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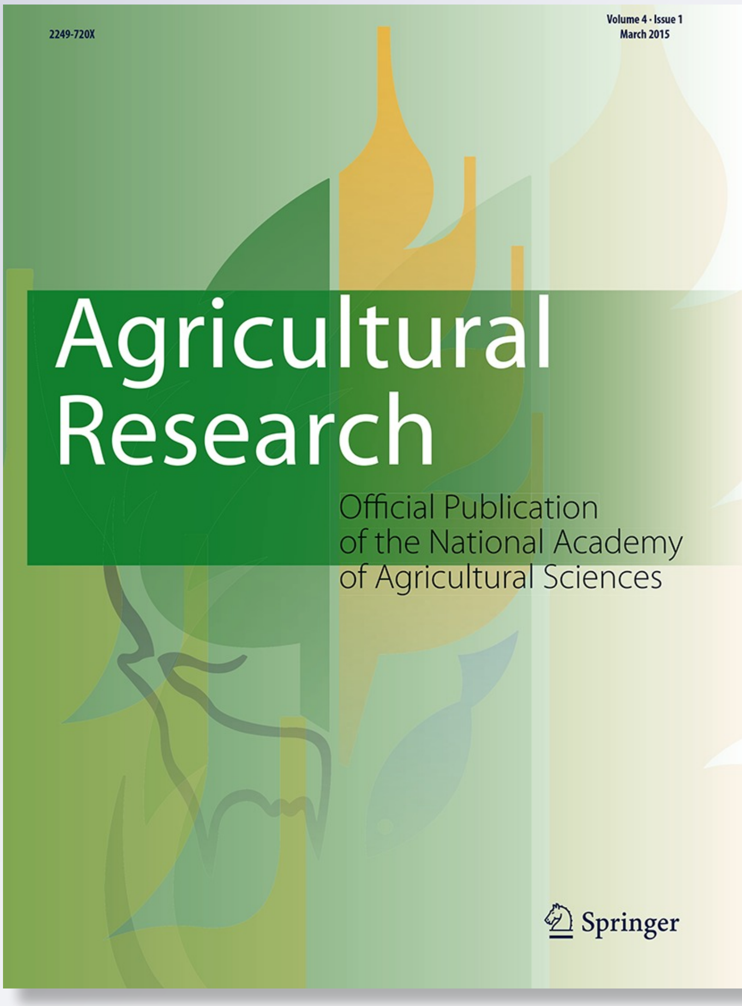

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FULL-LENGTH RESEARCH ARTICLE

Status of Available Sulfur in Soils of North-Western Indo-Gangetic Plain and Western Himalayan region and Responses of Rice and Wheat to Applied Sulfur in Farmer's Fields

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Abstract Widespread nutrient deficiencies have emerged as the major soil-related constraints, with sulfur (S) being one among them, for sustaining rice–wheat productivity in many parts of the north-western Indo-Gangetic Plain (IGP) and the Western Himalayan region (WHR). Therefore, soils from different agricultural development blocks (ADBs) of Meerut and Jyotiba Phule Nagar (J.P. Nagar) Districts in the Upper Gangetic Plain (UGP) zone, Sonipat, and Panipat Districts in Trans-Gangetic Plain (TGP) zone, and New Tehri District in Garhwal zone of WHR were analyzed for their available S-status. Farmers' fertilizer management practices revealed that fertilizer use was highly unbalanced, and use of S fertilizers was generally negligible. Deficiencies of S were noticed in 19–47 % of the soil samples. On-farm experiments at these sites showed that rice (*Oryza sativa* L.) yields improved by 0.84–1.90 t ha^{-1} with the additions of 30–45 kg S ha^{-1} on S-deficient soils of IGPs, whereas the crop response varied from 1.16 to 1.39 t ha^{-1} on WHR soils. Also, the residual effect of 30–45 kg S ha^{-1} was noticed in succeeding wheat (*Trititicum aestivum* L.). Averaged over S rates, 37–49 % of the applied S was recovered in the system at different locations. Skipping S application decreased the available S content of the soils (0.6–2.4 mg kg^{-1}) compared with initial content. Substantial yield gain and economic returns due to the use of S suggested for inclusion of S in the fertilizer schedules for these soils.

Keywords Rice–wheat · Sulfur · Yield · S-use efficiency · Indo-Gangetic Plain · Western Himalayan region

Abbreviations
ADBs: Agricultural Development Blocks; AE: Agronomic efficiency; AICRP: All India Coordinated Research Project; ANR: Additional Net Return; DAP: Di-ammonium phosphate; FAI: Fertilizer Association of India; FYM: Farm yard manure; IFA: International Fertilizer Association; IGP: Indo-Gangetic Plain; RE: Recovery efficiency; SOC: Soil organic carbon; SPM: Sulfitation pressmud; SSP: Single superphosphate; TGP: Trans-Gangetic Plain; TSI: The Sulfur Institute; UGP: Upper Gangetic Plain; VCR: Value Cost Ratio; WHR: Western Himalayan Region;

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Introduction

One of the most important soil fertility constraints endangering the sustainability of high-production agriculture in the post-Green Revolution era is the emergence of multi-nutrient deficiencies. In different agro-ecological regions, simultaneous deficiencies of 2–6 nutrients involving N, P, K, S, Zn, and B have been reported in intensive cropping systems [8]. The use of high-analysis NPK fertilizers worsened the secondary and micronutrient turnover in soil–plant system by increasing the removal of these nutrients on one hand, and restricting their inadvertent supply in the form of impurities on the other [6]. The decreased use of organic manures has also been one of the factors responsible for aggravating the secondary and micronutrient disorders [2, 6]. Nutrient management strategies that depended mainly on NP (K?) fertilizers, ignoring the replenishment of other nutrients through fertilizers or organic sources, led to a situation where the application of nutrients like sulfur (S) actually decides the productivity level of intensive cropping systems, as also the response to NPK fertilizers under many situations [20, 24]. Presently, deficiencies of secondary nutrient-S and micronutrient-Zn are widespread [37]. Close to 70 % of the soil samples analyzed under All India Coordinated Research Project (AICRP) on Secondary and Micronutrients and Pollutant Elements, TSI–FAI–IFA Project, and elsewhere have been found to be either deficient or marginal (prone to become deficient) in plant-available S. Major factors leading to S deficiency are inherent low S content of the soil, coarse sandy texture, low organic matter content, and the conditions that favor leaching losses of available S [39]. Important management factors responsible for emergence of S deficiency are (i) progressively greater removal of soil S owing to high production levels, (ii) negative S balances due to S removals exceeding S additions, and (iii) the use of S-free fertilizers [33].

Although fertilizer ($N + P_2O_5 + K_2O$) consumption in India has increased from merely 2.0 kg ha^{-1} in the early 1960s to 145 kg ha^{-1} in 2011–2012 [9], the use of traditional S-bearing fertilizers, like ammonium sulfate and single superphosphate, has largely decreased [27]. Since the currently used high-analysis fertilizers like, urea, diammonium phosphate, and muriate of potash are practically devoid of S, their use do not allow for addition and accretion of S in the soil, and the S requirements of crops are mainly met through native S reserves [18, 36]. Consequently, S deficiencies in soils, which were restricted to a few coarse-textured soils and oilseed growing areas during the 1970s, have now expanded to as many as 200 districts, and crop response to S application, have been reported in as many as 40 crops including cereals, pulses, oilseeds, tubers, and forage crops [25, 32, 40]. Farmers' participatory surveys undertaken in the Indo-Gangetic Plain (IGP) revealed that a rice–wheat system producing on average, 3.92 t ha^{-1} rice and 3.95 t ha^{-1} wheat in a year, removes annually about 331.0, 2.89, 9.19, 6.72, 3.84, and 0.76 thousand tonnes S, Zn, Fe, Mn, Cu, and B, respectively, from this region [22]. On the other hand, application of S is generally ignored. Thus, the apprehension of increasing S deficiency in the soil as one of the major causes for the yield decline in some of the long-term experiments [11, 20, 30] seems to be true as a result of nutrient withdrawals in excess of their replenishments.

Long–term studies conducted at Modipuram further underlined the importance of S in sustaining high yield levels of rice–wheat system, Hence, generation of pragmatic information on S-deficiency scenario and S-response behavior in this cropping system assumes practical significance. As the information on the extent of S deficiency and its management in the intensively cultivated rice–wheat-growing areas of TGP and UGP of the IGP, and Garhwal zone of Western Himalayan region (WHR), was not available, the present study was undertaken to (i) understand farmers' fertilizer management practices in rice–wheat system, (ii) assess S-deficient areas, and (iii) measure direct and residual effect of S in rice–wheat cropping system on farmers' field.

Materials and Methods

The Study Region

The study was undertaken in rice–wheat-dominated areas of the UGP and TGP, transacts of the IGP, and in Garhwal zone of the WHR. The UGP covering 36 districts in the western Uttar Pradesh and TGP covering 41 districts of Punjab and Haryana are the part of IGP. The Garhwal zone in Uttarakhand state represents submountainous ecosystem and falls under the WHR. The districts chosen for the study were Meerut and Jyotiba Phule Nagar (J.P. Nagar) in UGP; Sonipat and Panipat in TGP; and New Tehri in Garhwal zone. The cropping intensities in these zones ranged between 148 and 169 %. Crop management strategies, including nutrient management, evolved for these districts could be extrapolated to the entire UGP, TGP, and WHR.

The climatic conditions of Meerut and J.P. Nagar districts in UGP, and Sonipat and Panipat districts in TGP, are semi-arid subtropical with dry hot summers and cold winters. On the other hand, New Tehri District represents subhumid temperate climate with mildly cold summers and severe cold winters. The average annual rainfalls are in the district Meerut, 810 mm; in J.P. Nagar, 967 mm; in Sonipat, 567 mm; in Panipat, 680 mm; and that in New Tehri is 900 mm. At all the locations, about 80 % of the total rainfall is received through north-west monsoon during July–September.

Farmer-Participatory Diagnostic Survey

To understand farmers' fertilizer management practices in rice–wheat system and assess the extent of S deficiency, a survey was undertaken in Daurala and Hastinapur Agricultural Development Blocks (ADB: the administrative unit within a district, meant for implementation of the state development programs up to the village level) in district

Meerut, and Gajraula and Hasanpur ADBs in district J P. Nagar in the UGP. Similarly, Rai and Bapoli ADBs in districts Sonipat and Panipat, respectively, in TGP; and Fakot and Chamba ADBs in district New Tehri of Garhwal zone were surveyed for the same purpose. The villages and farmers selected for the diagnostic surveys were chosen from these ADBs, following stratified sampling technique [29]. The cropping intensities of Daurala, Hastinapur, Hasanpur, Gajraula, Rai, and Bapoli ADBs ranged between 154 and 179 %, whereas, those in Fakot and Chamba ADBs ranged between 139 and 157 %. The soils of the studied locations were alluvial Inceptisols, very deep (>2 m) loamy sand to loam in texture, neutral to mildly alkaline in reaction (pH 5.86–8.67), and nonsaline (electrical conductivity 0.20–0.56 dS m^{-1}). Taxonomically, soils of Daurala and Hasanpur are Typic Ustochrepts; Gajraula and Hastinapur, Aquic Ustochrept Typic Ustochrepts; Rai and Bapoli,Typic Ustipsamnents; and of Fakot and Chamba, Typic Haplaquepts. Occasional waterlogging up to 10–40-cm standing water during August–September occurs in Hastinapur, Hasanpur, and Gajraula ADBs. In Hastinapur, Daurala, Fakot, and Chamba ADBs, most of the farmers apply farmyard manure (FYM) at 10–35 t ha^{-1}once in three years, but in Gajraula, Hasanpur, Rai, and Bapoli ADBs, FYM is rarely used. At the harvest, aboveground biomasses of both rice and wheat is removed from the field, except in Hastinapur and Bapoli ADB wherein mechanized harvesting is generally practiced and crop residues are burnt in situ.

For recording farmers'current fertilizer management practices, 80 farmers each in UGP, TGP, and Garhwal zones representing different socioeconomic groups were selected. Researchers visited selected farmers at 15-day intervals during crop-growth periods, and recorded fertilizer management practices by interviewing the farmers, on a questionnaire developed for this purpose. While visiting and interviewing the farmers, fertilizer management practices adopted by them were not interfered. In each farmer's field, 1 m × 1 m area was harvested for recording grain yields of rice and wheat.

Field Selection for Soil Sampling

During the years 2003–2005, soil samples were collected during April–June, after the harvest of wheat from villages having at least 50 % gross-cropped area under rice–wheat rotation for more than two consecutive years. The total numbers of fields selected for soil sampling were 250 in Daurala, 277 in Hastinapur, 250 in Gajraula, 260 in Hasanpur, 584 in Rai, 607 in Bapoli, 611 in Fakot, and 642 in Chamba ADBs. From each selected field, four subsamples (0–15-cm depth) were collected and mixed thoroughly to make one representative homogeneous soil sample. A total of 3,481 soil samples were collected for S and organic carbon determination.

On-farm Experiments

The Experimental Sites

On-farm experiments were conducted on S-deficient fields in seven villages on a fixed layout, as shown in Table 1 along with soil fertility status of experimental fields before commencement of the experiments.

Treatments and Crop Culture

At each experimental site, four levels of S (0, 15, 30, and 45 kg S ha^{-1}) were evaluated in a randomized block design having five replications. The plot size was 8 m × 6 m. Single superphosphate (12 % S, 6.99 % P) was used to apply S to rice only. The residual effect of S was measured on succeeding wheat. Uniform doses of 120 kg N, 26 kg P, and 50 kg K ha^{-1} were applied to both rice and wheat. Urea (46.4 % N), di-ammonium phosphate (18 % N, 20.09 % P), or single superphosphate as per treatment, and muriate of potash (49.8 % K) were used to supply N, P, and K, respectively. A uniform dose of 5 kg Zn ha^{-1} as zinc chloride (65 % Zn) was also applied to rice. One third dose of N and all of P, K, and Zn were applied before transplanting/sowing of the crops, and the remaining N was top-dressed in two equal splits: 30 and 55 days after transplanting/sowing.

Twenty-five-day-old seedlings of rice cv. 'Saket 4' were transplanted at 20 × 10-cm spacings in puddled plots during the first week of July. Rice was harvested during the third week of October. Succeeding wheat cv. 'HD 2338' was sown in 20-cm-apart rows, using 100 kg seed ha^{-1}, during the second fortnight of November at all locations except Jajal and Nagini, where it was sown during the first week of November. The wheat crop was harvested at maturity during the second fortnight of April.

The crops were grown under irrigated conditions. In rice, about 5-cm standing water was maintained at each irrigation, and the frequency of irrigation (flooding) depended on disappearance of standing water. Wheat received five irrigations: at crown-root initiation (21 days after sowing, DAS), maximum tillering (55 DAS), jointing (75 DAS), ear emergence (100 DAS), and milking (135 DAS) stages. At maturity, both rice and wheat crops were harvested manually using sickle leaving 10–15-cm stubble for rice and 5-cm stubble for wheat. A net plot area of 30 m^2 (6 m × 5 m) was marked for harvesting of grain yield. After three-day sun drying in the field, the total biomass (grain + straw) was weighed and threshed with a plot-thresher. Thereafter, the grain yield was weighed as

Table 1 Physicochemical characteristics of the on-farm experimental sites and numbers of years of experiments conducted

Characteristics	Mohammedabad (J.P. Nagar district)	Dulhera (Meerut district)	Bharala (Meerut district)	Garh Meerakpur (Sonipat district)	Jalalpur I (Panipat district)	Jajal (New Tehri district)	Nagini (New Tehri district)
Year of experiments	1997–1998 to 1998–1999	1997–1998	1998–1999	2003–2004 to 2005–2006	2003–2004 to 2005–2006	2003–2004 to 2005–2006	2003–2004 to 2005–2006
Mechanical composition							
Sand (%)	60.5	64.5	73.8	70.2	66.2	62.6	64.4
Silt (%)	17.0	18.5	9.0	16.4	18.5	18.0	19.3
Clay (%)	20.0	15.0	16.0	13.6	15.3	19.4	16.3
Texture	Loam	Sandy loam	Sandy loam	Loamy Sand	Sandy loam	Loam	Sandy loam
Taxonomy	Typic Ustochrept	Typic Ustochrept	Typic Ustochrept	Typic Ustipsamnent	Typic Ustipsamnent	Typic Haplaquept	Typic Haplaquept
pH	8.02	7.67	7.58	7.62	7.45	7.00	6.50
Electrical conductivity (dS m^{-1})	0.41	0.30	0.32	0.33	0.39	0.21	0.21
Organic carbon (%)	0.43	0.35	0.39	0.48	0.42	0.52	0.59
Olsen-P (mg kg^{-1})	8.20	5.50	5.20	6.84	5.12	8.13	9.06
Available K (me 100 g^{-1})	0.18	0.12	0.14	0.14	0.11	0.19	0.15
Available S (mg kg^{-1})	7.80	5.20	5.80	6.8	4.91	10.0	6.41

adjusted to 13 % moisture content. Straw yield was obtained as the difference between the total biomass and the grain yield. The aboveground biomass was removed from the plots, and the underground stubble was disked into the soil. Soil samples (0–15-cm depth) were collected from each plot after harvest of final wheat crop of the experiments.

Soil and Plant Analyses

Soil samples were analyzed for available S [41] and OC content (Walkley and Black's method). Initial soil samples collected from on-farm experiments before commencement of the experiments were also analyzed for sand, silt, and clay content (international pipette method), pH, and electrical conductivity (1:2 soil–water suspension), available P (0.5 M $NaHCO_3$, pH 8.5), and available K (1 M NH_4OAc, pH 7.0), following standard analytic procedures [14, 28].

The grain and straw samples collected from each plot were washed thoroughly with tap water, 0.05 *N* HCl solution and de-ionized water in succession, and dried at 70 °C in a hot-air oven. The dried samples were ground in a stainless steel Wiley mill, digested in a di-acid mixture ($HClO_4$ and HNO_3 mixed in 4:1 ratio), and aqueous extracts were prepared. The total S content in the extracts was then determined turbidimetrically [4] using an UV–Vis spectrophotometer.

Computations and Statistical Analysis

The data collected during survey were compiled (Table 2) and standard deviations (SDs) for different parameters were computed. 'F-test' was used for treatment comparisons in the on-farm experiments, following the procedures of randomized block design [5].

The economic optimal S rate for rice was computed using following equation:

$$S_{opt} = 1/2c\,\{(P_S/P_R) - b\} \qquad (1)$$

where S_{opt} is the economic optimal dose of S (kg ha^{-1}), *b* and *c* are the constants of quadratic production function, P_S is the price of fertilizer S (i.e., ₹ 32.5 kg^{-1} S), and P_R the price of rice grain (₹ 10.8 kg^{-1}). The quadratic functions were calculated as

$$Y = a + bx + cx^2 \qquad (2)$$

where *Y* is the estimated rice yield, *a* is a constant, *x* is the dose of fertilizer S (kg ha^{-1}), and *b* and *c* are the regression coefficients of *x*.

In order to quantify the effects of fertilizer S on the S-use efficiencies in rice and rice–wheat system, computations were made using the following equations:

$$AE_S = \Delta Y\, F_S^{-1} \qquad (3)$$

where AE_S is the agronomic efficiency, often termed as incremental efficiency, of the applied S fertilizer; ΔY is the

Table 2 Fertilizer management practices in rice and wheat under rice–wheat system in UGP, TGP, and Garhwal zones of India

Particulars	UGP						TGP						Garhwal zone					
	Rice			Wheat			Rice			Wheat			Rice			Wheat		
	No. of cases[a]	Average	SD±	No. of cases[a]	Average	SD±	No. of cases	Average	SD±	No. of cases	Average	SD±	No. of cases	Average	SD±	No. of cases	Average	SD±
Fertilizer material used (kg ha^{-1})																		
Urea	80	266.7	23.8	80	282.5	24.3	80	285.4	18.6	80	298.4	30.7	80	126.0	21.7	80	94.6	11.4
DAP	61	113.6	19.5	73	113.78	18.2	64	172.7	20.4	80	127.2	18.4	52	59.4	11.9	32	26.8	5.4
SSP	9	134.8	69.9	4	122.6	1.8	5	113.5		–	–	–	3	44.7	14.4	–	–	–
CAN	7	102.4	32.4	6	79.0	13.5	–	–	–	–	–	–	–	–	–	–	–	–
AS	1	123.5	–				–	–	–				–	–	–			
NPK	8	115.6	27.3	6	120.4	12.4	2	102	8.2	1	125.0	–	4	40.3	6.2	–	–	–
MOP	6	35.0	5.0	5	56.8	14.1	16	22.5	4.9	14	56.4	9.7	5	22.7	4.1	2	19.4	3.2
ZS	74	22.5	6.2	3	16.5	7.1	66	16.2	2.3	–	–	–	22	9.4	1.7	–	–	–
Use of organic manure (t ha^{-1} $year^{-1}$)																		
FYM/SPM	29	8.8	5.6	7	11.4	3.8	22	0.8	0.3	9	1.8	0.4	52	5.1	2.3	61	6.1	0.1
Nutrients applied through fertilizers (kg ha^{-1})																		
N	80	126.1	35.0	80	136.9	33.1	80	162.4	29.1	80	172.6	16.7	80	79.4	24.2	80	48.4	4.9
P_2O_5	71	45.4	6.0	79	53.8	4.4	69	48.6	9.4	80	59.3	6.8	55	20.1	4.3	32	12.4	1.1
K_2O	14	23.4	4.8	11	20.1	4.9	18	14.8	3.1	1	27.4	5.3	8	18.6	3.5	2	9.5	0.8
S	74	6.0	0.6	7	9.5	6.6	66	4.2	0.8	–	–	–	22	5.1	3.7	–	–	–
Zn	74	4.5	1.3	3	3.5	1.5	66	3.4	0.6	–	–	–	22	3.2	1.2	–	–	–
Cropping intensity (%)	80	169	10.9				80	164	9.8				80	148	8.8			
Grain yield (kg ha^{-1})	80	4,199	864	80	4,108	725	80	5,032	532	80	4,516	823	80	3,346	541	80	2,582	221

Urea (46.4 % N); *DAP* di-ammonium phosphate (18 % N, 20.09 % P), *SSP* single superphosphate (6.99 % P, 12 % S), *CAN* calcium ammonium nitrate (26 % N), *AS* ammonium sulfate (20.5 % N, 24 % S), *NPK* mixed fertilizer (12 % N, 13.97 % P, 13.28 % K), *MOP* muriate of potash (49.8 % K), *ZS* zinc sulfate (21 % Zn, 15 % S), *FYM* farmyard manure, *SPM* sulfitation pressmud

[a] Total number of cases were 80 at each study location

incremental yield due to fertilizer S input; and F_S is the amount of fertilizer S applied. The ΔY and F_S are expressed as kg ha^{-1}.

Recovery efficiencies of S (RE_s) in rice as well as rice–wheat system were computed using the differential method [15] as the difference in S uptakes by the aboveground portions of S fertilized and unfertilized crop (ΔU) and expressed as the percentage of S fertilizer applied.

$$RE_S = \Delta U \, F_S^{-1} \times 100 \quad (4)$$

For economic evaluation of the treatments, computations were made to compute the increase in net return (₹ ha^{-1}) due to S fertilization, i.e., mean yield response (kg ha^{-1}) to S × $P_{R \text{ or } W}$. The price of wheat grain was taken as ₹ 12.85 kg^{-1}. The value–cost ratio (VCR) of S application for rice as well as in rice–wheat system was also computed as per the following formula:

$$VCR = ANR_{RorRw} P_S^{-1} \quad (5)$$

where, $ANR_{R \text{ or } Rw}$ is the additional net return (₹) in rice or rice–wheat system due to S application, and P_S is the price of sulfur applied (₹).

Results

Fertilizer Management Practiced by the Farmers

Application Rates and Sources

Surveys revealed that, on average, rice was fertilized with 126.1 kg N, 45.4 kg P_2O_5, 23.4 kg K_2O, 6 kg S, and 4.5 kg Zn ha^{-1} in UGP (with a cropping intensity of 169 %); with 162.4 kg N, 48.6 kg P_2O_5, 14.8 kg K_2O, 4.2 kg S, and 3.4 kg Zn ha^{-1} in TGP (with a cropping intensity of 164 %); and with 79.4 kg N, 20.1 P_2O_5, 18.6 kg K_2O, 5.1 kg S, and 3.2 kg Zn ha^{-1} in Garhwal zone (with a cropping intensity of 148 %) (Table 2). Subsequent wheat crop received 136.9 kg N, 53.8 kg P_2O_5, 20.1 kg K_2O, 9.5 kg S, and 3.5 kg Zn ha^{-1} in UGP; 172.6 kg N, 59.3 kg P_2O_5, and 27.4 kg K_2O ha^{-1} in TGP; and 48.4 kg N, 12.4 kg P_2O_5, and 9.5 kg K_2O ha^{-1} in Garhwal zone (Table 2). Overall, the nutrient application rates were in the order of TGP > UGP > Garhwal zone. Although all farmers applied N to both crops in the surveyed ADBs in these zones, only 89, 86, and 69 % fields received P in rice; and 99, 100, and 40 % in wheat in TGP, UGP, and Garhwal zone, respectively. Of the total farmers, 18, 23, and 10 % farmers applied K to rice and 14, 1, and 3 % to wheat crops in these zones, respectively. Although 28–93 % farmers applied S to rice in the surveyed ADBs, the quantity of the applied S was extremely low (4.2–6.2 kg ha^{-1}), and it was applied inadvertently along with Zn as zinc sulfate. A few farmers (4–11 % in different zones) applied P as SSP thus adding some S to rice. In wheat also, S was rarely applied (9 % farmers only in UGP) that too as zinc sulfate only.

Urea was the most preferred fertilizer for N top-dressing, whereas di-ammonium phosphate (DAP) was mainly the preferred source of P for basal dressing in rice and wheat at all the studied locations (Tables 2). To supply Zn, zinc sulfate (ZS) was used at the time of puddling before rice transplanting.

Use of Organic Manures and Crop Productivity

Organic manure, FYM or sulfitation pressmud (SPM, a bi-product of sugar industry), was applied by 36 % farmers in UGP, 28 % farmers in UGP, and 65 % farmers in Garhwal zone prior to puddling in rice; and by 9, 11, and 77 % farmers in wheat, respectively. On average, the uses of organic manure ranged between 7.1 and 26.5 t ha^{-1} in rice and between 18.2 and 34.1 t ha^{-1} in wheat at a 3-yr interval. Average uses of organic manure, in t $ha^{-1}year^{-1}$, for the rice–wheat system were 20.2 in UGP, 2.6 in TGP, and 11.2 in Garhwal region (Table 2). Average yields on farmers' fields, in t ha^{-1}, were 4.2 for rice and 4.1 for wheat in UGP; 5 for rice and 4.5 for wheat in TGP; and 3.3 for rice and 2.6 for wheat in Garhwal zone.

Available S Content and Occurrence of S Deficiency in Soils

In TGP, the mean available S content in soils in Rai ADB was 14.6 mg kg^{-1} with a range of 1.6–67.2 mg kg^{-1}, whereas in Bapoli ADB, the mean available S content was 12.8 mg kg^{-1} with a range of 2.1–64.8 mg kg^{-1} (Table 3). Similarly in UGP, the mean available S content was the highest (20.1 mg kg^{-1}) in Hastinapur, followed by 19.5 mg kg^{-1} in Gajraula, 14.7 mg kg^{-1} in Daurala, and 14.2 mg kg^{-1} in Hasanpur. Available S contents in Fakot and Chamba ADBs of Garhwal zone averaged at 18.2 and 16.3 mg kg^{-1}, respectively.

Considering 10 mg S kg^{-1} of soil as threshold value, 19–36 % soil samples in UGP, 42–47 % in ADB of TGP, and 31–34 % in Garhwal zone were rated S deficient (Table 3).

Relationship between Available S and SOC Contents

The soils of TGP contained SOC in a range of 0.14–1.74 % (mean 0.5 %) in Rai ADB and 0.11–1.77 % (mean 0.55 %) in Bapoli ADB (Table 3). In UGP, SOC averaged at 0.43 % in Daurala, 0.70 % in Hastinapur, 0.45 % in Gajraula, and 0.40 % in Hasanpur. The mean values of SOC in Fakot and Chamba ADBs in the Garhwal zone were 0.56 and 0.52 %, respectively.

Table 3 Soil organic carbon and available S contents in UGP, TGP, and Garhwal zone

ADB	No. of samples	Max.	Min.	Average	SD±	% samples in different categories		
						Deficient[a]	Marginal[a]	Adequate[a]
Organic carbon (%)								
UGP								
Daurala	250	0.80	0.11	0.43	0.16	67	32	1
Hastinapur	277	1.61	0.13	0.70	0.24	21	36	43
Gajraula	250	1.07	0.10	0.45	0.24	61	26	13
Hasanpur	260	0.93	0.07	0.40	0.18	67	31	2
Average				0.50		54.0	31.3	14.7
TGP								
Rai	584	1.74	0.14	0.41	0.21	63	34	3
Bapoli	607	1.77	0.11	0.44	0.16	60	31	9
Average				0.43		61.5	32.5	6.0
Garhwal zone								
Fakot	611	1.4	0.12	0.56	0.26	44	41	15
Chamba	642	1.23	0.10	0.52	0.12	40	37	23
Average				0.54		42.0	39.0	19.0
Available S (mg kg^{-1})								
UGP								
Daurala	250	36.4	3.4	14.7	5.7	26	59	15
Hastinapur	277	90.3	1.9	20.1	12.7	19	41	40
Gajraula	250	86.9	2.0	19.5	15.4	31	31	38
Hasanpur	260	54.2	2.2	14.2	9.0	36	46	18
Average	–	–	–	17.1	–	28.0	44.3	27.8
TGP								
Rai	584	67.2	1.6	14.6	7.4	47	35	18
Bapoli	607	64.8	2.1	12.8	14.7	42	37	21
Average	–	–	–	13.7	–	44.5	36.0	19.5
Garhwal zone								
Fakot	611	44.8	2.1	18.2	16.1	31	52	17
Chamba	642	60.8	1.4	16.3	9.4	34	48	18
Average	–	–	–	17.3	–	32.5	50.0	17.5

ADB agricultural development block

[a] Categories for deficient, marginal and adequate soil samples were <0.05, 0.05–0.75, and >0.75 % in organic carbon; and <10, 10–20, and >20 mg kg^{-1} in available S, respectively

Considering <0.50 % SOC as threshold value [31], 67 % soil samples each in Hasanpur and Daurala, 61 % in Gajraula, 21 % in Hastinapur, 63 % in Rai, 60 % in Bapoli, 44 % in Fakot, and 40 % in Chamba ADBs were rated as deficient in SOC (Table 3).

The higher the SOC, the higher was the available S content. The occurrence of S deficiency was also associated with SOC content, and the soil samples having low OC (<0.5 %) exhibited greater S deficiency (Table 4). The reverse was true for high OC (>0.75 %) soils. In Daurala and Hasanpur ADBs, none of the soil samples with high OC content was deficient in available S (Fig. 1).

On-farm Experiments

Response to Applied S

The application of S increased rice yields significantly ($p < 0.05$) at all sites, although the magnitudes of response varied according to S-application rate and available S content of the soil (Table 5). The grain yields of rice without S application were in the range of 3.07–4.77 t ha^{-1} at different locations, which increased by 0.67, 0.69, 0.48, 1.37, 0.75, 0.66, and 0.65 t ha^{-1} with application of S at 15 kg ha^{-1} at Garh Meerakpur, Jalalpur I,

Table 4 Relationship between soil OC and available S contents of the soil in different ADBs

ADB	Range of soil OC (%)	Average content of available S (mg kg^{-1})	% samples deficient in S
Hastinapur	<0.5	16.0	35.1
	0.5–0.75	19.1	24.5
	>0.75	21.3	19.5
Daurala	<0.5	14.8	27.1
	0.5–0.75	14.2	25.3
	>0.75	23.8	–
Gajraula	<0.5	17.6	33.3
	0.5–0.75	21.9	28.1
	>0.75	23.8	24.2
Hasanpur	<0.5	14.2	38.6
	0.5–0.75	15.3	35.4
	>0.75	29.1	–
Rai	<0.5	11.2	48.5
	0.5–0.75	14.9	34.6
	>0.75	19.7	9.4
Bapoli	<0.5	12.4	41.4
	0.5–0.75	16.5	30.7
	>0.75	24.1	6.9
Fakot	<0.5	15.4	40.6
	0.5–0.75	17.2	29.8
	>0.75	26.1	4.7
Jajal	<0.5	14.7	36.2
	0.5–0.75	16.8	30.1
	>0.75	24.9	1.3
Average		18.5	25.2

ADB agricultural development block

Mohammedabad, Dulhera, Bharala, Jajal, and Nagini, respectively. Further increases in yield by 0.45, 0.48, 0.36, 0.53, 0.63, 0.50, and 0.59 t ha^{-1} were noticed with 30 kg S ha^{-1}. The yields, however, remained unchanged with further increment in S-application rates. A quadratic response to S application was observed in rice (Fig. 2). The economic (optimal) rates of fertilizer S were computed to be in the range of 28.2–41.3 kg ha^{-1} at different locations. At optimal application rates, every kilogram of fertilizer S produced 22.5–59.7 kg of rice grain in different on-farm experiments.

Application of S at 30 or 45 kg ha^{-1} to rice brought significant ($p < 0.05$) increase in the yield of succeeding wheat at all sites (Table 5). Compared with control (no S fertilizer), 45 kg ha^{-1} S-application rates in rice at Garh Meerakpur and Jalalpur I resulted in 1.08 and 1.09 t ha^{-1} additional grain yields of succeeding wheat due to the residual effect. Residual S in the soil at this application rate (45 kg ha^{-1}) increased the grain yields of wheat versus control by 0.85 t ha^{-1} at Mohammedabad, by 1.31 t ha^{-1} at Dulhera, 0.90 t ha^{-1} at Bharala, by 1.06 t ha^{-1} at Jajal, and by 0.92 t ha^{-1} at Nagini. Smaller S fertilization rate, i.e., 15 kg ha^{-1}, did not produce any residual effect at either sites.

Compared with no S-control, the application of 30 kg S ha^{-1} increased the system (rice + wheat) productivity by 17–35 % at different locations, whereas the corresponding increases due to 45 kg S ha^{-1} were in the range of 20–42 %. Averaged across the locations, system productivity gains due to applications of 30 and 45 kg S ha^{-1} were of 26.5 and 32.0 %, respectively.

The agronomic S-use efficiencies of rice and rice–wheat system were decreased with the increasing S rates at all the locations. In rice, the agronomic efficiencies at 15-kg S-application rates were in the ranges of 45–46 kg grain kg^{-1} S in TGP, 32–91 kg grain kg^{-1} S in UGP, and 43–44 kg grain kg^{-1} S in Garhwal zone, which at 45-kg S rate decreased to 28–30 kg grain kg^{-1} S, 19–40 kg grain kg^{-1} S, and 30–31 kg grain kg^{-1} S, respectively. Agronomic S-use efficiency of the system (rice + wheat) followed the similar trend, although the values for kg grain kg^{-1} S were comparatively higher (Fig. 3).

S Uptake and Recovery Efficiency

Total S uptakes (aboveground portion) by the rice–wheat system ranged from 22.7 to 45.4 kg ha^{-1} at Garh Meerakpur; in the range of 20.5–41.9 kg ha^{-1} at Jalalpur I; in the range of 27.7–48.0 kg ha^{-1} at Mohammedabad; in the range of 35.2–52.5 kg ha^{-1} at Dulhera; in the range of 27.9–51.9 kg ha^{-1} at Bharala; in the range of 16.9–39.5 kg ha^{-1} at Jajal; and in the range of 15.9–35.4 kg ha^{-1} at Nagini. The S uptake in rice increased concomitantly with each increment in S-application rate at all sites (Table 5). Compared with control, total S uptakes under 45 kg S ha^{-1} were higher by 126, 156, 104, 67.6, 119, 176, and 138 % at Garh Meerakpur, Jalalpur, Mohmmedabad, Dulhera, Bharala, Jajal, and Nagini, respectively. Similar to yield, significant increase in total S uptake in wheat due to residual effect was recorded in the treatments receiving 30 or 45 kg S ha^{-1} in preceding rice crop. The magnitude of response was, however, not as large as in case of rice which received direct S application (Table 5). In both the crops, S concentration in grain was positively and significantly correlated with the grain yield at all the locations. Also, total S uptakes by rice and wheat were positively ($p < 0.05$) correlated with the soil-available S content (Fig. 4). The total S absorbed by the crops was almost equally partitioned between grain and straw components (Table 5).

Recovery efficiencies of S (REs) in rice varied from 15.8 % at Dulhera to 30.3 % at Jajal and Bharala. The AR was generally greater in the treatments receiving 30 kg S

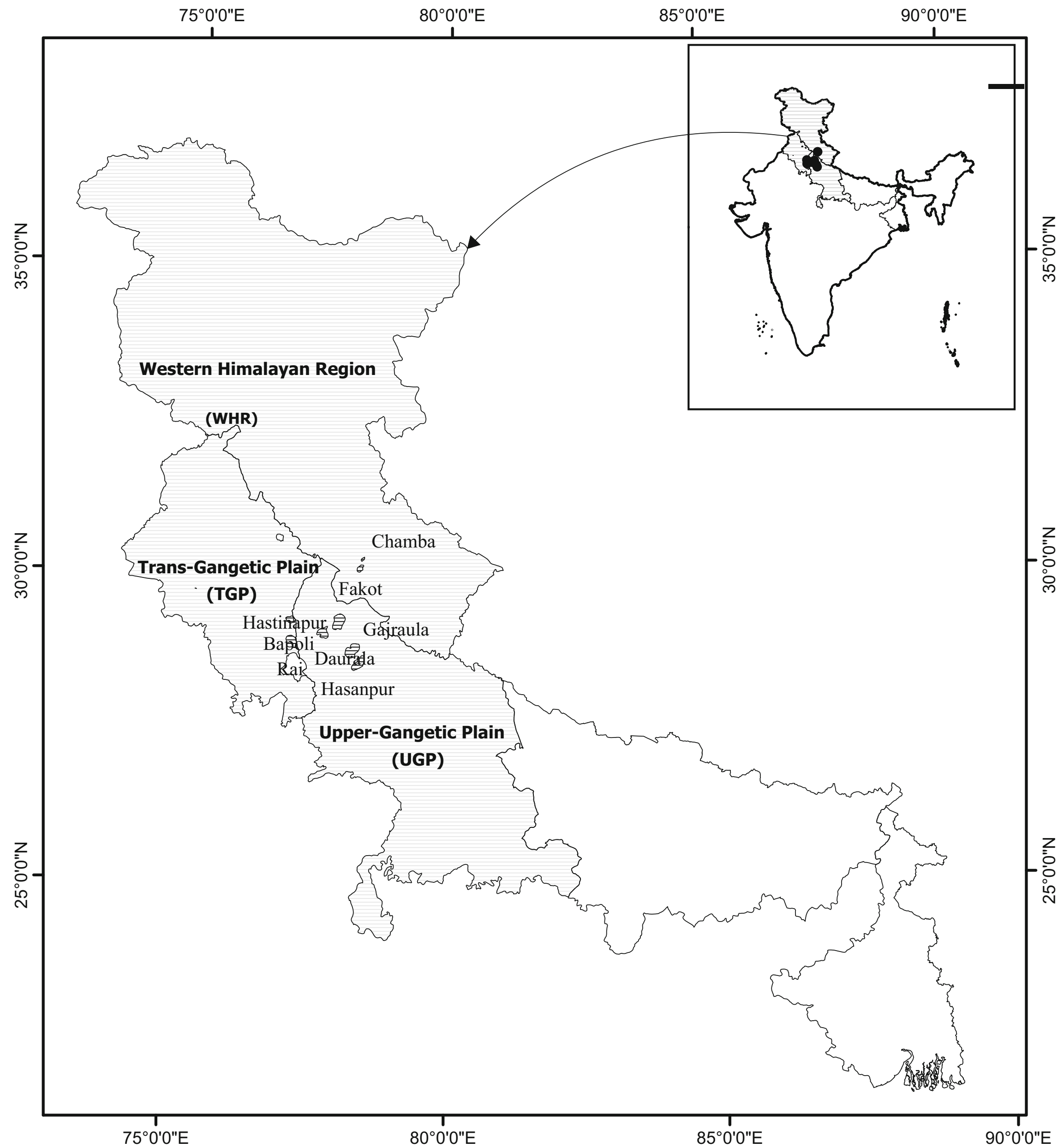


Fig. 1 Location map of the study area

ha^{-1} except Dulhera and Garh Meerakpur where it was the highest at 15 kg S ha^{-1}. The RE for the system (rice + wheat) revealed a pattern similar to that of rice (Fig. 5). Averaging over S rates, 37–49 % of the applied S was recovered in the system at different locations.

Change in Available S Content in Soil

The available S content of the soil decreased considerably over the initial S content with omission of S from the fertilizer schedule, although the magnitude of decline varied among the locations. The initial available S contents declined by 10–11 % at Dulhera and Bharala, 13 % at Mohammedabad, and 19–42 % at Garh Meerakpur, Jalalpur I, Jajal, and Nagini under no-S plots. Decreases in available S to the extent of 2–31 % over the initial content was also noticed in plots receiving 15 kg S ha^{-1} annually, indicating the inadequacy of this application rate for the succeeding crop. On the other hand, annual application of 45 kg S ha^{-1} increased the available S content, and the magnitudes of increase over the initial S content were in the range of 16–50 % at different locations (Fig. 5).

Table 5 Effects of S application on grain yield, grain and straw S uptakes of rice and wheat, and soil-available S content under rice–wheat system

Levels of S (kg ha^{-1})	Mohammedabad[@] $	Dulhera $	Bharala $	Garh Meerakpur[#] $	Jalalpur I[#] $	Jajal[#] $	Nagini[#] $	Average over the locations			
								Grain Yield (t ha^{-1})	Grain S uptake (kg ha^{-1})	Straw S uptake (kg ha^{-1})	Available S* (mg kg^{-1})
Grain yield (t ha^{-1})											
Rice											
0	3.99c	4.77c	4.56c	3.71c	3.36c	3.32c	3.07c	3.83	–	–	5.7
15	4.47b	6.14b	5.31b	4.38b	4.05b	3.98b	3.72b	4.58	–	–	6.1
30	4.83a	6.67ab	5.94a	4.83a	4.53a	4.48a	4.31a	5.08	–	–	8.3
45	4.84a	6.56a	6.02a	5.06a	4.63a	4.71a	4.39a	5.17	–	–	9.9
Residual wheat											
0	4.42c	4.11c	4.38c	3.72b	3.30c	2.63c	2.25c	3.54	–	–	5.4
15	4.57bc	4.31bc	4.46bc	4.03bc	3.61bc	3.04bc	2.51bc	3.79	–	–	5.9
30	4.97b	5.00a	4.89a	4.49a	3.93a	3.43 ab	2.87ab	4.23	–	–	7.8
45	5.27a	5.42a	5.28a	4.80a	4.39a	3.69a	3.17a	4.57	–	–	9.4
S uptakes (kg ha^{-1})											
Rice											
0	9.9d	10.5d	9.9d	7.6d	6.4d	6.3d	6.6d	–	3.7	4.1	–
15	13.8c	14.3c	13.1c	10.8c	9.4c	9.6c	9.2c	–	5.3	5.8	–
30	18.7b	16.1b	19.0b	15.2b	14.2b	15.4b	13.9b	–	7.6	8.0	–
45	19.9a	17.6a	21.7a	17.2a	16.4a	17.4a	15.7a	–	9.1	8.5	–
Residual wheat											
0	17.8d	24.8cb	17.9d	15.1d	14.1d	10.6d	9.3d	–	7.1	8.5	–
15	19.5cd	27.5b	18.8cd	17.7cd	16.6cd	12.3cd	12.6cd	–	8.5	9.4	–
30	25.0b	32.2a	25.5b	24.9b	22.4b	18.7b	16.3b	–	11.5	12.0	–
45	28.1a	34.9a	30.1a	28.2a	25.5a	22.1a	19.7a	–	14.1	12.9	–

@ Means of 1997–1998 and 1998–1999

Means of 2003–2004, 2004–2005, and 2005–2006

$ Within a column, means followed by the same letters are not significantly different at the 0.05 level of probability according to L.S.D

* Available S content after rice and wheat harvests in terminal year

Economics

The additional net returns (₹) due to S application in rice increased with the increasing S rates up to the highest level (Fig. 7). The net returns for rice–wheat system ranged between ₹ 21,780 and 39,435 ha^{-1} at the highest application rate of 45 kg S ha^{-1}. In general, the VCR decreased with each increment of S application. The VCRs in the first crop (rice) varied from ₹ 660 to 1,925 at 15 kg S ha^{-1}, from ₹ 605 to 1,320 at 30 kg S ha^{-1}, and from ₹ 385 to 825 at 45 kg S ha^{-1} in different locations (Data not shown). Such benefits were much more when residual response of succeeding wheat crop was taken into account. Overall, VCRs for rice–wheat system varied in accordance with S-application rate, the values being the highest at 15 kg ha^{-1} S (₹ 880–2,200). The VCRs at 30 and 45 kg ha^{-1} S-application rates were in the ranges of ₹ 990–2,035 and ₹ 825–1,485, respectively (Fig. 7).

Discussion

In the natural soil resource, the major factors leading to S deficiency are coarse soil texture, low organic matter, and greater S removals as a result of intensive cropping and neglect of S additions through fertilizers or manures [33, 39]. The fertilizer consumption statistics revealed that the use of S-containing fertilizers like ammonium sulfate and single superphosphate has decreased during the last five decades [9]. Incidentally, the S deficiency observed in the surveyed areas appears to be associated with all these factors. The soils were loamy sand to loam in texture, and more than 60 % the soils in five out of eight ADBs were deficient in OC content (Table 3). Further, the S deficiency was greater in the soil samples having low OC content (Table 4). Such coarse-textured and low OC soils have very low SO_4-S retention capacity, particularly in surface layers [1, 34]. In UGP, S deficiency of lesser magnitude in the soils of Hastinapur

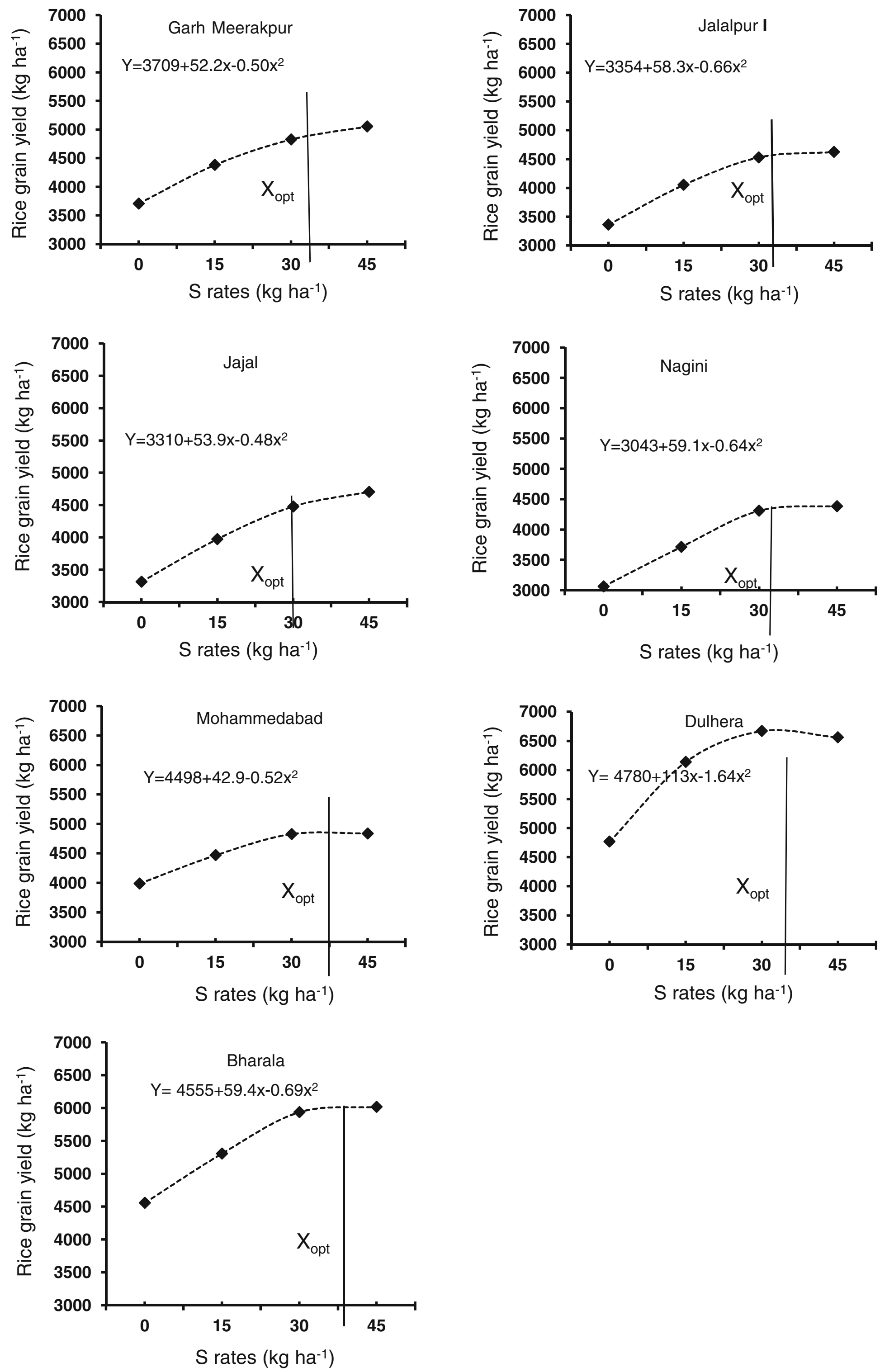


Fig. 2 Response curves of rice to incremental doses of S in the on-farm experiments. X_{opt} denotes the economic (optimal) dose of S fertilizer

(19 %) was associated with relatively greater soil SOC content in this ADB, compared to that in others ADB-s'(Table 3). Lesser deficiency of S in the soils of UGP (Daurala, Hastinapur, Gajraula, and Hasanpur), and Garhwal zone (Fakot and Chamba) compared to those of TGP (Rai and Bapoli) may also be ascribed to more quantity of organic manure (FYM) additions in the former case (Tables 2). Since organic S fraction in the soil is positively related to organic matter status [18, 31] and generally considered as an important donor pool to available S [38], lesser deficiencies are expected in the soils containing high OC, or in those receiving organic manure periodically.

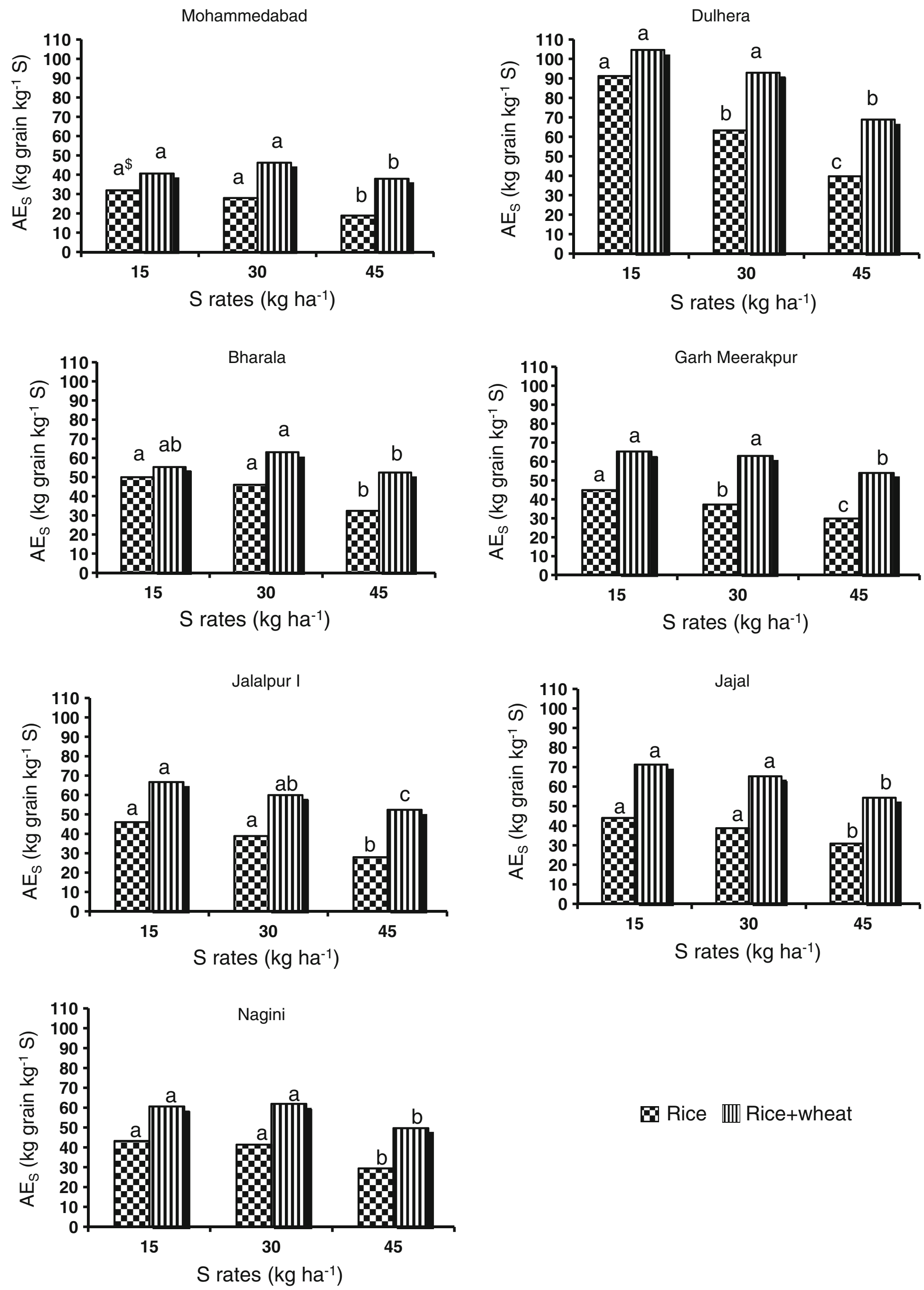


Fig. 3 Agronomic efficiencies (AEs) of fertilizer S in rice and rice + wheat system at different locations. *Dollar sign* similar *bar*s at each location followed by the same letters are not significantly different at the 0.05 level of probability according to L.S.D

High cropping intensities (148–169 %) of the study area and negligible replenishments of S through fertilizers had direct bearing on the occurrence of S deficiency in soils. The annual S additions through sporadically used S-containing fertilizers like, ammonium sulfate, ammonium phosphate sulfate, and single superphosphate in the state of Haryana (TGP), Uttar Pradesh (UGP), and Uttarakhand (Garhwal zone) are estimated to be 0.42, 3.71, and 1.07 kg ha^{-1}, respectively [33], which are quite inadequate to prevent the depletion of native S reserve arising due to heavy S removals under intensive cropping [16, 24, 35]. The survey conducted in the present study revealed that 11 % of the rice fields and 5 % of the wheat fields in UGP received SSP as P Fertilizer at the rates varying from 123 to 135 kg ha^{-1}, which also supplied 15–16 kg S ha^{-1}. The application of SSP was restricted to rice only in case of TGP (6 % fields) and Garhwal zone (4 % of the fields) with the average rates of 114 and 45 kg ha^{-1}, respectively (Table 2). In other cases, very small quantities of S, 1.4–5.9 kg S ha^{-1}, were added inadvertently when zinc sulfate was used as Zn fertilizer (Table 2). Since the removals of S by rice and wheat crops are often

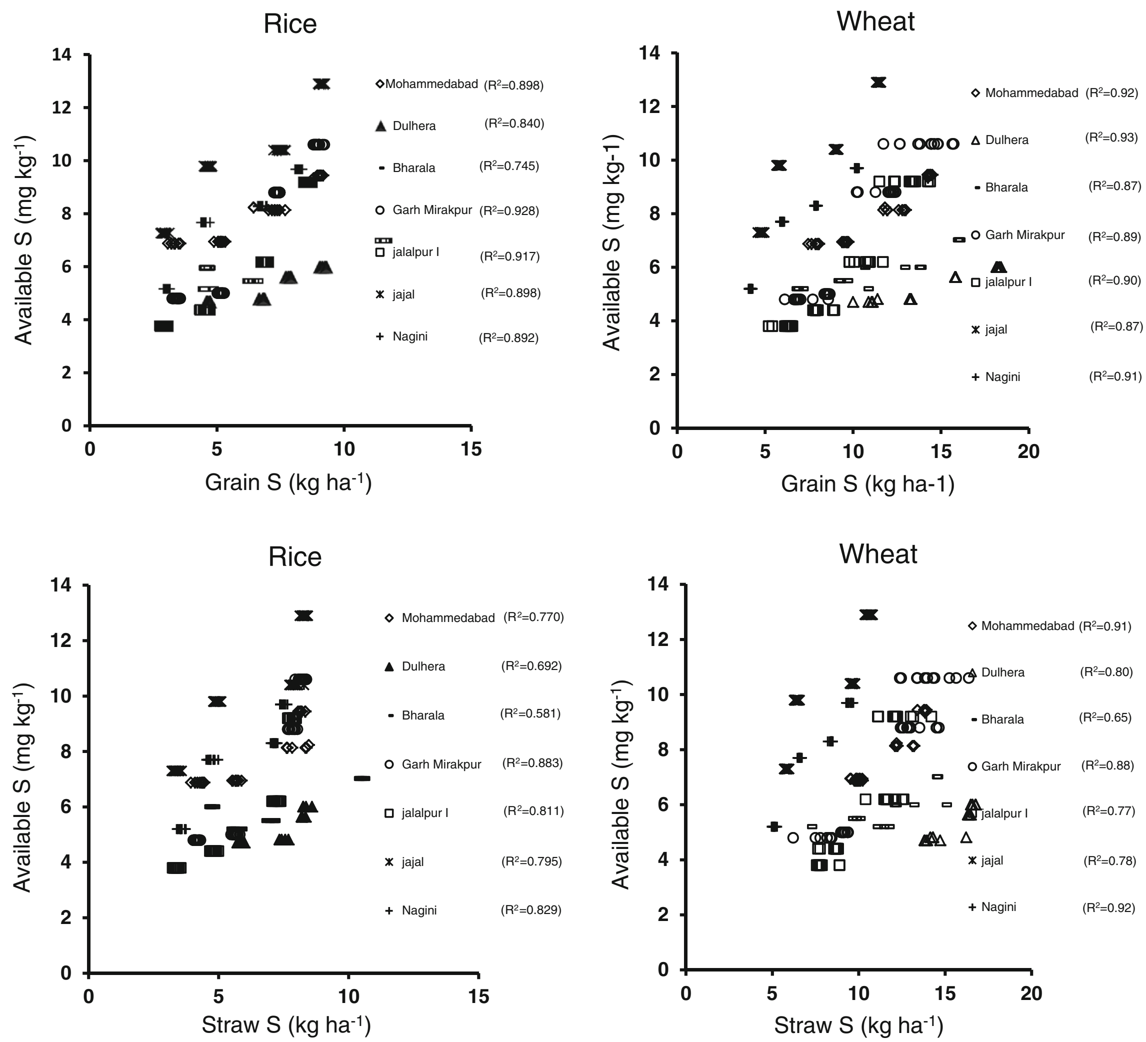


Fig. 4 Correlation between grain and straw S uptakes of rice and wheat and available soil S content

comparable to that of P, the quantities of S applied through fertilizers in the area are very small, leading certainly to greater incidence of S deficiency in the soils [7, 21, 23].

The nutrient use practices, other than S, adopted in the study area also appear to contribute to soil S deficiency. The use of S-free fertilizers, mostly urea and di-ammonium phosphate, more than the recommended rates (Table 2) may be one of the major factors contributing to poor S availability in the soil. The survey information apparently indicated that the farmers apply N similar to or greater than the recommended dose (120 kg N ha^{-1}), and P nearer to the recommended dose (60 kg P_2O_5 ha^{-1}), i.e., 45.4–48.6 kg ha^{-1} to rice in UGP and TGP zones. Besides substantial S removals by the crops grown with these fertilizers, the SO_4-S retention in the soil is also reduced. Since $H_2PO_4^-$ is a strong competitor of SO_4^{2-} for anion exchange sites, large P dressings cause concurrent desorption of SO_4^{2-} from the colloidal surfaces, and its subsequent leaching with irrigation and rain water [17, 33].

Cereals have a lower S requirement (10–30 kg ha^{-1}) than other agricultural crops like oil seeds (14–45 kg ha^{-1}), sugarcane (26 kg ha^{-1}), and forage crops (39–46 kg ha^{-1}) [33], yet an adequate level of S is considered necessary for optimal crop growth. Significantly ($p < 0.05$) large yield responses of rice and wheat to S fertilizer observed in the on-farm experiments at all sites indicate that, despite their relatively low S requirement, the productivities of these staple foodgrain crops were drastically reduced by an inadequate supply of S, say less than 30 kg S ha^{-1} (Table 5). Differential responses of rice to applied S, i.e., larger yield increase and improved agronomic efficiency (AE) at Dulhera, Bharala, Garh Meerakpur, Jalalpur I, and Nagini compared with Mohammedabad (Fig. 3) are associated with the differences in the initial S content of the soil which was distinctly greater (7.8 mg kg^{-1}) at Mohammedabad (Table 1). In fact, crops grown on low S soils do utilize fertilizer S more efficiently [12], and thus crop responses to S applied

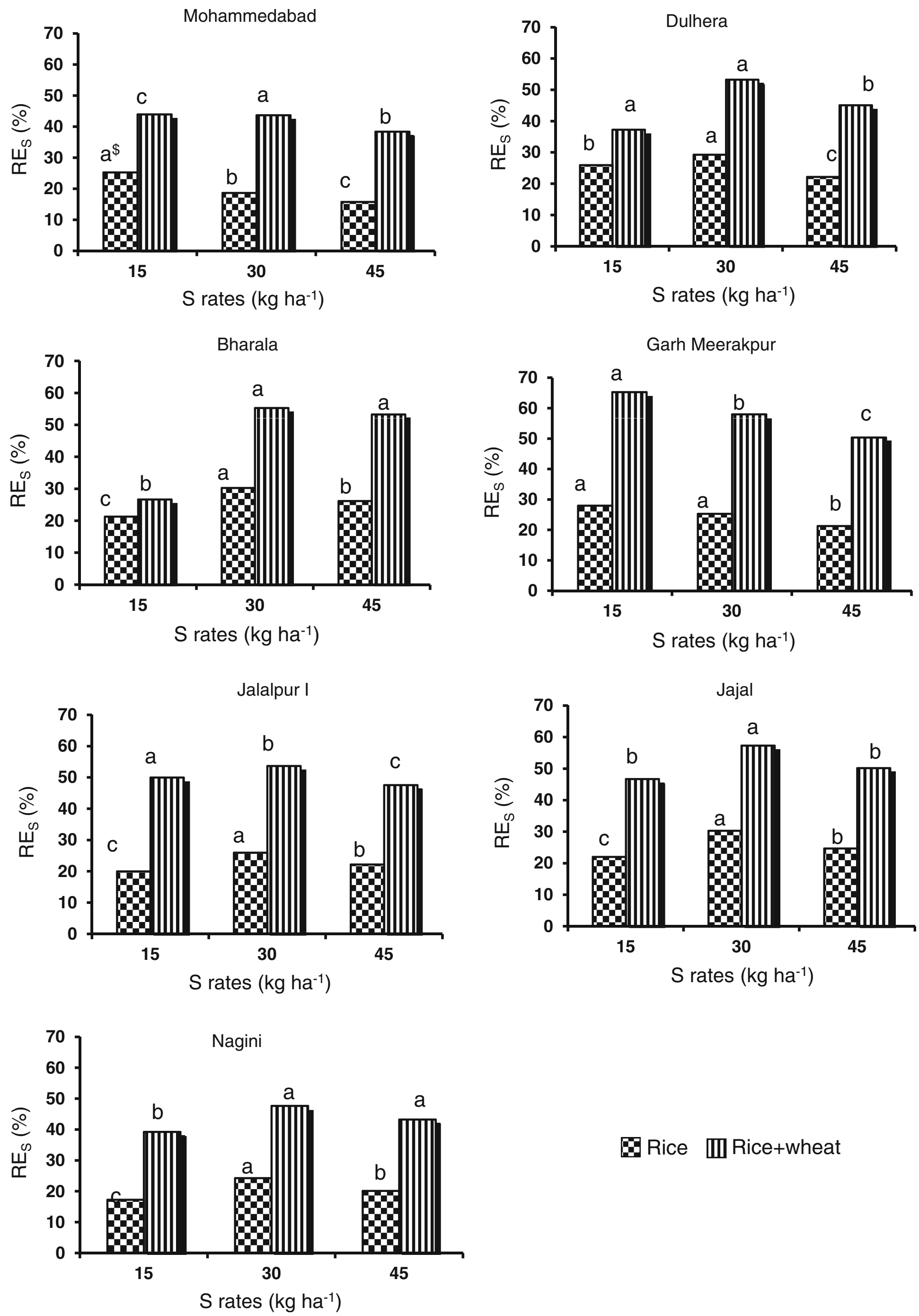
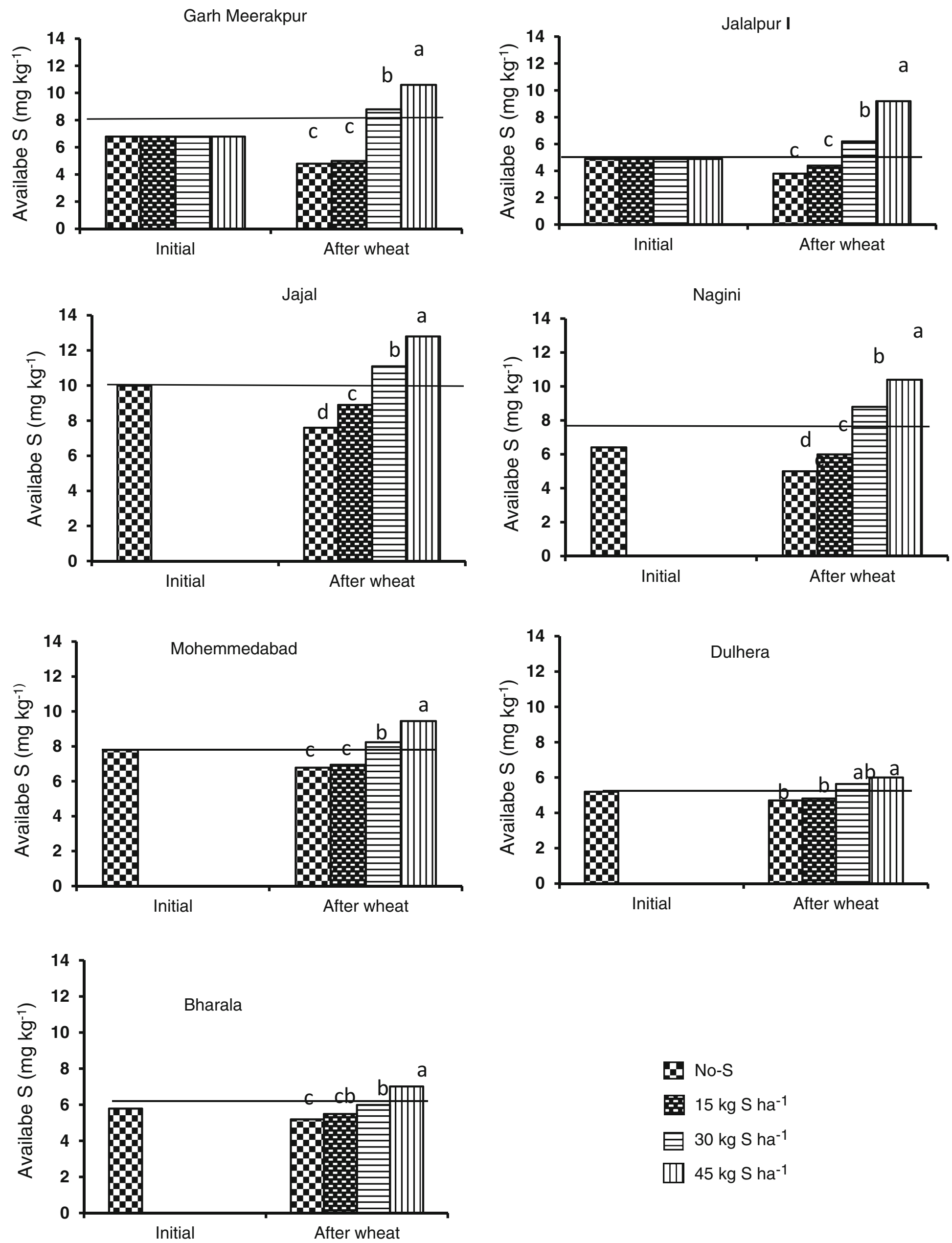


Fig. 5 Recovery efficiencies (REs) of S (%) in rice and rice–wheat system as influenced by S fertilization at different locations. *Dollar sign* Similar *bars* at each location followed by the same letters are not significantly different at the 0.05 level of probability according to L.S.D

at a particular rate depend largely on the severity of S deficiency in the soil [3, 13]. The experimental site at Jajal was, however, an exception wherein both crops responded to S, and the AE was greater despite relatively higher (10 mg kg^{-1}) initial available S content. Higher S-fertilizer recovery efficiencies (RE_S) in rice as well as rice–wheat system at Dulhera, Bharala, Garh Meerakpur, Jalalpur I, Jajal, and Nagini (Fig. 5), with relatively low available S content, compared with Mohammedabad are thus explainable (Fig. 6). This also applies to the residual effect of S in wheat, which was generally greater in low S soils (Fig. 7).

Fertilizer S applied to a crop is not utilized completely by that crop, and S left in the soil exhibits the residual effect on the growth and yield of subsequent crops [10, 21]. Substantial yield increases in wheat grown on S- fertilized rice plots (Table 5) imply that sufficient amount of added S remained in available form in the soil even after harvest of directly fertilized rice crop. This contention is supported by the 24–48 % increase in the available S content of soil over

Fig. 6 Effect of sulfur application on available S content of soil at different locations. *Dollar sign* similar *bar*s at each location followed by the same letters are not significantly different at the 0.05 level of probability according to L.S.D



the initial value after the harvest of terminal wheat crop in the 30–45 kg S ha^{-1} treatment at different locations. The RE_S of fertilizer S in wheat ranging between 44.1 and 52.7 %, on average also proved the utilization of residual S by the succeeding crop. These results are different from those of Sachdev and Deb [19], who showed negligible recovery of the applied S by succeeding crops in a mustard–maize–greengram sequence. Field studies representing diverse agro-climatic situations of the country, however, revealed considerable residual responses to applied S in intensive cereal–cereal cropping systems [2, 26, 37]. The crop responses to residual S observed in the present study may infer that (i) low rate of S application in rice failed to leave sufficient S residue to be translated in agronomic yield in the succeeding wheat, and (ii) soils with relatively low S content produced greater residual effect.

Conclusions

The soils of rice–wheat-growing areas included in the present study suffer from varying degrees of S deficiency (19–47 %). The magnitude is larger in the soils containing low OC content. Substantial direct and residual responses to S fertilizer in rice–wheat system confirmed the incidence of S deficiency in soil. As both the component crops of the

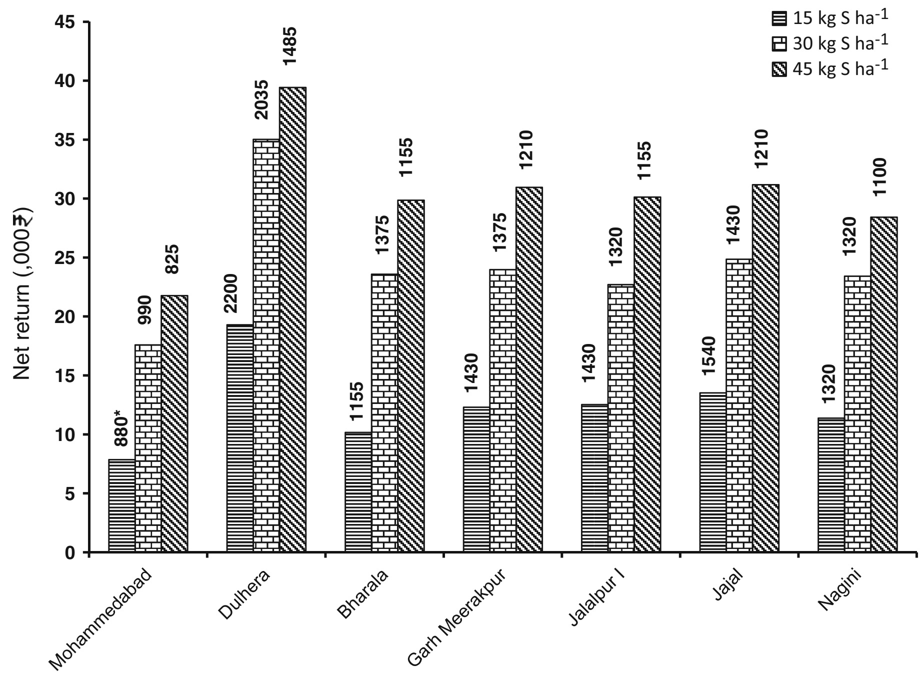


Fig. 7 Economics of S fertilization in rice–wheat system at different locations. *Asterisk* values on each *bar* indicating the net returns due to unit investment in S

system are staple foodgrains, any nutrient deficiency-induced yield loss (S in the present case) would have far-reaching undesirable implications. The study suggests the need for inclusion of S at the rate in the range of 30–45 kg ha^{-1} in the fertilizer schedules in the rice–wheat-growing areas. Detailed studies on soil S-fertility appraisal and on the phasing of S fertilizer in cropping system would, however, be necessary to develop rational S recommendations for the cropping system.

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