

See discussions, stats, and author profiles for this publication at: <https://www.researchgate.net/publication/284234535>

Site-Specific Nutrient Management under Rice-Based Cropping Systems in Indo-Gangetic Plains: Yield, Profit and Apparent Nutrient Balance

Article · November 2015

DOI: 10.1007/s40003-015-0179-1

CITATIONS

3

READS

527

9 authors, including:



Vinod K. Singh

Indian Agricultural Research Institute

95 PUBLICATIONS 857 CITATIONS

[SEE PROFILE](#)



Arvind K. Shukla

Indian Institute of Soil Science

114 PUBLICATIONS 1,259 CITATIONS

[SEE PROFILE](#)



Brahma S Dwivedi

Indian Agricultural Research Institute

133 PUBLICATIONS 1,851 CITATIONS

[SEE PROFILE](#)



Kaushik Majumdar

African Plant Nutrition Institute

86 PUBLICATIONS 688 CITATIONS

[SEE PROFILE](#)

Some of the authors of this publication are also working on these related projects:



light pollution [View project](#)



AICRP LTFE [View project](#)

Site-Specific Nutrient Management under Rice-Based Cropping Systems in Indo-Gangetic Plains: Yield, Profit and Apparent Nutrient Balance

**Vinod K. Singh, Arvind K. Shukla,
Brahma S. Dwivedi, Mahendra P. Singh,
Kaushik Majumdar, Vinod Kumar,
Rajendra P. Mishra, et al.**

Agricultural Research

ISSN 2249-720X

Agric Res

DOI 10.1007/s40003-015-0179-1



Your article is protected by copyright and all rights are held exclusively by NAAS (National Academy of Agricultural Sciences). This e-offprint is for personal use only and shall not be self-archived in electronic repositories. If you wish to self-archive your article, please use the accepted manuscript version for posting on your own website. You may further deposit the accepted manuscript version in any repository, provided it is only made publicly available 12 months after official publication or later and provided acknowledgement is given to the original source of publication and a link is inserted to the published article on Springer's website. The link must be accompanied by the following text: "The final publication is available at link.springer.com".

Site-Specific Nutrient Management under Rice-Based Cropping Systems in Indo-Gangetic Plains: Yield, Profit and Apparent Nutrient Balance

Vinod K. Singh¹ · Arvind K. Shukla³ · Brahma S. Dwivedi² · Mahendra P. Singh¹ ·
Kaushik Majumdar⁴ · Vinod Kumar¹ · Rajendra P. Mishra¹ · Meenu Rani¹ ·
Susheel K. Singh¹

Received: 9 March 2015 / Accepted: 31 August 2015
© NAAS (National Academy of Agricultural Sciences) 2015

Abstract High fertilizer use efficiency in rice (*Oryza sativa* L.)-based cropping systems in Indo-Gangetic Plains (IGP) is not achieved because farmers' fertilizer practices (FFP) and blanket state recommendations (BSR) do not take into account the site-specific variability of nutrient availability in the soil. We evaluated the site-specific nutrient management (SSNM) option against existing FFP, blanket state recommendation (BSR), improved BSR (IBSR i.e., 25 % higher than BSR), and state soil testing laboratory recommendation (STLR) in six pre-dominant rice-based cropping systems namely wheat–rice (W–R), mustard–rice (M–R), potato–rice (P–R), garlic–rice (G–R), chickpea–rice (C–R) and berseem fodder–rice (B–R) in terms of yield gain, economics, nutrient harvest index, soil fertility, and apparent nutrient balances. System rice equivalent yield (SREY) improved by 15.7, 9.5, 13.9 and 30 %, in SSNM over BSR, IBSR, STLR and FFP, respectively. SSNM involved additional cost of ₹ 2940–5291 ha⁻¹ over BSR and ₹ 5492–10120 ha⁻¹ over FFP under different cropping systems but contributed higher added net return of ₹ 23236–75056 ha⁻¹ and ₹ 39577–143899 ha⁻¹ over BSR and FFP, respectively. The output: input ratio and nutrient harvest index for N, P, K were also highest in SSNM. At the end of the experiment, soil available N, Olsen-P and available K content were either maintained or improved over their initial values in SSNM treatments, whereas soil available K in FFP declined by -1.65 % and increased over initial content in BSR and STLR in 0–15 cm soil profile depth. After three crop cycles, apparent N and P balances were positive in all the cropping systems and fertilizer treatments; only exception was a negative N balance in C–R and B–R systems in different fertilizer treatments. The apparent K balances were negative in all the cropping systems irrespective of nutrient management options. But, the magnitude of negative balance was lower in plots received SSNM treatment as compared to other nutrient management strategies, indicating a potential for improving yields, nutrient use efficiency and farm profit without deteriorating soil fertility in different rice based systems in IGP.

Keywords Site-specific nutrient management · Nutrient harvest index · Economics · Apparent nutrient balance · Farmers' fertilizer practices · Rice-based cropping systems

✉ Vinod K. Singh
vkumarsingh_01@yahoo.com

- ¹ ICAR-Indian Institute of Farming Systems Research, Modipuram, Meerut 250 110, India
- ² Division of Soil Science and Agricultural Chemistry, ICAR-Indian Agricultural Research Institute, New Delhi 110012, India
- ³ ICAR-Indian Institute of Soil Science, Bhopal, India
- ⁴ International Plant Nutrition Institute (IPNI), South Asia Program, Gurgaon, Haryana, India

Abbreviations

IGP: Indo-Gangetic Plain; FFP: Farmers' fertilizer practices; BSR: Blanket state recommendations; SSNM: Site-specific nutrient management; STLR: Soil testing laboratory recommendation; SREY: System rice equivalent yield; UGP: Upper Gangetic Plain; RIE: Reciprocal Internal Efficiency; AICRP: All India Coordinated Research Project; INS: Indigenous nutrient supply; IBSR: Improved blanket state recommendation; MSP: Minimum support price; NHI: Nutrient harvest index

Introduction

Different rice based cropping systems are practiced depending on soil types, ecologies and resource available for crop management across the Asia and important systems for livelihood of millions of people in India [10]. These production systems are of paramount significance to provide food, income and employment, and to ensure livelihood security for millions of rural and urban producers and consumers in the region. Recent reports reveals that intensively cultivated rice based system is levelling off annual growth in production [10] over the past decade. The prospects of area expansion are very narrow with burgeoning population of the country. Intensification of cropping systems has often over-exploited natural resources [27] and resulted in depletion of soil fertility and emergence of multi-nutrient deficiencies [5]. Consequently, the annual productivity of the different pre-dominant cropping systems has been declining for the past one decade. Decline in crop yields and factor productivity has become a common phenomenon, because the ratios of nutrients applied to crops do not match the ratios in which they are removed from the soils. Recent diagnostic surveys in intensively cultivated areas of Indo-Gangetic Plains (IGP) revealed that farmers often apply greater than recommended rates of fertilizer N and P, but ignore the sufficient application of other limiting nutrients [18]. Such an unbalanced and inadequate fertilizer use not only aggravates the deficiency of K, S and micronutrients in the soil, but also proves uneconomic and environmentally unsafe [6, 13, 20]. Excess N application can also enhance emission of nitrous oxide arising from nitrification–denitrification nexus [29]. Under these circumstances, high yield potential of modern varieties cannot ever be exploited with existing fertilizer practice, which fail to provide adequate and balanced doses needed for the crops. Therefore, agronomic management has to be improved for greater efficiency of applied inputs to sustain yields [22]. In this context, site-specific nutrient management (SSNM) based on crop nutrient demand and variability in indigenous nutrient supplying capacity of the soil could serve as an ideal tool to enhance nutrient use efficiency.

Attainable yield of crops under farmers' fertilizer practices (FFP) in the IGP vary with inherent soil fertility level, crop residue and fertilizer use management, organic materials input, rate of applications, method and schedule of fertilizer application, and variation in nutrient requirements by cultivars etc. [15, 18]. In contrast, one standard recommendation (popularly known as blanket fertilizer recommendation) of plant nutrients in rice-based systems across large areas exists in the IGP. However, drastic changes in crop cultivars and other agronomic management

has witnessed during this period. This leads to inefficient use of added nutrients as application rates do not consider the spatial variability in nutrient requirements among the fields [3]. SSNM has been proposed as an approach to tailor fertilizer application to match field-specific needs of crops to improve productivity and profitability [3, 4, 28]. This could be done by utilizing available information on indigenous nutrient supplying capacity, nutrient contributions from organic manures, irrigation water, rainfall and crop residue pools and finally crop nutrient demand for targeted yield of crops/cropping systems. With these considerations, the present investigation was undertaken to identify the best nutrient management strategy for various production systems in Upper Gangetic Plains (UGP) for achieving maximum attainable yields and profits, and to see its effect on important soil fertility parameters, nutrient harvest index and apparent nutrient balance.

Materials and Methods

Study Site

A field experiment was carried out during 2007–2008 to 2009–2010 on a Typic Ustochrept soil of the research farm of Indian Institute of Farming Systems Research, Modipuram, Meerut, India, located at 29°4'N latitude, 77°46'E longitude and at elevation of 273 m above mean sea level. Modipuram falls under a semi-arid sub-tropical climate zone with very hot summers and cool winters. The average annual rainfall is 810 mm and potential evapotranspiration is 1500 mm. The experimental site represents irrigated, mechanized and input intensive cropping areas of IGP region. The soil of the experimental site was sandy loam (164 g clay kg⁻¹, 196 g silt kg⁻¹ and 640 g sand kg⁻¹) of Gangetic alluvial origin, very deep (>2 m), well-drained, flat (about 1 % slope), and represented an extensive soil series i.e., Sobhapur series of north-west India [6]. The top soil (0–15 cm) of the experimental field at the start of experiment was non-saline (EC 0.35 d S m⁻¹) and mildly alkaline (pH 8.4), CEC (8.6 mol kg⁻¹) and contained 0.46 % organic carbon, 23.4 kg ha⁻¹ Olsen-P, 172 kg ha⁻¹ available K, 12.2 mg kg⁻¹ sulphur, 0.54 mg kg⁻¹ zinc and 0.39 mg kg⁻¹ boron.

Computation of SSNM Doses

The site-specific nutrient management doses for the different cropping systems were worked out based on plant nutrient demand for a targeted yield considering the indigenous nutrients supplying capacity of soil and nutrient use efficiency. On-farm data from field experiments

conducted under All India Coordinated Research Project on Integrated Farming Systems (AICRP-IFS) were used to estimate the Reciprocal Internal Efficiencies (RIE) expressed as kilogram plant nutrient uptake per tonne grain production [28] for rice, wheat, mustard, chickpea, garlic, potato and berseem crops. These values were subsequently combined with information on indigenous nutrient supply (INS) and yield gains from added nutrients to determine nutrient requirements for these crops for a pre-determined yield target. The components of INS calculations included nutrient (N, P and K) contributions from soil available pool, irrigation water, and rainfall and their availability (% efficiency) to the crop. The following equation was used to estimate the nutrient (N, P and K) balance under different crops.

$$B_{n(c)} = \{(IW_n \times \text{Eff}) + (CR_n \times \text{Eff}) + (RF_n \times \text{Eff}) + (S_n \times \text{Eff})\} - \{(GY_c \times RIE_{nc})\} \quad (1)$$

where, B_n is the nutrient balance (N or P or K; kg ha^{-1}), and the IW_n , CR_n , RF_n and S_n are the nutrient (N or P or K) contribution from irrigation water, crop residue, rainfall and soil during entire crop cycle. The term “Eff” is the efficiency (%) of different nutrients from various pools of INS in terms of their availability to the crops. GY_c and RIE_{nc} are attainable grain yields (t ha^{-1}) and the reciprocal internal efficiencies (N or P or K) of a crop in the system.

The nutrient contributions from IW and RF (kg ha^{-1}) were estimated using total amount of irrigation water applied/rainfall received (ha-cm) during the crop cycle, and their N, P, K content. Average available soil N, P and K content (kg ha^{-1}) at the start of the study was used as contribution from soil. The nutrient input from residues of a crop (CR_n) was determined from the amount and nutrient content of the above ground crop biomass retained in the field after harvest and expressed in kg ha^{-1} . The total fertilizer nutrient requirement (kg ha^{-1}) for the crop ($F_{n(c)}$) was worked out as:

$$F_{n(c)} = B_{n(c)} RE_{n(c)}^{-1} \quad (2)$$

where, $F_{n(c)}$ and $RE_{n(c)}$ are the fertilizer nutrient (N or P or K) requirement (kg ha^{-1}) and recovery efficiency (%) of nutrient N, P and K of a crop, respectively.

On the basis of above, SSNM (N-P-K) doses were calculated for hybrid rice, wheat, potato, chickpea, mustard, garlic and berseem, and being given in Table 1.

Treatments and Crop Management Practices

The experiment comprising of six cropping system namely wheat–rice (W–R), mustard–rice (M–R), potato–rice (P–

R), garlic–rice (G–R), chickpea–rice (C–R) and berseem (f)–rice (B–R) in main plot and five nutrient management options viz. farmers fertilizer practice (FFP), blanket state

Table 1 Crop wise fertilizer rates under different nutrient management options

| Treatments | Nutrient use (kg ha^{-1}) | | |
|------------------------------|--------------------------------------|-------------------------------|------------------|
| | N | P ₂ O ₅ | K ₂ O |
| Rice | | | |
| FFP | 178 | 59 | |
| BSR | 150 | 75 | 60 |
| IBSR | 187.5 | 93.75 | 75 |
| STLR | 137.5 | 56.25 | 70.5 |
| SSNM | 150 | 75 | 99 |
| Wheat | | | |
| FFP | 168 | 64 | |
| BSR | 150 | 60 | 40 |
| IBSR | 187.5 | 75 | 50 |
| STLR | 134 | 45 | 57 |
| SSNM | 150 | 60 | 99 |
| Potato | | | |
| FFP | 250 | 150 | 40 |
| BSR | 180 | 80 | 100 |
| IBSR | 225 | 100 | 125 |
| STLR | 198 | 60 | 103 |
| SSNM | 210 | 99 | 150 |
| Garlic | | | |
| FFP | 80 | 58 | |
| BSR | 125 | 60 | 60 |
| IBSR | 156.3 | 75 | 75 |
| STLR | 136.5 | 45 | 62 |
| SSNM | 150 | 90 | 99 |
| Chickpea | | | |
| FFP | 22.5 | 58 | |
| BSR | 20 | 50 | 30 |
| IBSR | 25 | 62.5 | 37.5 |
| STLR | 24.5 | 37.5 | 45 |
| SSNM | 30 | 75 | 75 |
| Mustard | | | |
| FFP | 85 | 60 | |
| BSR | 120 | 50 | 40 |
| IBSR | 150 | 62.5 | 50 |
| STLR | 132.5 | 37.5 | 64 |
| SSNM | 125 | 75 | 90 |
| Berseem (fodder crop) | | | |
| FFP | 75 | 50 | |
| BSR | 20 | 50 | 0 |
| IBSR | 25 | 62.5 | |
| STLR | 37.5 | 41.5 | |
| SSNM | 40 | 60 | 75 |

recommendation (BSR), improved blanket state recommendation i.e., 25 % higher than BSR (IBSR), soil testing lab recommendations (STLR) and site-specific nutrient management (SSNM) in sub-plots were evaluated in split plot design with three replications. Nutrient application under FFP for different crops were decided based on farmers' participatory survey conducted with farmers growing the respective cropping systems, and highest mode value for N, P, K and Zn application were used for FFP at each cropping system. Crop wise fertilizer rates applied under different treatments are given in Table 1. Except for fertilizer application, standard crop management practices were followed in all the crops. Grain and straw yields of all the crops were determined from 20 m² area in each plot. After sun-drying for 3 days in the field, the total biomass (grain + straw) was weighed and threshed with a plot thresher, except potato and berseem (f) which were weighed as tuber and green fodder, respectively.

Soil and Plant Analysis

Soil samples (0–15 cm depth) were collected from four places from experimental fields using a core sampler of 8 cm diameter before commencement of the experiment in 2007 and after completion of 03 cropping system cycles (i.e., post rice season 2010). Soil samples collected from each field were mixed thoroughly, and a sub-sample was pulverized using a wooden pestle and mortar and passed through a 100 mm sieve. Soils were analyzed for extractable N by the alkaline KMNO₄ method [25], Olsen-P (0.5 M NaHCO₃, pH 8.5 extraction) [11] and exchangeable K (1 M NH₄OAc, pH 7.0 extraction) [8].

Representative grain and straw sub-samples of crops were dried at 70 C, ground in a stainless steel Wiley mill, and then wet-digested with concentrated H₂SO₄ for determination of total N, while for total P and K, samples were digested with concentrated HNO₃ and HClO₄ (mixed in 1:4 ratio). The N content was determined by the Kjeldahl method using an auto analyzer, P was determined by the vanadomolybdate yellow colour method [12], and total K content was determined by flame photometry.

Computations and Economic Analysis

Nutrient harvest index for N, P and K (NHI_{N or P or K}) was computed as

$$\text{NHI}_{\text{N or P or K}} = \left[\frac{G_u}{G_u + S_u} \right] \times 100 \quad (3)$$

where G_u and S_u are the N or P or K uptake in economic and straw/halm part of different crops, expressed in kg ha⁻¹.

Added net return with different treatments relative to FFP was determined using the minimum support price

(MSP) fixed by the government for rice, wheat, mustard and chickpea grain plus straw prices for these crops as per local market. The price of garlic, potato and berseem fodder was taken as per local market, and the cost of fertilizers on a nutrient basis [7]. The total cost of fertilizer for a treatment was computed as the sum of cost for each applied nutrient.

An apparent nutrient balance sheet at the end of the experiment were calculated by subtracting the nutrient removed in the crops from those added in the fertilizer, crop residue, irrigation water and rainfall.

Results and Discussion

Effect on Crop Productivity

Effect on Winter Crop

The productivity gain under SSNM treatment over FFP was of 30.8, 41.8, 67.3, 70.1, 42.1 and 24.1 % for wheat, mustard, potato, garlic, chickpea and berseem (f) (Table 2), respectively. Higher productivity under SSNM was observed due to sufficient nutrient supply as per crop demand through external application as well as indigenous soil nutrient supplying capacity. On the other hand, in FFP treatment, with excess N use, sub-optimal P and no-K application led to the inadequate and imbalanced plant nutrient supply, and resulted in lowest productivity among all the nutrient management options.

The IBSR option of nutrient management wherein 25 % extra N, P and K over BSR was applied, had edge over BSR and STLR method of fertilizer application, underlining necessity for an upward revision in fertilizer recommendations. These findings corroborate the reports of long-term experiments which suggested inadequacy of current fertilizer recommendation to sustain high productivity under intensive cropping systems [16]. The increase in yield under IBSR over BSR and STLR was to the tune of 0.31–0.41 t ha⁻¹ in wheat, 0.08–0.11 t ha⁻¹ in mustard, 1.8–2.7 t ha⁻¹ in potato, 0.37–0.48 t ha⁻¹ in garlic, 0.25–0.30 t ha⁻¹ in chickpea and 1.9–6.9 t ha⁻¹ in berseem (f) crop (Table 2). The yield obtained in different monsoon crop under BSR and STLR fertilizer treatment was almost similar in but had an edge over FFP.

Effect on Rice Crop

Irrespective of the previous crop grown, the grain yields of rice, raised on same layout were also the highest under SSNM treatment followed by IBSR, and the lowest in FFP (Table 2). Among the cropping system, the highest rice yield with SSNM was registered after potato (9.5 t ha⁻¹),

which was closely followed by rice grown after berseem, chickpea, garlic and mustard crops. Although, BSR proved its superiority over FFP for rice crop but it exhibited 17.1–25.1 % lower yield as compared to SSNM in various cropping system. The enhanced rice yield in SSNM and IBSR treatment options is attributed to larger ear length, more number of grain ear⁻¹, higher grain weight ear⁻¹ and greater number of effective tillers m⁻² (data not reported), obviously due to better nutrient management i.e. improved nutrient supplies [23].

Effect on System Productivity

Comparing the system productivity, in terms of rice equivalent yield indicated that SSNM out yielded different nutrient management options across the cropping systems. System rice equivalent yield (SREY) in BSR, IBSR, STLR and FFP treatments was 15.7, 9.5, 13.9, and 30.0 %, lower than that of SSNM option (Table 2). These results clearly showed that the generalized adhoc recommendations at state level and recommendations made by soil testing laboratory based on initial soil status (i.e. high, medium and low) may not help to achieve high yield target. On the

other hand, SSNM recommendations, which take into account of indigenous nutrients supplying capacity of soil (INS), targeted yield and nutrient use efficiency together, proved to be an efficient nutrient management option for attaining high yields under different crops and cropping systems. Further, significantly higher system productivity in SSNM over BSR may partially be ascribed to the inclusion of S and Zn in SSNM fertilizer schedule. It is pertinent to mention here that the high yielding cultivars of different crops were grown in this study, and their nutrient uptake demands were considerably higher compared with commonly grown cultivars in the region. Theoretically, as the yield goal moves up, the nutrient demand of the crops increases but also becomes more varied and complex leading to multiple nutrient deficiencies [24]. Therefore, nutrient harvest index (NHI) computed for N, P and K in different rice-based systems was highest under SSNM, implying that the balanced nutrient supply through SSNM regulated efficient nutrient utilization towards the sink (Fig. 1). Averaged over the nutrient management options, the highest system productivity was recorded in G–R (31.74 t ha⁻¹) followed by P–R (21.69 t ha⁻¹), W–R (13.42 t ha⁻¹), C–R (13.33 t ha⁻¹), M–R (12.47 t ha⁻¹) and B–R

Table 2 Productivity (t ha⁻¹) of different crops and cropping systems as influenced by various nutrient management options (Mean over 03 years)

| Nutrient management options | Wheat–rice | Mustard–rice | Potato–rice | Garlic–rice | Berseem–rice | Chickpea–rice | Average over cropping system |
|-------------------------------------|------------|--------------|-------------|-------------|--------------|---------------|------------------------------|
| Winter crop | | | | | | | |
| FFP | 4.91d | 1.65c | 16.8e | 4.46d | 75.1e | 1.9e | 17.47d |
| BSR | 5.63bc | 2.1ab | 22.5c | 6.52bc | 85.4d | 2.26c | 20.74bc |
| IBSR | 6.04ab | 2.21ab | 24.3b | 7ba | 87.3c | 2.51b | 21.56b |
| STLR | 5.73b | 2.13ab | 21.6d | 6.63b | 80.4b | 2.21cd | 19.78c |
| SSNM | 6.42a | 2.34a | 28.1a | 7.62a | 93.2a | 2.7a | 23.40a |
| Mean | 5.75tu | 2.09u | 22.66s | 6.45t | 84.28r | 2.32u | |
| Monsoon crop | | | | | | | |
| FFP | 6.77c | 6.8c | 7.29c | 7.06cd | 7.2c | 6.84c | 6.99d |
| BSR | 7.24bc | 7.23bc | 8.13bc | 7.3c | 8.01bc | 7.91bc | 7.64c |
| IBSR | 7.73ba | 8.16ba | 8.47ba | 8.2bc | 8.53ba | 8.14b | 8.21b |
| STLR | 7.28b | 7.74b | 8.4b | 8.51b | 8.41b | 8.04bc | 8.06bc |
| SSNM | 8.48a | 9.02a | 9.5a | 9.13a | 9.4a | 9.32a | 9.14a |
| Mean | 7.50st | 7.79s | 8.36r | 8.04rs | 8.31r | 8.05rs | |
| System rice equivalent yield (SREY) | | | | | | | |
| FFP | 11.82d | 10.50d | 17.17d | 23.46d | 9.96d | 11.17d | 14.01d |
| BSR | 13.04c | 11.94c | 21.37c | 31.27c | 11.15c | 13.06c | 16.97c |
| IBSR | 13.95b | 13.12b | 22.76b | 33.94b | 11.74b | 13.86b | 18.23b |
| STLR | 13.18bc | 12.52bc | 21.11cd | 32.89bc | 11.37bc | 13.08bc | 17.35bc |
| SSNM | 15.09a | 14.27a | 26.03a | 37.14a | 12.83a | 15.47a | 20.14a |
| Mean | 13.42t | 12.47tu | 21.69s | 31.74r | 11.41u | 13.33t | |

Within a column values of the same group (except mean) with the same letter are not significantly different at $P < 0.05$

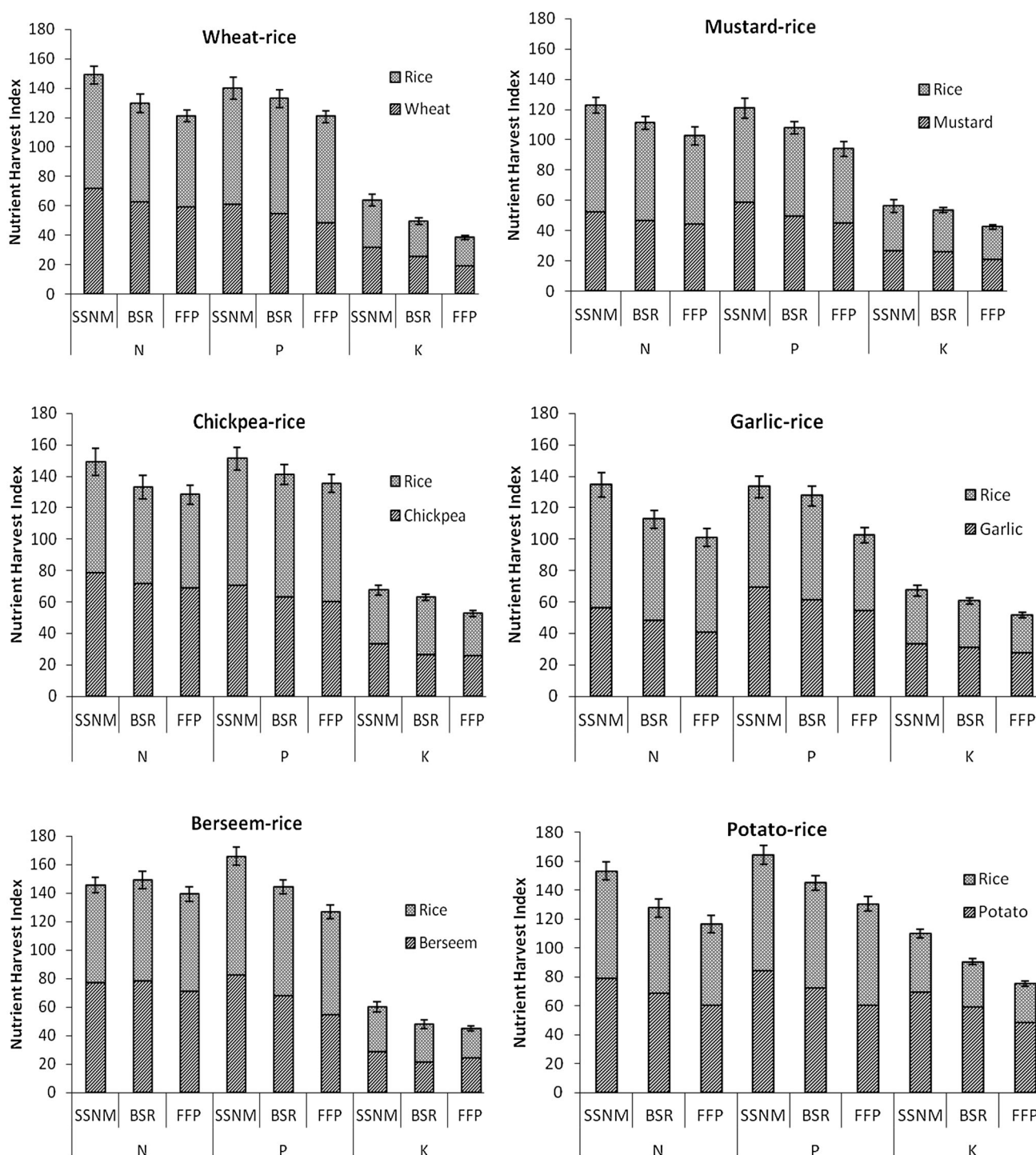


Fig. 1 Nutrient harvest index (NHI) of N, P and K as influenced by different nutrient management options. @ Bar indicates standard error of mean ($n = 9$)

(11.41 t ha⁻¹) cropping system. Across the cropping systems, SREY under SSNM (20.14 t ha⁻¹) was significantly higher ($p < 0.05$) compared with other nutrient management options, whereas the same was lowest (14.01 t ha⁻¹) under FFP. Among the studied cropping systems, highest

increase due to SSNM option over FFP was recorded in G-R system (13.68 t ha⁻¹) followed by P-R system (8.86 t ha⁻¹). The highest system equivalent productivity under G-R system may be ascribed to the maximum yield increase due to SSNM plot for garlic (70.1 %) over FFP and higher

unit price of garlic economic yield (₹ 34998 t⁻¹). Relatively higher yield gain over FFP under both the crop of the P-R system also resulted in increased system equivalent productivity. The beneficial effect of potato based system on succeeding crops and system productivity is already documented in earlier reports [14].

Effect on Nutrient Harvest Index

Nutrient harvest index (NHI) for N, P and K were highest under SSNM in all the cropping system followed by BSR and FFP (Fig. 1). The magnitude of increased NHI for N, P and K over FFP was in the range of 6.1–18.1, 5.9–27.9 and 3.8–21.3, respectively under different crops. In general, sequences having legumes or potato as a component crop had highest NHI_P for all the crops of the system. Higher NHI for N, P and K values under SSNM and IBSR may be ascribed due to inclusion of K under fertilizer application schedule and its role towards assimilation of nutrients in the economic parts [22]. Physiologically, potassium helps in regulating the activity of several enzymes leading to control of diseases, building up resistance in plant towards invading pathogens and several abiotic stress [1]. On the other hand, excessive accumulation of N compounds in plants disrupts the phloem transport and thus restricts P absorption under K deficient conditions. Thus, increasing K levels in fertilizer prescription, can be utilized advantageously for protecting the crop from several health hazards and consequently for enhancing nutrient use efficiency.

Changes in Soil Fertility Status

Available N Content

In general, available N content in soil was more under potato and legume based system as compared to other cropping system (Table 3). Averaged across the nutrient management options, the available N content was maximum under P-R system (294.8 kg ha⁻¹) followed by C-R (283.2 kg ha⁻¹), B-R (282.2 kg ha⁻¹), G-R (280 kg ha⁻¹), W-R (154.6 kg ha⁻¹) and M-R system (253.8 kg ha⁻¹). Higher residual soil N availability after potato cultivation due to relatively more balanced N, P, K use and better soil condition was already reported by earlier researcher [9]. Further, the higher N content in legume based system may be ascribed to sizeable additions of N through BNF and leaf litter fall and its subsequent decomposition enriching different pools of N [6, 20, 21]. In addition, relatively greater amount of rice residues recycled owing to higher yield of rice after legume (chickpea) also had added advantage in enriching the N pools [23]. Averaged over the cropping system, IBSR had the highest soil N content (310 kg ha⁻¹) followed by SSNM option (292 kg ha⁻¹) and the lowest N

content was recorded with FFP (230 kg ha⁻¹). The lower N content under FFP, BSR and STLR indicates potential N loss from soil caused by imbalance or insufficient nutrient applications [6, 17, 21]. After three crop cycles, available N content in the soil increased under all the nutrient management options but the magnitude of increase was more under IBSR (66 %) and SSNM (56 %) options. Increased soil N availability may be corroborated with earlier reports of Singh et al. (2010) [21], wherein better root foraging caused by balanced nutrition helps to trap NO₃-N losses and made it available in upper soil profile. Balancing the N P K ratio by increasing fertilizer K input is practical way to improve agronomic N efficiency [30].

Olsen-P Content

After three crop cycles, Olsen-P content of the soil (0–15 cm depth) increased over the initial content, consequent to different fertilizer management options under all the cropping systems and magnitude of increase was more under W-R system (27.44 %) followed by M-R system (27.35 %) and P-R system (18.9 %) (Table 3), whereas sequences having legumes as a component crop of the system did not show any significant change over initial P status. Lower P content in the soil under legume based cropping system may be due to higher P need of legumes and better P utilization efficiency as indicated in NHI_P (Fig. 1) due to its deeper root system [19–21]. The higher P content of soil in R-W system corroborated with the earlier studies by Dwivedi et al. (2003) [6], wherein continuous P application at 26 kg ha⁻¹ to both the crops resulted in build up of P content in the soils.

Among nutrient management options, IBSR treatment showed superiority over all other treatments as far as Olsen-P content of 0–15 cm profile depth is concerned. Relatively lower P under SSNM treatment may be ascribed to the higher P utilization efficiency as indicated by NHI_P (Fig. 1). Further, soil P content under STLR treatment was identical under all the cropping system indicating that recommendations of soil testing laboratory are inadequate and needs a fresh look in the view of changing management practices, cultivars' yield potential and indigenous soil nutrient supply capacity of soil.

Available K Content

Soil K content varied among the cropping systems and it ranged between 169 to 236 kg ha⁻¹ (Table 3). In general, available K content increased over initial K status under different crop sequences with exception of G-R wherein it declined by 2 % over its initial status. Negative K content under this system may be ascribed as relatively lower K application rate to the garlic crop, almost nil-K recycling

Table 3 Soil available N, Olsen P and available K content after 03-crop cycles in 0–15 cm soil profile as influenced by different nutrient management option and cropping systems

| Treatments | Wheat–rice | | Mustard–rice | | Chickpea–rice | | Garlic–rice | | Berseem–rice | | Potato–rice | | Average over cropping systems | | |
|---|------------|-----------------------------|--------------|-----------------------------|---------------|-----------------------------|-------------|-----------------------------|--------------|-----------------------------|-------------|-----------------------------|-------------------------------|-----------------------------|-------|
| | Initial | After 03 cycle over initial | Initial | After 03 cycle over initial | Initial | After 03 cycle over initial | Initial | After 03 cycle over initial | Initial | After 03 cycle over initial | Initial | After 03 cycle over initial | Initial | After 03 cycle over initial | |
| Available N (kg ha⁻¹) | | | | | | | | | | | | | | | |
| FFP | 187 | 207c | 10.70 | 201c | 7.49 | 241c | 28.88 | 230c | 22.99 | 248c | 32.62 | 254c | 35.83 | 230.17c | 23.08 |
| BSR | 187 | 238bc | 27.27 | 240bc | 28.34 | 269b | 43.85 | 262b | 40.11 | 266bc | 42.25 | 286bc | 52.94 | 260.17bc | 39.13 |
| IBSR | 187 | 296a | 58.29 | 288a | 54.01 | 312a | 66.84 | 312a | 66.84 | 323a | 72.73 | 330a | 76.47 | 310.17a | 65.86 |
| STLR | 187 | 256b | 36.90 | 264b | 41.18 | 296ab | 58.29 | 294ab | 57.22 | 284b | 51.87 | 294ab | 57.22 | 281.33b | 50.45 |
| SSNM | 187 | 276ab | 47.59 | 276ab | 47.59 | 298ab | 59.36 | 302ab | 61.50 | 290ab | 55.08 | 310ab | 65.78 | 292.00ab | 56.15 |
| Mean | | 254.6s | 36.15 | 253.8s | 35.72 | 283.2r | 51.44 | 280r | 49.73 | 282.2r | 50.91 | 294.8r | 57.65 | – | – |
| Olsen P (kg ha⁻¹) | | | | | | | | | | | | | | | |
| FFP | 23.4 | 28.5bc | 21.79 | 28.2bc | 20.51 | 25.9a | 10.68 | 24.8ab | 5.98 | 25.2b | 7.69 | 30.4a | 29.91 | 27.17bc | 16.10 |
| BSR | 23.4 | 30.2ab | 29.06 | 29.8b | 27.35 | 23.2ab | -0.85 | 22.8b | -2.56 | 24.3bc | 3.85 | 26.1c | 11.54 | 26.07b | 11.40 |
| IBSR | 23.4 | 33.9a | 44.87 | 32.9a | 40.60 | 24.8ab | 5.98 | 26.3a | 12.39 | 27.3a | 16.67 | 28.4ab | 21.37 | 28.93a | 23.65 |
| STLR | 23.4 | 26.31c | 12.44 | 27.4bc | 17.09 | 21.4b | -8.55 | 20.4c | -12.82 | 23.2c | -0.85 | 26.3bc | 12.39 | 24.17c | 3.28 |
| SSNM | 23.4 | 30.2ab | 29.06 | 30.7ab | 31.20 | 23.9ab | 2.14 | 24.3ab | 3.85 | 24bc | 2.56 | 27.9b | 19.23 | 26.83ab | 14.67 |
| Mean | | 29.822r | 27.44 | 29.80r | 27.35 | 23.84s | 1.88 | 23.72s | 1.37 | 24.8rs | 5.98 | 27.82r | 18.89 | – | – |
| Available K (kg ha⁻¹) | | | | | | | | | | | | | | | |
| FFP | 172 | 149c | -13.37 | 156b | -9.30 | 141b | -18.02 | 132c | -23.26 | 149c | -13.37 | 288a | 67.44 | 169.17c | -1.65 |
| BSR | 172 | 186bc | 8.14 | 184ab | 6.98 | 186ab | 8.14 | 170b | -1.16 | 196b | 13.95 | 214bc | 24.42 | 189.33b | 10.08 |
| IBSR | 172 | 287a | 66.86 | 203a | 18.02 | 212a | 23.26 | 184a | 6.98 | 230a | 33.72 | 236bc | 37.21 | 225.33a | 31.01 |
| STLR | 172 | 207b | 20.35 | 189ab | 9.88 | 160b | -6.98 | 163ab | -5.23 | 202ab | 17.44 | 202c | 17.44 | 187.17b | 8.82 |
| SSNM | 172 | 293a | 70.35 | 212a | 23.26 | 216a | 25.58 | 195a | 13.37 | 234a | 36.05 | 242b | 40.70 | 232.00a | 34.88 |
| Mean | | 224.4r | 30.47 | 188.8 s | 9.77 | 183 s | 6.40 | 168.8st | -1.86 | 202.2rs | 17.56 | 236.4 | 37.44 | – | – |

Within a column values of the same group (except mean) with the same letter are not significantly different at $P < 0.05$

through residues stubbles and greater K uptake by the crops.

Averaged over the cropping systems, highest soil K content was recorded under SSNM (232 kg ha^{-1}) followed by IBSR, STLR, BSR and least under FFP (169.2 kg ha^{-1}). After 03 crop cycle, whereas SSNM and IBSR enhanced available soil K pool by 34.8 and 31 % over initial soil K status, a depletion soil K was noted under FFP (-1.65%). The highest K depletion under FFP treatment was noted under G–R system (-23%). Here it may be argued that the higher K rates under SSNM and 25 % additional K use under IBSR led to greater crop yields and an enhanced residue (root stubble) recycling, which in turn resulted in higher available K status of the soil under these treatments. On the other hand, depletion of K under FFP may be ascribed to imbalanced crop nutrition and lower residue recycling [18, 22]. Soil K depletion (5–7 %) over initial content under C–R and G–R system with STLR treatment further cautioned that soil test-based K recommendation on soil fertility rating basis needs to be relooked and changed in the view of crop demand, indigenous nutrient supply and other management factors.

Apparent Nutrient Balance Sheet and Output: Input Ratio

During the experiment, nitrogen additions through fertilizer, residues, irrigation water and rainfall under different nutrient management option were $931\text{--}1063 \text{ kg N ha}^{-1}$ in W–R, $805\text{--}847 \text{ kg N ha}^{-1}$ in M–R, $572\text{--}654 \text{ kg N ha}^{-1}$ in C–R, $793\text{--}930 \text{ kg N ha}^{-1}$ in G–R, $581\text{--}715 \text{ kg N ha}^{-1}$ in B–R and $1015\text{--}1306 \text{ kg N ha}^{-1}$ in P–R system (Table 4). The apparent balance sheet, computed as nutrient addition from different sources less nutrient off take in the crops revealed positive N balances under all the treatments of different cropping systems, except in C–R and B–R system where the N balance were negative and had wider output: input ratios. The negative N balance under C–R and B–R systems may be explained in two ways: (i) the N addition through fertilizer to pigeonpea and groundnut was much lower than the other crops, though the N removal in former case was invariably greater (data not reported) and (ii) the contribution of BNF in chickpea and berseem was not measured while computing apparent N balance. Literature indicates that legumes may derive 54–70 % of their N requirement through BNF [2]. Thus, considering possible contribution from BNF, the extent of negative N balance could be lower than what is reported here and may not reflect depletion in soil N reserve. Averaged over cropping systems, the excessive N balance under FFP as compared to SSNM indicates the inefficient use of N by the crops caused by imbalanced fertilizer use.

All the crop sequences revealed a positive P balance, which was comparatively greater in P–R followed by G–R system (Table 4). Since component crops of these crop sequences removed less P than the additions through fertilizers and other sources, the P balances were positive. These results corroborate with the findings of Singh et al. [22] wherein higher P use in Upper Gangetic Plain to crop like potato and garlic lead to more P availability to succeeding crops and many times farmers grow residual crops without P application. Our results are supported with long-term fertilizer experiments being conducted on diverse soils, under All Indian Coordinated Research Project, the application of P at recommended rate led to positive balance in intensive production system [26]. The higher input: output ratio and comparatively smaller apparent P balance under SSNM in all the cropping system reveals that the SSNM treatment facilitated judicious P use and its higher accumulation in the crops. Whereas, lower output: input ratio under FFP shows the inefficient P fertilizer use by the crops.

In contrast to P, the apparent balances for K were negative in all the crop sequences and the magnitude was more under M–R and R–W system. Among the different nutrient management options highest negative apparent K balance was noticed with FFP followed by BSR and least in SSNM (Table 4). Relatively higher negative K balance under FFP and BSR underline the neglectance of K use in existing farmer fertilizer practices and or sub-optimal K recommendations by the state departments are not sustainable for modern high yielding cultivars in intensive cropping systems. Further, these results advised to develop fertilizer recommendations based on crop demand for a specified yield targeted and indigenous soil nutrient supplying capacity.

Economics of SSNM

Economic return varied with the cropping systems and within the systems as per nutrient management options. Average across the treatments, in potato–rice system, fertilizer cost was maximum (₹ 18854) as well as total returns (₹ 346465) whereas lowest cost of cultivation and total return were noted under B–R system (Fig. 2). Comparing the net return from different nutrient management options, the SSNM was the premier option among the treatments, which on average contributed ₹ 236763, ₹ 207121, ₹ 224597, ₹ 396985, ₹ 180879 and ₹ 416803 as profit in W–R, M–R, C–R, G–R, B–R and P–R systems, respectively. The additional fertilizer input cost accrued for SSNM treatment was in the range of ₹ 5492.4–10119.7, ₹ 2940–5290.6, ₹ 674.14–2236.86 and ₹ 2773.94–4948.69 ha^{-1} as compared FFP, BSR, IBSR and STLR treatments in different cropping system. The added net return in SSNM

Table 4 Effect of nutrient management options on apparent nutrient balance sheet and output: input ratio under different cropping systems after 03 year of cropping

| Treatments | Nitrogen | | | | | | Phosphorus | | | | | | Potassium | | | | | |
|-----------------------------|--|------------------------------------|---|---|---------------------|-------|--|-----------------------|---|---|---------------------|-------|--|-----------------------|---|---|---------------------|-------|
| | Nutrient addition (kg ha ⁻¹) | | Nutrient removal (kg ha ⁻¹) | Apparent balance (kg ha ⁻¹) | Output: input ratio | Total | Nutrient addition (kg ha ⁻¹) | | Nutrient removal (kg ha ⁻¹) | Apparent balance (kg ha ⁻¹) | Output: input ratio | Total | Nutrient addition (kg ha ⁻¹) | | Nutrient removal (kg ha ⁻¹) | Apparent balance (kg ha ⁻¹) | Output: input ratio | Total |
| | Fertilizer | INS [@] and other sources | | | | | Fertilizer | INS and other sources | | | | | Fertilizer | INS and other sources | | | | |
| Wheat-rice system | | | | | | | | | | | | | | | | | | |
| FFP | 1038 | 25 | 1063 | 622 | 441 | 0.59 | 161 | 8 | 169 | 100.0 | 69.1 | 0.59 | 71 | 71 | 728.0 | -657.0 | 10.25 | |
| BSR | 900 | 31 | 931 | 729 | 202 | 0.78 | 177 | 15 | 192 | 123.0 | 68.9 | 0.64 | 85 | 358 | 804.0 | -446.3 | 2.25 | |
| SSNM | 900 | 40 | 940 | 876 | 64 | 0.93 | 177 | 17 | 194 | 140.0 | 53.9 | 0.72 | 88 | 628 | 938.0 | -310.0 | 1.49 | |
| Mustard-rice system | | | | | | | | | | | | | | | | | | |
| FFP | 789 | 16 | 805 | 702 | 103 | 0.87 | 156 | 7 | 163 | 94.0 | 68.9 | 0.58 | 35 | 35 | 765.0 | -730.0 | 21.86 | |
| BSR | 810 | 17 | 827 | 745 | 82 | 0.90 | 164 | 12 | 176 | 104.0 | 71.8 | 0.59 | 28 | 301 | 854.0 | -553.3 | 2.84 | |
| SSNM | 825 | 22 | 847 | 811 | 36 | 0.96 | 197 | 16 | 236 | 134.0 | 102.0 | 0.57 | 42 | 557 | 928.0 | -370.5 | 1.66 | |
| Chickpea-rice system | | | | | | | | | | | | | | | | | | |
| FFP | 602 | 52 | 654 | 680 | -27 | 1.04 | 153 | 10 | 163 | 98.0 | 65.3 | 0.60 | 33 | 33 | 445.0 | -412.0 | 13.48 | |
| BSR | 510 | 62 | 572 | 754 | -182 | 1.32 | 164 | 16 | 180 | 112.0 | 67.8 | 0.62 | 39 | 284 | 556.0 | -271.5 | 1.95 | |
| SSNM | 540 | 81 | 621 | 816 | -195 | 1.31 | 197 | 20 | 217 | 143.0 | 73.5 | 0.66 | 42 | 517 | 615.0 | -98.5 | 1.19 | |
| Garlic-rice system | | | | | | | | | | | | | | | | | | |
| FFP | 774 | 19 | 793 | 412 | 381 | 0.52 | 153 | 13 | 166 | 89.0 | 77.3 | 0.54 | 40 | 40 | 579.0 | -539.0 | 14.48 | |
| BSR | 825 | 25 | 850 | 512 | 338 | 0.60 | 177 | 18 | 195 | 94.0 | 100.9 | 0.48 | 44 | 371 | 643.0 | -271.7 | 1.73 | |
| SSNM | 900 | 30 | 930 | 574 | 356 | 0.62 | 216 | 21 | 237 | 126.0 | 111.2 | 0.53 | 45 | 585 | 711.0 | -126.0 | 1.22 | |
| Berseem-rice system | | | | | | | | | | | | | | | | | | |
| FFP | 659 | 56 | 715 | 724 | -9 | 1.01 | 143 | 10 | 153 | 101.0 | 51.8 | 0.66 | 36 | 36 | 529.0 | -493.0 | 14.69 | |
| BSR | 510 | 71 | 581 | 788 | -207 | 1.36 | 164 | 12 | 176 | 117.0 | 58.8 | 0.67 | 42 | 206 | 612.0 | -406.4 | 2.98 | |
| SSNM | 570 | 82 | 652 | 834 | -182 | 1.28 | 177 | 16 | 193 | 132.0 | 60.9 | 0.68 | 52 | 527 | 683.0 | -156.5 | 1.30 | |
| Potato-rice system | | | | | | | | | | | | | | | | | | |
| FFP | 1284 | 22 | 1306 | 822 | 484 | 0.63 | 274 | 12 | 286 | 123.0 | 162.8 | 0.43 | 38 | 147 | 572.0 | -424.9 | 3.89 | |
| BSR | 990 | 25 | 1015 | 896 | 119 | 0.88 | 203 | 15 | 218 | 141.0 | 77.1 | 0.65 | 44 | 480 | 624.0 | -143.6 | 1.30 | |
| SSNM | 1080 | 30 | 1110 | 931 | 179 | 0.84 | 228 | 19 | 247 | 174.0 | 72.9 | 0.70 | 51 | 730 | 710.0 | 20.1 | 0.97 | |

[@] Includes nutrient addition through rainfall, irrigation water and root stubbles during the course of study

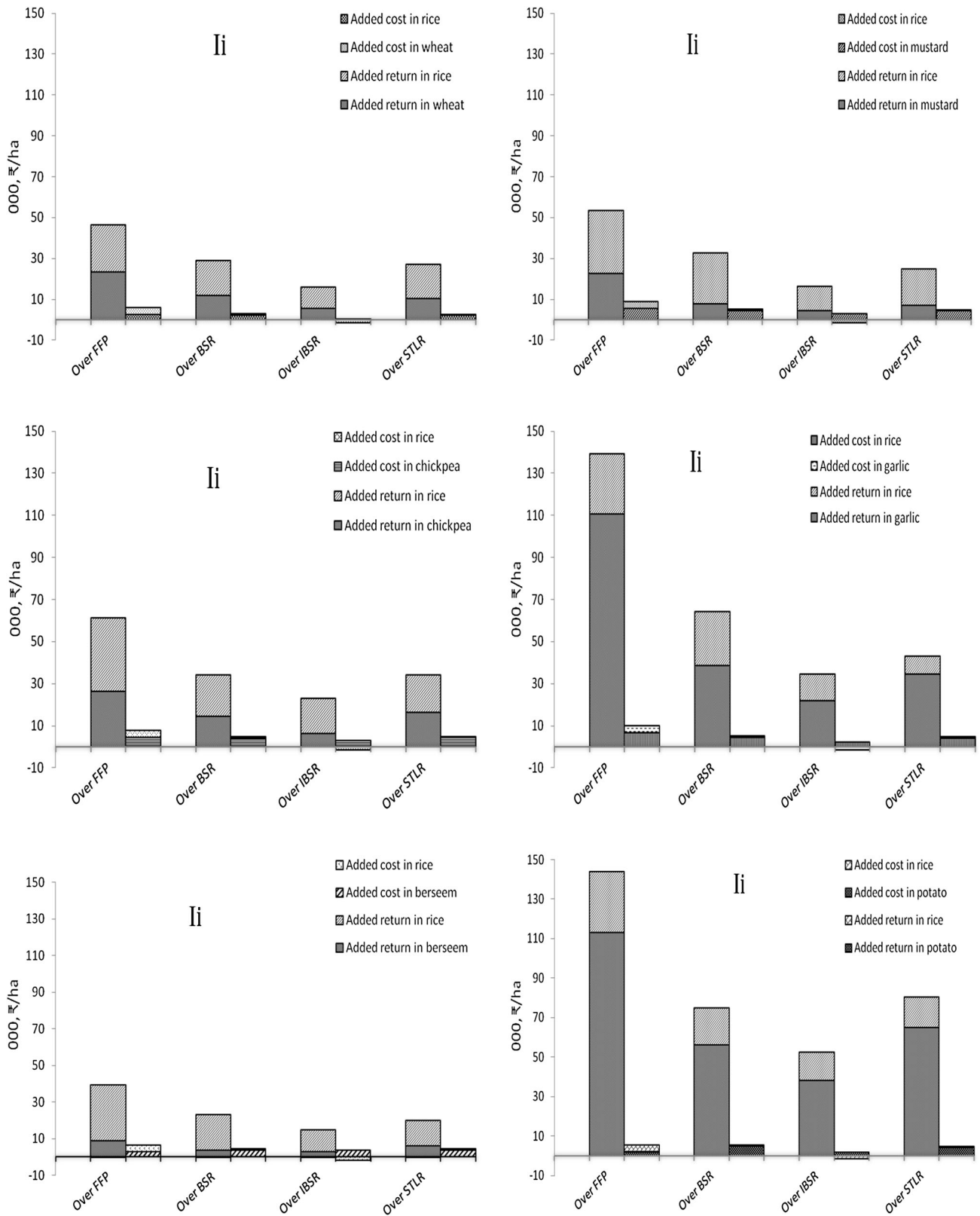


Fig. 2 Added cost and added net return in SSNM treatment over FFP, BSR, IBSR and STLR. \bar{I} indicates LSD at 0.05 for added cost and added return of the system, respectively

over other nutrient management options depended upon grain and straw yield and their prices in each cropping systems, and it varied from ₹ 39577–143899 (mean ₹ 80655) over FFP, ₹ 23236–75056 (mean ₹ 43013) over BSR, ₹ 15165–52470 (mean ₹ 26271) over IBSR and ₹ 20164–80263 (mean ₹ 38243) over STLR. The favourable economics of SSNM over FFP, BSR, IBSR and STLR underlines the significance of balanced nutrition in improving crop yield as well as farm profitability, and counter the effect of increasing fertilizer cost, which is a major challenge towards sustainability of intensive cropping systems [18].

Conclusions

Foregoing results reveals that the existing nutrient management options, i.e. BSR and STLR posing a constant threat of long-term deterioration in soil fertility due to greater drain of native nutrient reserves, particularly in intensive production system. The recommendation emerging from state soil testing labs could be useful, only if they are specific to the site and as per yield target. Otherwise, the yield grains with STLR may not be different from adhoc state recommendations. The SSNM based on indigenous nutrient supply capacity, nutrient use efficiency and target yield, is a promising nutrient management option for attaining higher productivity and sustaining soil health. There is need to develop SSNM options for other locations-specific pre-dominant cropping systems considering farmers' resource availability and socio-economic conditions. In view of negative K balance observed under all nutrient management options including SSNM, there is need to integrate crop residue management with SSNM in order to curb excessive K mining from the soil.

Acknowledgments We are thankful to the International Plant Nutrition Institute (IPNI) for providing financial support for this study. We acknowledge the encouragement and facilities provided for the field and lab studies by Director, Indian Institute of Farming Systems Research, Modipuram, India.

References

1. Aulakh MS, Malhi SS (2004) Fertilizer nitrogen use efficiency as influenced by interactions of N with other nutrients. In: Mosier A, Syers JK, Freny JR (eds) *Agriculture and the nitrogen cycle: assessing the impact of fertilizer use on food production and the environment*. Island Press, Covelo, pp 181–191
2. Awonaike KO, Kumarasinghe KS, Danso SKA (1990) Nitrogen fixation and yield of cowpea (*Vigna unguiculata*) as influenced by cultivar and Bradyrhizobium strain. *Field Crops Res* 24:163–171
3. Buresh RJ, Pampolino MF, Witt C (2010) Field-specific potassium and phosphorus balances and fertilizer requirement for irrigated rice-based cropping systems. *Plant Soil* 335:35–64
4. Dobermann A, Cassman KG, Sta. Cruz PC, Adviento MA, Pampolino MF (1996) Fertilizer inputs, nutrient balance, and soil nutrient-supplying power in intensive, irrigated rice ecosystems. II. Effective soil K supplying capacity. *Nutr Cycling Agroecosyst* 46:11–21
5. Dwivedi BS, Singh Dhyani, Chhonkar PK, Sahoo RN, Sharma SK, Tiwari KN (2006) Soil fertility evaluation-A potential tool for balanced use of fertilizers. IARI, New Delhi and PPI/PPIC-India Programme, Gurgaon, pp 1–60
6. Dwivedi BS, Shukla Arvind K, Singh VK, Yadav RL (2003) Improving nitrogen and phosphorus use efficiencies through inclusion of forage cowpea in the rice-wheat system in the Indo-Gangetic Plains of India. *Field Crops Res* 84:399–418
7. FAI (2011) Fertiliser statistics (2010–11). Fertiliser Association of India, New Delhi
8. Helmke PA, Sparks DL (1996) Lithium, sodium, potassium, rubidium, and cesium. In: Sparks DL et al (ed) *Methods of Soil Analysis, Part 3. Chemical methods*. SSSA Book Series No. 5, SSSA, Madison, WI, pp 551–574
9. Khan MA, Shukla Arvind K, Upadhyay NC, Singh OP, Singh BP (2007) System productivity and soil status with different nutrient management options in sorghum (fodder)-potato-chickpea cropping system. *Potato J* 34(1–2):115–116
10. Ladha JK, Yadvinder-Singh Erenstein O, Hardy B (2009) Integrated crop and resource management in the rice-wheat system of South Asia. International Rice Research Institute, Los Banos
11. Olsen SR, Cole CV, Watanabe FS, Dean LA (1954) Estimation of available phosphorus in soils by extraction with sodium bicarbonate. *USDA Circ.* 939, USDA, Washington DC
12. Piper CS (1966) *Soil and plant analysis*. University of Adelaide Press, Adelaide
13. Prasad R (2006) Zinc in soils and in plant, human and animal nutrition. *Indian J Fertil* 2(9):103–119
14. Shukla Arvind K, Khan MA, Upadhyay NC, Singh OP (2005) Evaluation of nutrient management options for rice-potato-wheat cropping system of upper gangetic plain region. *Potato J.* 32(3–4):159–160
15. Shukla Arvind K, Ladha Jagdish K, Singh VK, Dwivedi BS, Balasubramanian V, Gupta Raj K, Sharma SK, Singh-Yogendra PH, Pandey PS, Padre Agnes T, Yadav RL (2004) Calibrating the Leaf Color Chart for nitrogen management in different genotypes of rice and wheat in a systems perspective. *Agron J* 96:1606–1621
16. Singh M, Dwivedi BS, Dutta SP (2012) Integrated nutrient management for enhancing productivity, nutrient use efficiency and environmental quality. In: Goswami NN et al (eds) *Soil science in the service of nation*. ISSS, New Delhi, pp 55–67
17. Singh VK, Dwivedi BS (2006) Yield and nitrogen use-efficiency in wheat, and soil fertility status as influenced by substitution of rice with pigeon pea in a rice-wheat cropping system. *Aust J Exp Agric* 46:1185–1194
18. Singh VK, Dwivedi BS, Buresh RJ, Jat ML, Majumdar K, Gangwar B, Govil V, Singh SK (2013) Potassium fertilization in rice-wheat system on farmer's fields in India: crop performance and soil nutrients. *Agron J* 105:471–481
19. Singh VK, Dwivedi BS, Shukla AK (2006) Yield, nitrogen and phosphorus use efficiency as influenced by fertiliser NP additions in wheat under rice-wheat and pigeonpea-wheat system on a Typic Ustochrept soil. *Indian J Agric Sci* 76(2):114–119
20. Singh VK, Dwivedi BS, Shukla AK, Chauhan YS, Yadav RL (2005) Diversification of rice with pigeonpea in a rice-wheat cropping system on a Typic Ustochrept: effect on soil fertility, yield and nutrient use efficiency. *Field Crops Res* 92:85–105

21. Singh VK, Dwivedi BS, Shukla AK, Mishra RP (2010) Permanent raised bed planting of the pigeonpea–wheat system on a Typic Ustochrept: effects on soil fertility, yield and water and nutrient use efficiencies. *Field Crops Res* 116:127–139
22. Singh VK, Dwivedi BS, Tiwari KN, Majumdar K, Rani Meenu, Singh Susheel K, Timsina J (2014) Optimizing nutrient management strategies for rice–wheat system in the Indo-Gangetic Plains of India and adjacent region for higher productivity, nutrient use efficiency and profits. *Field Crops Res* 164:30–44
23. Singh VK, Sharma BB, Dwivedi BS (2002) The impact of diversification of a rice–wheat cropping system on crop productivity and soil fertility. *J Agric Sci* 139:405–412
24. Singh VK, Govil V, Singh SK, Dwivedi BS, Meena MC, Gupta VK, Majumdar K, Gangwar B (2012) Precision nutrient management strategies using GIS-based mapping in Western Uttar Pradesh. *Better Crops-South Asia* 6(1):15–18
25. Subbiah BV, Asija GL (1956) A rapid procedure for the determination of available nitrogen in soils. *Current Sci* 25:259–260
26. Swarup A, Wanjari RH (2000) Three Decades of All India Coordinated Research. Project on Long-term Fertilizer Experiments to Study Changes in Soil Quality, Crop Productivity and Sustainability. IISS, Bhopal, India
27. Timsina J, Connor DJ (2001) Productivity and management of rice–wheat cropping systems: issues and challenges. *Field Crops Res* 69:93–132
28. Witt C, Dobermann A, Abdurachman S, Gines HC, Wang G, Nagarajan R, Satawatanont S, Son TT, Tan PS, Tiem LV, Simbahan GC, Olk DC (1999) Internal nutrient efficiencies of irrigated lowland rice in tropical and sub-tropical Asia. *Field Crops Res* 63:113–138
29. Yadvinder-Singh, Bijay-Singh (2001) Efficient management of primary nutrients in the rice–wheat system. *J Crop Prod* 4:23–85
30. Zhu ZL, Chen DL (2002) Nitrogen fertilizer use in China contributions to food production, impacts on the environment and best management strategies. *Nutr Cycling Agroecosyst* 63:117–127