents the number of livestock category (sheep, goat, buffalo, and cattle); N_T represents the total number of animals in each category; $N_{ex(T)}$ is the average annual N excretion (Mg year^{-1} head^{-1}) for each livestock category; and AM_{CN}, AM_{CL}, and AM_{FL} represent the fractions of animal manure, which are lost during collection, used as construction material, and burnt as fuel, respectively. The values of these fractions were taken from Pathak et al. (2010).

Contribution of biologically fixed N (N_{LG}) was calculated using the following Eq. (6) (IPCC 2006).

$$N_{LG} = \sum\left(LG_{GY} * LG_{GN}\right) \quad (6)$$

where LG_{GY} represents grain yield of leguminous crops (Mg ha^{-1}) and LG_{GN} is the N content in grain (Table 2). Data of the grain yield for leguminous crops were obtained from FAOSTAT (2021).

In addition, a considerable amount of N is fixed in soils of rice (lowland) and aerobic (upland) crops. The free-living and non-symbiotic microorganisms play an important role in this fixation. Blue green algae fix about 10 kg N ha^{-1} in rice crop and the free-living microbes fix about 5 kg N ha^{-1} in aerobic soils (Regmi et al. 2002). To calculate the N fixation by non-leguminous crops in soil, the following Eq. (7) was used.

$$N_{NL}\left(\text{Mg N year}^{-1}\right) = \text{Area of lowland rice(Mha)}x10\left(\text{kg N ha}^{-1}\right) + \left[\text{Total agricultural area(Mha)} - \text{area of lowland rice (Mha)}\right]x5\left(\text{kg N ha}^{-1}\right) \quad (7)$$

Amount of N added to soils with the incorporation of the crop residues (N_{CR}) was calculated using the Eq. (8).

$$N_{CR}\left(\text{Mg N year}^{-1}\right) = \sum 0.05x(SYxSN) \quad (8)$$

where SY is straw yield (Mt), SN is straw N content of non-leguminous crops, and 0.05 is the fraction of straw that is incorporated into the agricultural soil (Pathak et al. 2010; Ladha et al. 2016). All the major crops grown in India such as rice, wheat, maize, pearl millet, sorghum, barley, small millets, jute, cotton, and sugarcane were included in the calculation. Residues of several crops are used for fuel, feed for animal, and other domestic purposes in India. Some of the

Table 2 Harvest index and N, P, and K contents in grain and residues of various crops used for the estimation of nutrient budget in Indian agriculture. The values are the averages obtained from a comprehensive review of published literature (FAI 2015–2020; Ladha et al. 2016; Pathak et al. 2010)

Crop	Harvest index	N content (%)		P content (%)		K content (%)	
		Grain	Residues	Grain	Residues	Grain	Residues
Rice	0.40	0.93	0.36	0.16	0.06	0.91	0.35
Wheat	0.37	1.41	0.53	0.21	0.08	1.06	0.40
Sorghum	0.40	1.64	0.40	0.43	0.10	2.07	0.51
Pearl millet	0.40	3.26	0.65	0.76	0.15	5.82	1.16
Maize	0.40	2.00	0.42	0.46	0.10	2.27	0.48
Ragi	0.40	2.38	0.40	0.39	0.07	2.60	0.44
Small millets	0.40	2.38	0.40	0.39	0.07	2.60	0.44
Barley	0.37	1.16	0.53	0.19	0.09	1.18	0.54
Chickpea	0.20	2.72	0.72	0.14	0.06	1.56	0.64
Pigeon pea	0.20	2.38	1.00	0.29	0.12	1.31	0.55
Groundnut	0.25	4.82	0.33	0.71	0.05	2.08	0.14
Soybean	0.25	5.33	0.45	0.62	0.05	2.95	0.25
Sugarcane	0.70	0.02	0.35	0.00	0.02	0.02	0.34
Cotton	0.50	4.01	0.44	1.11	0.12	5.61	0.62
Jute	0.50	1.60	0.75	0.39	0.18	2.37	1.11

residues are also burnt on field to clear and prepare the field for the next crop. Thus, a small amount of crop residues is incorporated into the soil. Amount of crop residues used for animal feed, burned for fuel, and incorporated into soils were assessed according to IPCC (2006) and Smil (1999). The amount of N addition to soil through crop residue incorporation was calculated using the N content of crop residues (Table 2). Data on grain yield (GY in Mt) and harvest index (HI, Table 2) of the crops were used for the calculation of straw yield (SY in Mt) using the following Eq. (9).

$$SY = (GY/HI) - GY \tag{9}$$

Equations (10) and (11) were used for the calculation of P and K inputs, respectively.

$$\text{P input}\ \left(\text{Mg P year}^{-1}\right) = P_{IN} + P_{AM} + P_{CM} + P_{CR} + P_{SP} + P_{RN} + P_{IR} \tag{10}$$

where P_{IN}, P_{AM}, P_{CM}, P_{CR}, P_{SB}, P_{RN}, and P_{IR} are the inputs of P with inorganic fertilizer, animal manure, compost, crop residues, seed, rain, and irrigation, respectively.

$$\text{K input}\ \left(\text{Mg K year}^{-1}\right) = K_{IN} + K_{AM} + K_{CM} + K_{CR} + K_{SK} + K_{RN} + K_{IR} \tag{11}$$

where K_{IN}, K_{AM}, K_{CM}, K_{CR}, K_{SK}, K_{RN}, and K_{IR} are the inputs of K with inorganic fertilizer, animal manure, compost, crop residue, seed, rain, and irrigation, respectively.

The data on P and K fertilizer consumption in Indian agriculture were obtained from FAOSTAT (2021). Contributions of manure, compost, and crop residues for P and K inputs were calculated by multiplying P and K contents in manure, compost, crop residues, and seed, respectively, using the methodology similar to the calculation of N inputs. Irrigation water and rain were considered to contain 0.05 and 0.1 mg L^{-1} P and 2.0 and 0.7 mg L^{-1} K, respectively (Regmi et al. 2002).

2.3 Output of N, P, and K

Removals of N, P, and K by each crop were calculated based on the removal of nutrients by the above ground biomass (grain and straw) to produce 1 Mg of economic (grain) yield. The nutrient removal values consider the quantity of crop products (grain and straw), nutrient concentration of crop products, and proportion of crop products exported from the fields. The removals of nutrients for each crop, i.e., rice (Witt et al. 1999), wheat (Pathak et al. 2003), and other crops (FAI 2015–2020), have been derived based on a large number of datasets from different regions, crop varieties, and management practices to capture the diversity of nutrient concentrations in grain and straw. Recovery efficiency of fertilizer N was based on Ladha et al. (2005, 2016) and was used to calculate the losses of N from soil–plant system. The fraction of fertilizer N added to agricultural soil, which was not recovered/uptake by crops, is considered as loss of N. Recovery of N applied through manure was based on van Groenigen et al. (2004); Krishnakumar et al. (2013); and Ladha et al. (2016), and the recovery of crop residue N was based on IAEA (2003). Non-symbiotic N_2 fixation generally occurs in the rhizosphere soil. Hence, its recovery efficiency was assumed very high (80%). Similarly, recovery efficiency of N added through seed was estimated to be 80%. Recovery efficiency of deposition N was taken equal to fertilizer N because both will behave similarly in soils due to inorganic form. The unrecovered fraction of N added through various sources was considered as loss of N from the soil (Ladha et al. 2016). Most of the added P is fixed in the soil system;

therefore, no loss of P was assumed from soil through leaching. Fifteen percent of applied K has been considered as the leaching losses of K (Regmi et al. 2002).

Linear model equations were developed for prediction inputs, outputs, and balance of N, P, and K for the period 2019–2030 and 2019–2050 using the dataset from 1970 to 2018.

2.4 Nutrient Use Efficiency

The PFP and recovery efficiency (RE)/partial nutrient balance (PNB) of nutrients were calculated using the Eqs. (12) and (13), respectively (Dobermann 2007; Norton et al. 2015). The PNB is the simplest form of nutrient RE and sometimes used as RE (Fixen et al. 2015).

$$\text{Partial factor productivity}\left(\text{kg nutrient kg}^{-1}\text{yield}\right) = \text{Grain production (kg)/Nutrient applied (kg)} \quad (12)$$

$$\text{Recovery efficiency}\left(\text{kgkg}^{-1}\right) = \text{Removal of nutrient by crop (kg)/Nutrient applied (kg)} \quad (13)$$

3 Results and Discussion

3.1 N Budget

During 1970–2018, Indian agriculture received a total N input of 666.4 Mt (Table 3). Fertilizer contributed the majority of N input (68.1%) followed by deposition (14.1%). The fertilizer N consumption increased over the time and the consumption was 11.7 times more in 2018 (17.6 Mt N year^{-1}) than in 1970 (1.5 Mt N year^{-1}) (Fig. 2a). The average N consumption per unit agricultural area from all sources increased from 58.0 during 1970–1980 to 172.3 kg N ha^{-1} year^{-1} during 2010–2018 (Fig. 3). The total N output during the last 48 years from 1970 to 2018 was 298.8 Mt (Table 3). The total 242.0 Mt of added N that is not taken by crops was most likely lost to the environment (Table 3) with 46.7% recovery efficiency (Table 4). Some portion of N is also mobilized in the soil and contributes to enrich the soil organic matter pools (Jacoby et al. 2017). The N budget showed an accumulation of 12.2 Mt (Table 3), which is equal to 1.8 kg N ha^{-1} year^{-1} (Table 5). The positive N balance in Indian agricultural soil was also estimated by Krishna Prasad et al. (2004), Krishna Prasad and Badarinath (2006), Murugan and Dadhwal (2007), and Pathak et al. (2010).

Inputs and outputs of N in Indian agriculture have changed dramatically in 2018 compared to that of 1970 (Fig. 4). The consumption of fertilizer N has increased 12 times, whereas manure use has increased by 1.4 times. Inputs of N through crop residues and biological fixation as well as removal of N by crops have increased by 2.7–2.9 times. However, loss of N has increased by 4 times. For the predicted scenario of 2050, N inputs were higher than the outputs over the years (Fig. 5a) and the difference between the input and output increases over the years leading to more accumulation of N in Indian soils (Fig. 5a and d). If the present trends continue with business-as-usual scenario, Indian agriculture will receive a total of 1150.2 Mt of N input with an output of 874.8 Mt, leading to 276.2 Mt of N accumulations and/or increasing N losses during 2019–2050 (Table 6). These results suggest the need for the better management of N fertilizers to enhance the NUE and reduce environmental pollution; although the numbers provide a fairly good idea of the nutrient budget in the coming years in the business-as-usual scenario, the predicted values will vary depending upon the population growth, food requirement, change in food habit, and development of new fertilizer technologies including new fertilizer products and methods of application.

Table 3 Budget of N, P, and K in Indian agriculture during the last 48 years (1970–2018)

Inputs and outputs		N (Mt)	P	K	Total
Inputs	Fertilizer	454.0	172.7	70.4	697.0
	Manure†	56.1	5.0	28.1	89.2
	Crop residue	22.7	4.5	36.3	63.6
	Biol. fixation‡	36.9	0.0	0.0	36.9
	Deposition*	94.1	5.5	107.5	207.2
	Seed	2.6	1.4	2.6	6.5
	Total	666.4	189.1	244.8	1100.4
Outputs	Crop removal	298.8	50.0	287.0	635.9
	Loss/unavailable	242.0	150.8	115.7	621.9
	Total	654.3	200.8	402.7	1257.8
	Change in soil♣	12.2	−11.7	−157.9	−157.4

†Manure = includes green manure, animal manure, crop residues, and compost

‡Fixation = includes symbiotic N fixation by leguminous crops, N fixation by blue green algae in lowland rice, and free-living N fixation in aerobic crops

*Deposition = includes addition of nutrient through rain, irrigation, and grazing animal

♣Change in soil = inputs − outputs. For P, it includes fixation into unavailable forms in soil

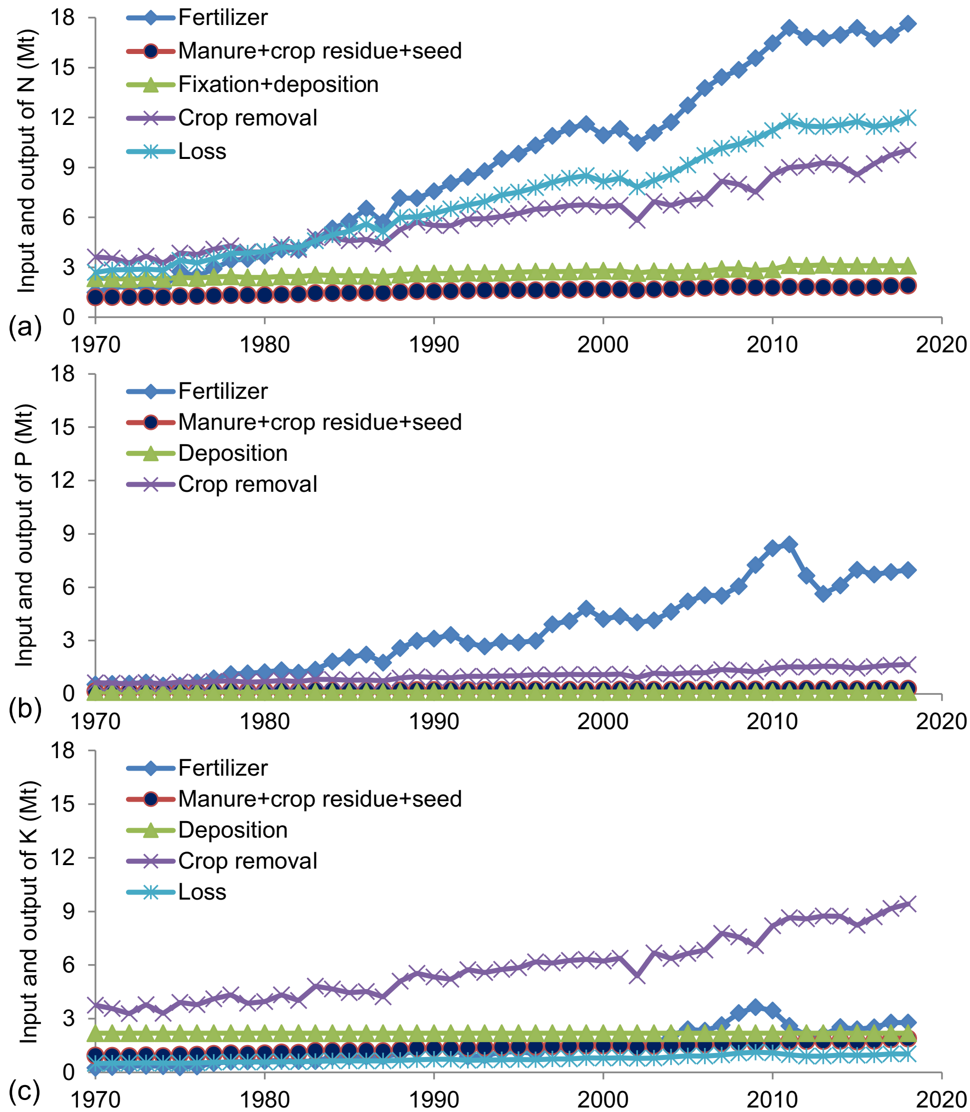

Fig. 2 Inputs and outputs of (**a**) N, (**b**) P, and (**c**) K from various sources in Indian agriculture during 1970–2018

3.2 P Budget

Total P input during 1970–2018 was 189.1 Mt and fertilizer contributed the maximum (91.3%) of this, and contribution of other sources (manure, crop residues, and deposition) was small (Table 3). Fertilizer P consumption increased by 12.9 times from 1970 (0.54 Mt) to 2018 (6.97 Mt) (Fig. 2b). The consumption of P increased with a linear trend over the year (Fig. 2b) with a 48-year average consumption of 25.1 kg P ha^{-1} year^{-1} (Fig. 3). During 1970–2018, total P removal by crops was 50.0 Mt (Table 3) with the average annual removal of 7.3 kg P ha^{-1} year^{-1} (Table 5). Most of the added P is fixed or converted into unavailable form in the soil system. Several earlier studies reported that losses of P due to leaching and runoff are negligible (Bhandari et al. 2002; Regmi et al. 2002; Gami et al. 2001). Therefore, it was assumed that there would be no loss of P through leaching and runoff. The output of 150.8 Mt of P (Table 3) accounts for P fixed in the soil system, which can be made available during the subsequent crops. Overall, a negative balance (P fixed in soil) of 11.7 Mt P in agricultural soils of India during 1970–2018 is estimated (Table 3) with an average annual negative balance of 1.7 kg P ha^{-1} year^{-1} (Fig. 6, Table 5). Lun et al. (2018) reported a cumulative increase of 11.4 Mt P in Indian crop land soil for 9 years from 2002 to 2010. Linear model equations for hypothetical prediction of P input and output are given in Table 6. Trends showed that difference between input and output is decreasing over the time (Fig. 5b and e) leading to a balanced use of P by 2030 (Fig. 5e). If the trend continues, P input will be 327.3 Mt and output will be 325.3 Mt by 2050 leading the net balance of 2.1 Mt of P in Indian agriculture (Table 6).

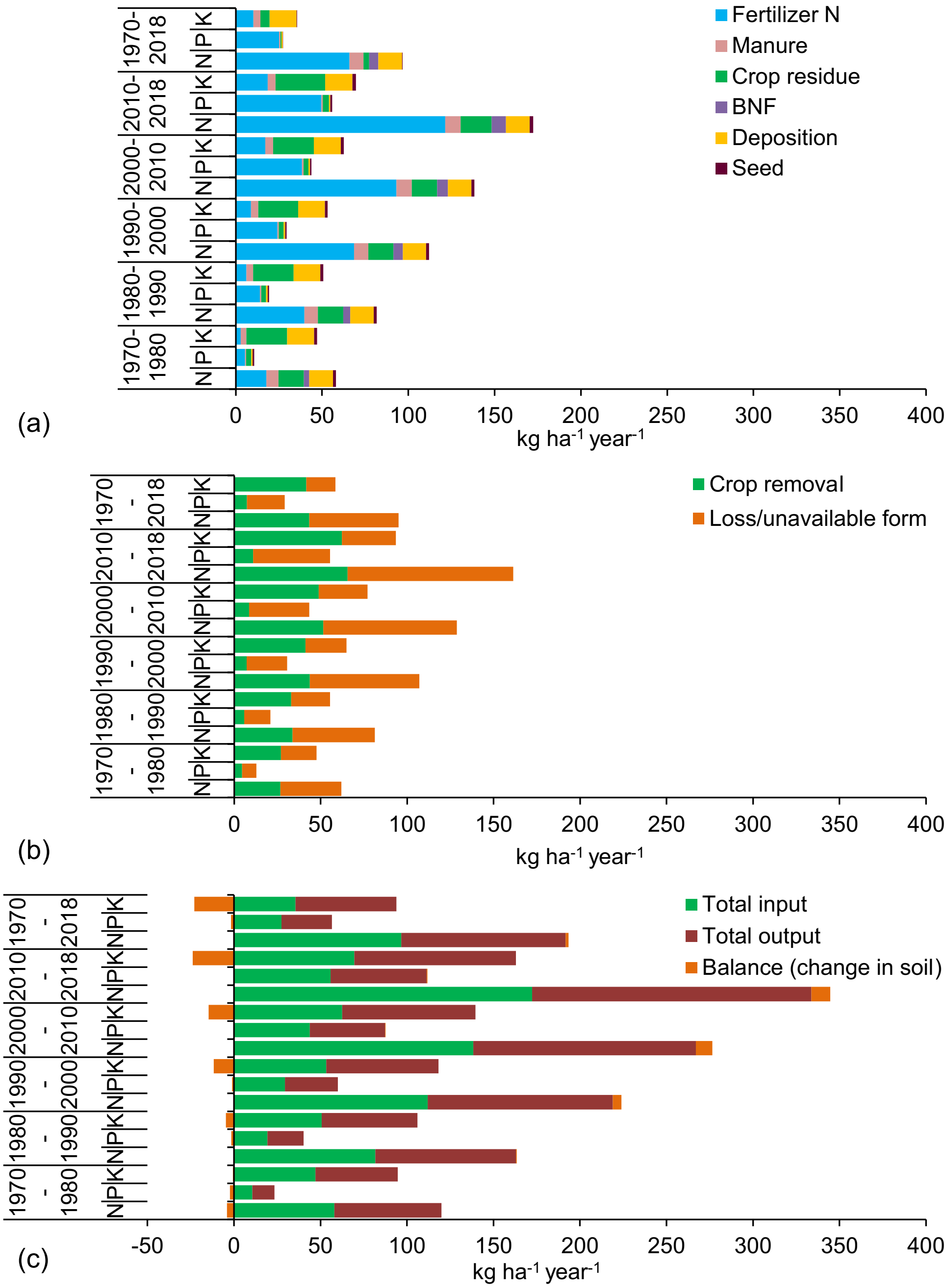

Fig. 3 Inputs (**a**), output (**b**), and balance (**c**) of nutrients in Indian agriculture during 1970–2018

Table 4 Recovery efficiency of nutrients from various sources in Indian agriculture. The values are the averages obtained from a comprehensive review of published literature (FAI 2015–2020; Ladha et al. 2016; Pathak et al. 2010; Subrian et al. 2000)

Source	N	P	K
	(% of applied nutrient)		
Fertilizer	46.7	20.0	50.0
Manure	37.7	25.0	60.0
Crop residue	10.0	25.0	60.0
Biological fixation	80.0	0.0	0.0
Deposition	46.7	20.0	50.0
Seed	80.0	25.0	60.0

3.3 K Budget

During 1970–2018, Indian agriculture received a total of 244.8 Mt of K input (Table 3). The majority of K came from rain, irrigation water, and grazing of animal (107.5 Mt) contributing about 43.9% of total K input. It was followed by fertilizer, crop residues, and manure, and fertilizer K contributed only 28.8% to total K input (Table 3). During the period, fertilizer K consumption increased by 11.6 times, i.e., 0.24 Mt in 1970 to 2.78 Mt in 2018, with the 48-year average of 10.2 kg K ha^{-1} year^{-1} (Fig. 3). The contribution of soil, deposition, and fertilizer in total K removal by crop

Table 5 Average contributions of different sources to nutrient removal by crops in Indian agriculture during 1970–2018

Source	N (kg ha^{-1} year^{-1})	P	K
Fertilizer	30.8	5.0	5.1
Manure	3.1	0.2	2.4
Crop residue	0.3	0.2	3.2
Biol. fixation	4.3	0.0	0.0
Deposition	6.4	0.2	7.8
Seed	0.3	0.1	0.2
Soil	− 1.8	1.7	22.9
Total	43.4	7.3	41.6

is 22.9, 7.8, and 5.1 kg K ha^{-1} year^{-1}, respectively (Table 5). Overall, a negative balance of 157.9 Mt of K was estimated from the agricultural soil of country during the 48 years period (Tables 3 and 6) with the depletion of 22.9 kg K ha^{-1} year^{-1}. The linear model equations showed that difference between K input and output is increasing (Fig. 5f) leading to the imbalance of K in agriculture soils. With the present scenario of K application, there would be further negative balance of 202 Mt of K in Indian agriculture by 2050 (Table 6). These results suggested that there is an immediate need for the adequate application and supply of K fertilizers to agricultural crops in India for sustaining the productivity.

3.4 N:P:K Ratio

Generally, the mass ratio of N, P, and K consumption is used to measure the degree of imbalance of one nutrient relative to another. A ratio of 4:2:1 of N:P:K application through fertilizers is considered to be optimum (FAI 2007). During 1970–2018, the country had an N:P ratio varying between 2.0:1 and 3.8:1, except in 1 year when it increased up to 5.9:1 (Fig. 7). The N:K was, however, much wider than the optimum ratio 4:1. It varied between 5:1 and 8:1, and in a few occasions, it increased up to 9:1 or more, which sowing the imbalance application of N and K in India (Business Standard 2021).

3.5 Partial Factor Productivity and Nutrient Use Efficiency

Partial factor productivity of fertilizer N consistently decreased from 71.2 in 1970 to 16.1 kg grain kg^{-1} N in 2018 (Fig. 8a). The recovery efficiency of N also decreased from 2.44 to 0.57 kg N removal kg^{-1} N applied during the period (Fig. 8b). The partial factor productivity since 1998 remained between 15 and 17 kg grain kg^{-1} N, which is much lower than the global (44 kg grain kg^{-1} N) and South Asia (41 kg grain kg^{-1} N) average PFP (Fixen et al. 2015). Moreover, N use per unit area since 1970 has increased by 11 times but per unit area, food grain production has increased by 4 times only. This indicates that there are declines in N use efficiency. The cropping system NUE in India decreased from about 55 during 1960 to about 35% during 2009 (Lassaletta et al. 2014).

Partial factor productivity as well as recovery efficiency of P and K fertilizers showed similar trends but with different magnitudes (Fig. 8). Partial factor productivity of P decreased from 195.1 during 1970 to 40.7 kg grain kg^{-1} P during 2018 (Fig. 8a). Overall, partial factor productivity of P varied between 28.4 and 244.5 kg grain kg^{-1} P and since 1998, it remained below 50 kg grain kg^{-1} P. The recovery efficiency of P also decreased from 1.16 to 0.24 kg P output kg^{-1} P applied during the period (Fig. 8b). Likewise, partial factor productivity of K decreased from 438.9 to 102.0 kg grain kg^{-1} K during 1970 to 2018 (Fig. 8a). Since 1998, partial factor productivity of K remained stable near about 100 kg grain kg^{-1} K. The recovery efficiency of K also decreased from 15.63 applied during 1970 to 3.39 kg K output kg^{-1} K (Fig. 8b). Partial

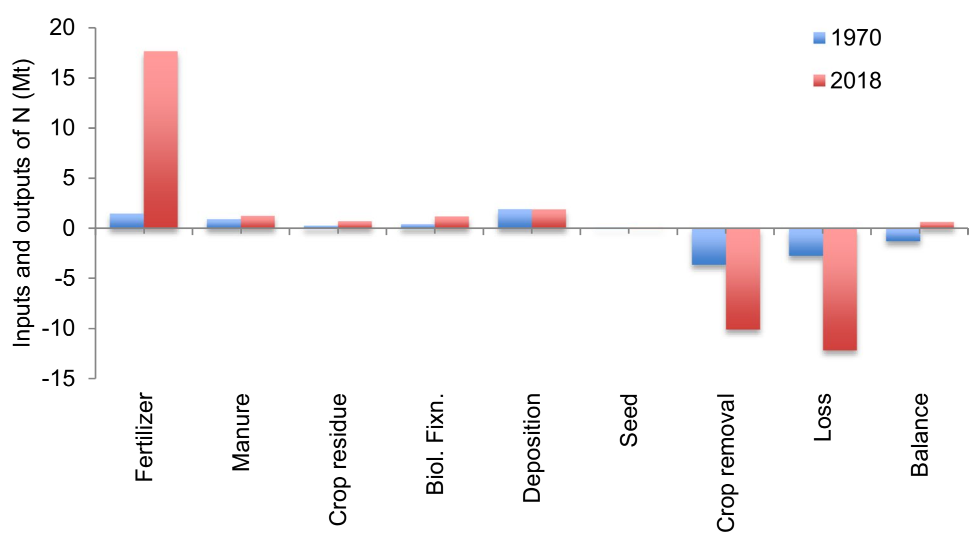

Fig. 4 Inputs and outputs of N in Indian agriculture in 1970 and 2018

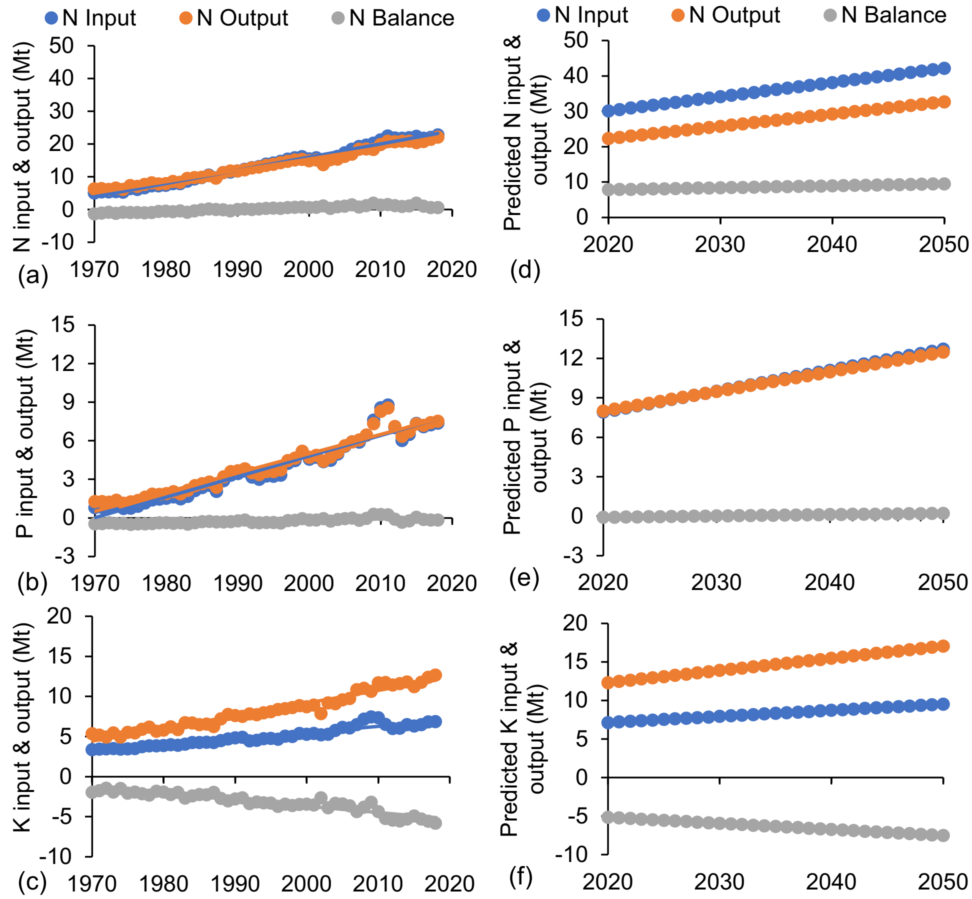

Fig. 5 Total inputs and outputs of N (**a**), P (**b**), and K (**c**) in Indian agriculture during 1970–2018 and predicted values of N (**d**), P (**e**), and K (**f**) for 2019–2050

factor productivity of N, P, and K remained stable since 1998 and not decreasing with the pace as it was during 1970s and 1980s. This is because of better management of fertilizer by the farmers due to large-scale adoption of soil testing for efficient fertilizer use, development of better fertilizer materials such as neem-coated urea, increasing cost of fertilizer, and more awareness of environmental pollution due to inefficient use of fertilizer.

4 General Discussion

Nutrients, particularly N, P, and K, are crucial for agricultural productivity as well as food and climate security. Agriculture being one of the major economic activities in India with the major cropping systems being cereal-based, fertilizer is one of the major agricultural inputs. Application of fertilizer along with high-yielding varieties has increased

Table 6 Predicted consumption of nutrients in Indian agriculture during 2019–2030 and 2019–2050

Inputs and outputs		Time period			Linear equation[†]
		1970–2018	2019–2030[*]	2019–2050[*]	
N	Input (Mt)	666.4	383.2	1150.2	Input (N) = 0.4017 × (Year) – 786.57
	Output (Mt)	654.3	286.3	874.8	Output (N) = 0.346 × (Year) – 676.13
	♣Balance (Mt)	12.2	96.9	276.2	-
P	Input (Mt)	189.1	103.6	327.3	Input (P) = 0.1597 × (Year) – 314.68
	Output (Mt)	200.8	104.0	325.3	Output (P) = 0.1494 × (Year) – 293.79
	♣Balance (Mt)	– 11.7	– 0.5	2.1	-
K	Input (Mt)	244.8	89.7	264.5	Input (K) = 0.0793 × (Year) – 153.07
	Output (Mt)	402.7	156.0	466.5	Output (K) = 0.1579 × (Year) – 306.67
	♣Balance (Mt)	– 157.9	– 66.3	– 202.0	-

[†]Linear model equations developed using data of input and output of N, P, and K during 1970–2018

[*]Predicted values of input and output using linear model equations

♣Balance = Inputs – outputs

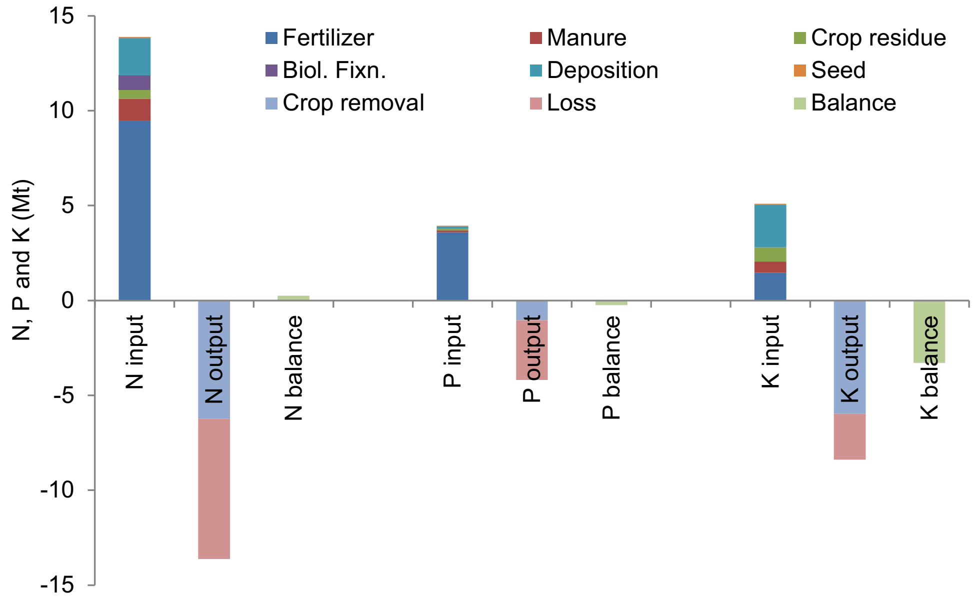

Fig. 6 Average annual budget of N, P, and K in Indian agriculture during 1970–2018

the productivity of Indian agriculture substantially after the Green Revolution. However, indiscriminate use of fertilizer, particularly N, during the last five decades has increased the losses with considerable negative impacts on biodiversity, climate change, air and water quality, and ecosystem services besides increasing the cost of cultivation. India accounts for about 16% of the global N consumption. Currently, application of N fertilizer in India (98.5 kg ha^{-1}) is almost at par with the European Union (94.0 kg ha^{-1}) countries and is higher than the global average (69.6 kg ha^{-1}) (FAOSTAT 2021). The application rate showed sharp increase in the last 25 years and is projected to double by 2050. Application of fertilizers in the country is generally based on the blanket recommendations, formulated on the basis of crop response data averaged over large geographic areas (Bijay-Singh 2017). Such broad-based application may not actually reflect exact requirement of fertilizer by the crops. The scenario is compounded by the under-use of fertilizer in some regions leading to nutrient depletion in soil. On the other hand, the over-use of fertilizer by in the intensively cultivated regions is leading to economic loss as well as leakage of reactive N to the environment.

Nutrient budgeting is a useful tool in assessing the past, present, and future productivity of agriculture; efficiency of input use; and undesirable effects of nutrient mining and pollution. Quantifying nutrient budgets, including the nutrient inputs and outputs in agriculture, is essential for sustainable nutrient management with enhanced productivity. It also provides critical inputs to agronomic, biogeochemical, and climate models for assessing the effectiveness of current management practices and project for future scenarios. The synthesis of input–output budget of N, P, and K in Indian agriculture provides new insights into the leakages of the nutrients emphasizing the need for their sustainable

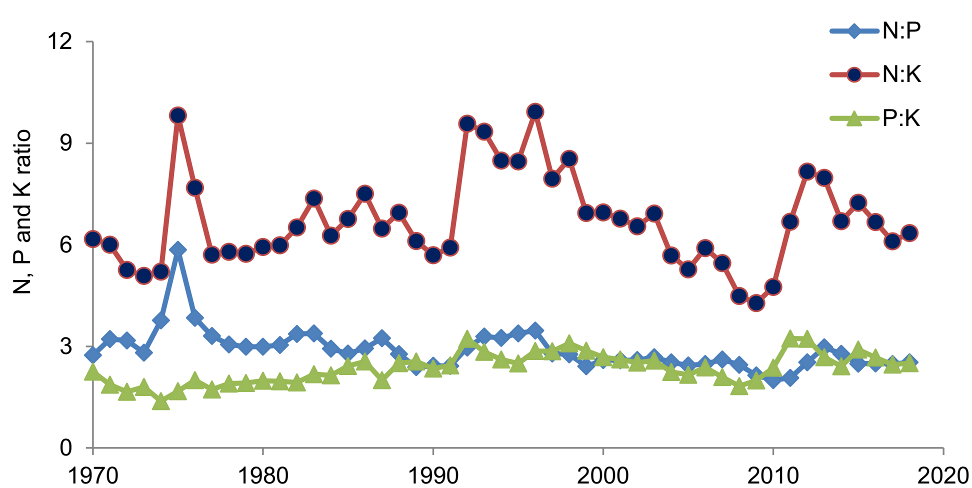

Fig. 7 Ratio of applied fertilizer N, P, and K in Indian agriculture during 1970–2018

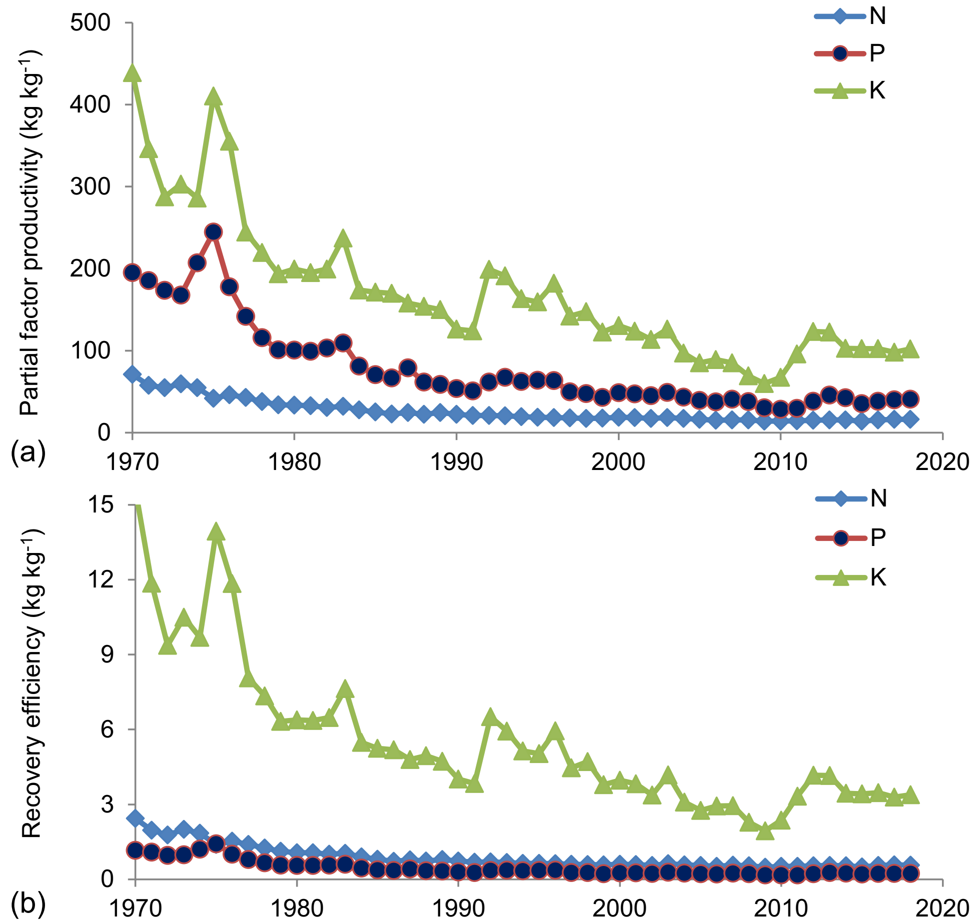

Fig. 8 Partial factor productivity (**a**) and recovery efficiency (**b**) of fertilizer N, P, and K in Indian agriculture during 1970–2018

management and helps to establish a basis for future research needs and policy advocacy.

Many research efforts have been devoted to quantify nutrient budgets and improve nutrient management for different farming systems at different spatial scales (Oenema et al. 2003; Meisinger et al. 2008; Liu et al. 2010; Boumann et al. 2013 and Ladha et al. 2016). However, the lack of consistency in the system definition and its budget terms affected the inter-comparison among the studies and experience-sharing among the regions. Moreover, due to the complex nature of nutrient cycles and incomplete datasets, challenges remain in quantifying and understanding nutrient budgets to inform policies and actions for sustainable nutrient management. The methodology used for the estimation of various components of the nutrient budget is based on a few assumptions. There are variations associated with the estimation of the input and losses of nutrients, particularly N. BNF was estimated with assumption that 100% N in legume seeds come from the BNF. However, legume may take N from soil N pool, which become the part of N input through BNF (Anglade et al. 2015). Therefore, N input through BNF in this study is over estimated. The magnitude of losses of N through leaching, denitrification, and volatilization is driven by several soil, crop, and climatic factors, which vary in space and time. The leaching, denitrification, and volatilization losses from the applied inorganic and manure N ranged from 10 to 30%, 0.5 to 2.5%, and 10 to 20%, respectively (Bhatia et al. 2013), which is again a source of variations in the N output from the soil.

Dynamics of P, which remain in soil in the unavailable forms, also remain uncertain as in which time period and what rate this will become available to the next crops. These variations can be reduced with the help of direct measurements of different components of nutrient budget. Crop- and system-specific mechanistic models can also be used for the more precise estimation of the nutrient output and losses from the soil. While the consumption of fertilizers is increasing globally, the NUE is gradually decreasing (Bijay-Singh et al. 2020). Nitrogen use efficiency generally declines with mineral fertilizer use and increases with the proportion of inputs represented by crop N fixation (Lassaletta et al. 2014). The major challenge is to combine intensive production with high NUE (Móring et al. 2021). The options to achieve this goal include employing the strategies for integrated soil and crop management to utilize nutrient mobilization process in the soil and avoid accumulation of mineralized nutrient in the soil; use of organic as well as inorganic sources of nutrients; and enhancement of biological N fixation and improvement of NUE at the plant level through improved crop varieties by targeted breeding.

McCrackin et al. (2018) have examined the potential for increased manure use efficiency in improving NUE and reducing nutrient losses. Promoting legumes in crop rotation and integrated N management will help in reducing application of chemical fertilizer and enhance NUE. Experiments in India, China, and in many other countries have shown that Integrated Soil-Crop System Management (ISSM) increased productivity, reduced chemical N fertilizer inputs, and decreased N losses (Bhattacharyya et al. 2020; Chen et al. 2011; Pathak 2016; Sapkota et al. 2014; Zhang et al. 2012). The solution being embraced around the world is the implementation of the principles of 4R Nutrient Stewardship (Johnston and Bruulsema 2014), ensuring that the right source of nutrient is applied at the right time, in the right place, and at the right rate. Increase in use efficiency of the applied fertilizer can be achieved by synchronizing the fertilizer application with the crop growth and decrease losses into the environment. To enhance the NUE of the applied inorganic fertilizers, approaches such as split application of fertilizers, placement of fertilizers, use of slow-release N fertilizers, use of nitrification inhibitor, and better agronomic management practices need to be intensified.

5 Conclusions

The sustainability of crop production is governed by the adequate supply of N, P, and K to soils. The present study of N, P, and K budget provides information on the long-term trend and the present status of nutrient use in Indian agriculture. These results can be down-scaled to specific crops and regions for the benefits of the farming community and policy formulation. The results are helpful in identifying and assessing the loss of nutrients to the environment causing pollution problems. The methodology used for the nutrient budget estimation is based on a few assumptions leading to some variations, which can be minimized with direct measurements and use of mechanistic models. To enhance the NUE of the inorganic fertilizers, several approaches have been suggested. Appropriate policy mechanisms are required to promote their implementation.

Acknowledgements We are thankful to the Chief Editor and two anonymous reviewers for their constructive and insightful comments which improved the quality of the manuscript a lot.

Author Contribution HP conceptualized the manuscript, acquired the data, and wrote the manuscript; RKF processed the data, prepared the figures and tables, and wrote the manuscript; both the authors gave final approval for publication.

Declarations

Conflict of Interest The authors declare no competing interests.

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