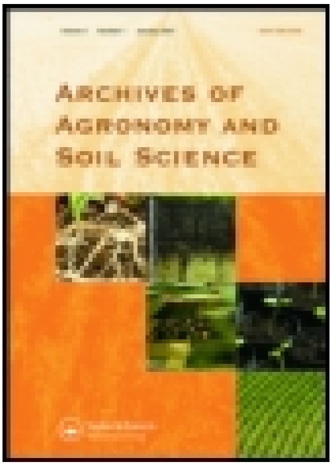

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Enhanced nutrient and rainwater use efficiency in maize and soybean with secondary and micronutrient amendments in the rainfed semi-arid tropics

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Enhanced nutrient and rainwater use efficiency in maize and soybean with secondary and micronutrient amendments in the rainfed semi-arid tropics

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In view of widespread deficiencies, a long-term experiment was started at the International Crops Research Institute for the Semi-Arid Tropics, Patancheru, India in 2007 to identify economically efficient application strategy (full or 50% dose every or every second year) of sulphur (S) (30 kg ha^{-1}), boron (B) (0.5 kg ha^{-1}) and zinc (Zn) (10 kg ha^{-1}). During the fourth year in 2010, balanced fertilization through adding S, B and Zn increased maize grain yield by 13–52% and soybean yield by 16–28% compared to nitrogen (N) and phosphorus (P) fertilization alone. Balanced nutrition increased N and P uptake, utilization and use efficiency for grain yield and harvest index indicating improved grain nutritional quality. The N, P plus 50% of S, B and Zn application every year recorded highest crop yields and N and P efficiencies indices and increased rainwater use efficiency with a benefit:cost ratio of 11.9 for maize and 4.14 for soybean. This study showed the importance of a deficient secondary nutrient S and micronutrients B, Zn in improving N and P use efficiency while enhancing economic food production.

Keywords: micronutrients deficiency; N use efficiency; nutrient uptake; P use efficiency; rainfed agriculture; rainwater use efficiency

Introduction

Rainfed agriculture is practised in 80% of the world's physical agricultural area and generates 62% of the world's staple food (FAOSTAT 2014). But current crop yields (0.5–2 t ha^{-1}) under rainfed agriculture in semi-arid and dry sub-humid regions are two to four times lower than achievable yields (Rockström & Falkenmark 2000; Wani, Pathak, Jangawad, et al. 2003; Wani, Pathak, Sreedevi, et al. 2003; Rockström et al. 2007). Data from long-term experiment at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) heritage watershed site has demonstrated that improved management can sustainably increase rainfed crop yield by fivefold as compared to that under traditional farmer's practices (Wani, Pathak, Jangawad, et al. 2003; Wani, Rockström, et al. 2011; Wani et al. 2012). Thus, there is a large untapped potential for yield increase to meet the global food and feed demands that have been projected to double in the twenty-first century (Spiertz & Ewert 2009).

Nitrogen (N) is often the most limiting nutrient for crop yield in many regions of the world (Giller et al. 2004), and, in a quest to achieve high yields, is applied in large quantity from external sources (Wade 2009) resulting in low nitrogen use efficiency (NUE), which is approximately 33% for cereal production (Raun & Johnson 1999). The increase in agricultural food production worldwide over the past four decades has been associated with a

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sevenfold increase in the use of N fertilizers (Rahimizadeh et al. 2010). Similarly, an overview of agriculture in India indicates that since the late 1960s (1966–71), the period that coincides with the launch of Green Revolution, the foodgrain production is more than doubled during 2006–09 with almost no change in area but accompanied by more than 12 times increase in N fertilizer consumption (Table 1). N-fertilizer-based pollution is also becoming a serious issue for many agricultural regions (Garnett et al. 2009). Inefficient use of N fertilizer is causing serious environmental problems associated with the emission of NH_3, N_2 and N_2O (the last being an important greenhouse gas implicated both in the global warming and in the ozone layer depletion in the stratosphere) to the atmosphere and contamination of groundwater and surface water resources via nitrate leaching or run-off (Singh & Verma 2007). In response to continually increasing economic and environmental pressures, there is urgent need to enhance efficient use of N fertilizers and increase profitability by developing sustainable farming systems (Mahler et al. 1994).

Similarly, phosphorus (P) is another limiting nutrient in the semi-arid tropics (SAT) with very low fertilizer recovery efficiency. Moreover, research showed that rainfed regions have low rainwater use efficiency (RWUE) (Rockström et al. 2007; Wani et al. 2009). In the context of economic and environmental limitations to increase the supply of water to meet the increased demand, the prospects for water scarcity are increasing. The looming climate-related risks and probability of occurrence of extreme events (Zhang et al. 2007) call for enhancing RWUE.

Evidences show that in the drylands, the amount of water is not only the key limiting factor for improved yields (Klaij & Vachaud 1992; Agarwal 2000; Hatibu et al. 2003; Wani, Pathak, Sreedevi, et al. 2003), rather it is also a result of differences in soil and crop management. Research at ICRISAT showed that SAT soils are deficient not only in N and P but also in sulphur (S), boron (B) and zinc (Zn) (Sahrawat et al. 2007, 2010; Wani et al. 2009; Wani, Rockström, et al. 2011; Wani, Sahrawat, et al. 2011; Chander et al. 2012, 2013, 2014). Multiple nutrient deficiencies could be holding back the yield potential resulting in low crop yields, low nutrient use efficiency and more N losses. Much of available water is also not utilized efficiently apparently due to nutrient imbalances resulting in low RWUE. Moreover, soil nutrient depletion adversely affects crop yields and thereby sets in further degradation of soil organic carbon and other soil properties and

Table 1. All India consumption of nitrogen, phosphorus fertilizers and food production details.

	Consumption of nutrients		Food grains	
Period	Nitrogen (10^3 t)	Phosphorus (10^3 t)	Area (10^6 ha)	Production (10^6 t)
1951–56	82	10	105	63
1956–61	177	35	113	74
1961–66	418	108	117	81
1966–71	1165	369	121	94
1971–76	1876	546	124	106
1976–81	3193	994	127	122
1981–86	4929	1676	128	142
1986–91	6813	2644	126	160
1991–96	8918	2933	123	181
1996–01	11,014	4003	123	200
2001–06	11,460	4471	120	202
2006–09	14,428	5855	124	228

Source: Directorate of Economics & Statistics, Department of Agriculture & Cooperation, Ministry of Agriculture, Government of India (2011a, 2011b).

so affects water availability for crops through poor rainfall infiltration and plant water and nutrient uptake due to weak roots (Rockström et al. 2007).

In this context, we hypothesized that balanced nutrient management through application of N, P and deficient secondary nutrient S and micronutrients viz. S, B and Zn would increase productivity of rainfed systems in the SAT and also result in increased resource use efficiency. The specific objectives of this study are to investigate the effect of balanced nutrient management options on (1) the productivity of maize and soybean crops along with economic viability of different nutrient management options and (2) resource (N, P and rainwater) use efficiencies under rainfed situation.

Materials and methods

Experiment site and detail

A long-term experiment was started in rainy season in 2007 at the ICRISAT farm in Patancheru, Andhra Pradesh, India (17°30′35.3″N, 78°15′53.4E) with soybean (rainy season/Jun–Sept) and sorghum (post-rainy season/Oct–Jan) and with maize (rainy season/June–Sept) and chickpea (post-rainy season/Oct–Jan) cropping systems under rainfed conditions. Patancheru is located 545 m above mean sea level and receives around 900 mm rainfall per annum. The site falls under SAT climate and the temperature ranges between 13°C (minimum) and 39°C (maximum) throughout the year. The site soils are vertisols with high clay content. To avoid soil structure distortion with run-off rainwater that ultimately affects yields, a common problem observed in vertisols, the crops were grown on raised beds (1 m) alternated with furrows (0.5 m) to safely drain excess run-off water, a landform management called as broadbed and furrow (BBF) system recommended particularly for vertisols.

The objective of the study was to identify economically efficient application strategy [full dose of S (30 kg ha^{-1}), B (0.5 kg ha^{-1}) and Zn (10 kg ha^{-1}) or 50% dose] every year or every second year.

The treatments consisted of:

(1) Absolute control without any fertilizer (control);
(2) Application of only N and P (NP);
(3) Application of N, P plus full dose of S, B and Zn every year [NP + SBZn (every year)];
(4) Application of N, P plus 50% dose of S, B and Zn every year [NP + 50%SBZn (every year)];
(5) Application of N, P plus full dose of S, B and Zn the alternate year [NP + SBZn (every second year)] and
(6) Application of N, P plus 50% dose of S, B and Zn the every second year [NP + 50%SBZn (every second year)].

In every year application treatments, S, B and Zn applications were done in all years (2007–2010), while in every second year application treatments, they were done only in 2007 and 2009. The N and P recommendations were 100 kg N and 26 kg P ha^{-1} for maize; while 30 kg N and 26 kg P ha^{-1} for soybean. All fertilizers were added as per treatments during the rainy season crop as basal application, except for N in maize that was added in two splits, 50% as basal and the rest as top dressing after 1 month of sowing. The sources of N, P, S, B and Zn were urea (46% N), diammonium phosphate (DAP)

Table 2. Climate data at ICRISAT, Patancheru, India, 2007–2010.

Season	Rain (mm)	Max. temp. (°C)	Min. temp. (°C)	Relative humidity at 07:17 (%)	Relative humidity at 14:17 (%)	Wind velocity (km h^{-1})	Solar radiation (MJ m^{-2})	Bright sunshine (h)
Rainy seasons								
Rainy, 2007	590	33.2	22.0	89.3	63.5	9.9	15.1	4.52
Rainy, 2008	756	33.8	21.0	87.5	61.2	10.4	16.0	4.64
Rainy, 2009	842	36.3	22.5	85.7	56.9	10.7	16.8	5.80
Rainy, 2010	982	34.8	22.3	90.2	67.0	8.7	15.5	4.51
Post-rainy seasons								
Post-rainy, 2007–08	50	30.3	12.5	90.7	39.4	4.5	16.5	8.43
Post-rainy, 2008–09	112	31.0	12.9	92.9	41.7	4.5	16.5	8.43
Post-rainy, 2009–10	151	30.8	13.9	90.1	45.6	4.9	15.2	7.69

(20% P, 18% N), gypsum (15% S), agribor (20% B) and zinc sulphate (20% Zn), respectively. All the treatments were applied in 9 × 8-m plot size and replicated thrice.

During the fourth year in the 2010 rainy season, the SBZn application strategies were evaluated on soybean (cv. JS-335) and maize (cv. K-235) crops. Both soybean and maize crops were sown in lines at 4–5 cm depth using tropicultor (a low cost implement designed for seed and fertilizer placement under BBF system) on 22 June 2010. Two rows of maize spaced at 0.75 m were sown on the raised bed with plant-to-plant distance of 0.15–0.20 m (about 76,000 plants ha^{-1}), while three rows of soybean spaced at 0.30 m were sown on raised bed with plant-to-plant distance of 0.10–0.15 m (about 1,60,000 plants ha^{-1}). Two weedings were done at 20-day interval to keep the plots free of weeds. Plant growth was recorded both in maize and in soybean at 30, 45 and 60 days after sowing (DAS). In soybean, nodule count was also recorded at 60 DAS. The soybean crop was harvested on 4 October 2010 and maize on 7 October, 2010. At maturity, the yields were recorded in all plots (9 × 8 m) representing different treatments and were converted into kg ha^{-1}.

The climate data during 2007–2010 seasons are shown in Table 2. During rainy 2010 season particularly, a total of 982-mm rainfall was recorded and rainy events were fairly distributed among 60 days. Similarly, rainfalls during rainy seasons were 590 mm with 40 rain events (2007), 756 mm with 38 rain events (2008) and 842 mm with 37 rain events (2009). Highest rainfall events recorded during rainy seasons were 75 mm (2007), 125 mm (2008), 122 mm (2009) and 91 mm (2010). Similarly, rainfalls received were 50, 112, and 151 mm during post-rainy seasons 2007–08, 2008–09 and 2009–10, respectively.

The data recorded were subjected to statistical analysis using the GenStat 13th statistical package, VSN International Ltd, UK (Ireland 2010) to determine the least significant difference of means at 5% level (LSD 5%).

Economic analysis

For economic analysis, the additional cost on fertilizer application was worked out on per kg market prices at INR 6.25 for urea, INR 11.00 for DAP, INR 2.20 for gypsum, INR 33.00 for zinc sulphate and INR 120.00 for agribor. Additional returns were calculated based on farm gate price per kg grain produce at the rate of INR 10.00 for maize, INR 17.00 for soybean. Benefit-to-cost ratio (B:C ratio) was also worked out for comparative evaluation of balanced nutrition over the control by dividing additional returns with additional costs over and above the control. The currency conversion factor is 1US$ = INR 62.

Nitrogen efficiency indices

N input efficiency was worked out in terms of different standard parameters (Delogu et al. 1998; López-Bellido & López-Bellido 2001; Cazzato et al. 2012) like N uptake efficiency, N utilization efficiency, N use efficiency and N harvest index.

Nitrogen uptake efficiency (NUpE) was worked out by dividing total plant N uptake with N supply (Equation (1)):

$$\text{NUpE (kg kg}^{-1}\text{)} = \text{Nt/N supply} \tag{1}$$

where Nt is the total plant N uptake and was determined by multiplying dry weight of plant parts by N concentration and summing over parts for total plant uptake. N supply is the sum of soil N content at sowing, mineralized N and N fertilizer. N supply was defined (Limon-Ortega et al. 2000) as the sum of (1) N applied as fertilizer and (2) total N uptake in control (0 N applied).

Nitrogen utilization efficiency (NUtE) was worked out by dividing grain yield with total plant N uptake (Equation (2)):

$$\text{NUtE (kg grain kg}^{-1}\text{N)} = \text{Gy/Nt} \tag{2}$$

where Gy is the grain yield.

NUE was estimated by dividing grain yield with N supply (Equation (3)):

$$\text{NUE (kg grain kg}^{-1}\text{N)} = \text{Gy/N supply} \tag{3}$$

And nitrogen harvest index (NHI) was determined by dividing total grain N uptake with total plant N uptake and multiplying by 100 (Equation (4)):

$$\text{NHI (\%)} = (\text{Ng/Nt}) \times 100 \tag{4}$$

where Ng is the total grain N uptake. Ng was determined by multiplying dry weight of grain by N concentration.

In line with N efficiency indices, P efficiency indices were also worked out and studied.

Rainwater use efficiency

The total amount of rainfall (982 mm) received at experimental site during the crop growth phase (June–September, 2010) was used to work out the RWUE, which is kilogram of foodgrain produced per millimetre of water per hectare and is expressed as kg mm^{-1} ha^{-1}.

Plant analysis

After crop harvest, the plant samples were collected for chemical analysis. The plant samples were separated into grain and straw, dried to a constant weight in oven at 65 ± 5 °C and then ground and analysed for N, P, K, S, B and Zn in the Charles Renard Analytical Laboratory at ICRISAT, Patancheru. Total N, P and K in plant materials were determined by digesting the samples with sulphuric acid–selenium. N and P in the digests were analysed using an auto-analyser (Skalar SAN System, AA Breda, Netherlands), and K in the digests was analysed using an atomic absorption spectrophotometer (SavantAA, GBC Scientific Equipment, Braeside, VIC, Australia) (Sahrawat, Ravi Kumar, Murthy 2002). Zn in plant samples was determined by digesting them with triacid mixture, and Zn in digests was analysed using atomic absorption spectrophotometer (Sahrawat, Ravi Kumar, Rao 2002). Total S and B in plant samples were determined by inductively coupled plasma emission spectrophotometer (Prodigy High Dispersion ICP, Teledyne Leeman Labs, Hudson, NH, USA) in the digests prepared by digesting the samples with nitric acid (Mills & Jones 1996).

Results and discussion

Yield response 2007–2009

The application of NP during 2007–2009 recorded a productivity improvement over the control by 47–85% in maize and 12–18% in soybean (Table 3). The conjoint application of NP + SBZn recorded the highest productivity improvement (39–119% in maize and 13–68% in soybean); however, in general, the increase was significant in maize only. During the first year (2007), NP + SBZn, which was actually similar for both every and every second year application treatments, tended to record highest increase in productivity

Table 3. Effects of balanced nutrient management strategies on crop yield under maize–chickpea and soybean–sorghum systems at ICRISAT, Patancheru, India, 2007–2009.

	Maize–chickpea cropping system					
	Maize (kg ha^{-1})			Chickpea (kg ha^{-1})		
Treatment	2007	2008	2009	2007–08	2008–09	2009–10
Control	3350	3920	2210	1440	710	730
NP	6200*	5920	3260	1610	800	1240
NP + SBZn (every year)	7340*	6580*	3090	1690	1060	1430
NP + 50%SBZn (every year)	6760*	6550*	4230*	2010*	1070	1300
NP + SBZn (every second year)	7040*	5630	3140	1790*	1120	1110
NP + 50%SBZn (every second year)	6720*	5870	3620	1840*	830	1280
LSD (5%)	729	2075	1459	286	489	1054
	Soybean–sorghum cropping system					
	Soybean (kg ha^{-1})			Sorghum (kg ha^{-1})		
Treatment	2007	2008	2009	2007–08	2008–09	2009–10
Control	1430	1090	1700	1290	1160	1010
NP	1600	1250	2010	1920*	1430	1350*
NP + SBZn (every year)	1690	1640	2100	2090*	1490	1200
NP + 50%SBZn (every year)	1620	1600	2130	1800*	1850*	1650*
NP + SBZn (every second year)	1750	1820*	2190	2360*	1830*	1430*
NP + 50%SBZn (every second year)	1610	1660	2010	1810*	1700*	1600*
LSD (5%)	760	582	686	155	465	328

Note: * significant at $p \leq .05$.

both in maize and in soybean crops. But in the third year (2009), NP + 50%SBZn proved significantly superior in terms of productivity enhancement in maize, while in case of soybean NP + SBZn (every second year) followed by NP + 50%SBZn (every year) tended to record the highest productivity with overall lower yields compared to 2007 and 2008.

In chickpea crop followed by maize and sorghum crops followed by soybean grown on residual nutrients also, the highest productivity improvements (18–95% in chickpea and 19–63% in sorghum) in general were recorded in plots having conjoint application of NP + SBZn. In contrast to chickpea, clearly significant results were noticed in case of sorghum crop, wherein NP + SBZn recorded highest yields during the first season (2007–08), while NP + 50%SBZn (every year) proved superior during the second (2008–09) and third seasons (2009–10).

Growth, yield response and benefit: cost ratio during rainy 2010 season

The applied N and P fertilizers significantly improved maize productivity along with a favourable economics (B:C = 10.5:1) as compared with the control (Table 4). But in soybean, the NP application did not record a significant response probably due to meeting nutrient needs of control plots through biological N_2-fixation and higher root activity to dissolve fixed-P in vertisols. The application of NP + SBZn significantly increased maize and soybean crop productivity over both control and NP fertilized plots. The additionally included S, B and Zn in NP fertilization increased the maize grain productivity over the only NP fertilization by 13–52% and soybean by 16–28% (Table 4). Maximum productivity increase was observed with NP + 50%SBZn (every year) both in maize and in soybean, which was a more efficient fertilizer management strategy than NP + SBZn (every year), the next best alternative. The application 50%SBZn through 100 kg gypsum, 25 kg zinc sulphate and 1.25 kg agribor every year also proved an economically viable option, which recorded the highest B:C ratio of 11.9 in maize and 4.14 in soybean as compared with other management options. Similar benefits were also evaluated in straw yield in maize and soybean, which is an important fodder for cattle, and cattle rearing is a common feature in farm-based livelihoods in the SAT. So, the favourable economic drivers make balanced nutrition acceptable at farm level to address the issue of food security and livelihood improvement of smallholders in the SAT.

Table 4. Effects of balanced nutrient management strategies on soybean and maize yield at ICRISAT, Patancheru, India, rainy season 2010.

	Maize		Soybean	
Treatment	Grain yield (kg ha^{-1})	Straw yield (kg ha^{-1})	Grain yield (kg ha^{-1})	Straw yield (kg ha^{-1})
Control	860	1200	2040	1570
NP	3440* (10.5)	2010*	2110 (0.78)	1600
NP + SBZn (every year)	3950* (6.36)	2590*	2440 (1.74)	1620
NP + 50%SBZn (every year)	5230* (11.9)	2610*	2700* (4.14)	1950*
NP + SBZn (every second year)	4540* (10.1)	2520*	2620* (3.63)	1930*
NP + 50%SBZn (every second year)	3900* (9.92)	2470*	2500 (3.70)	1900
LSD (5%)	1015	781	515	331

Note: Figures in the parentheses indicate B:C ratios over the control at full costing of SBZn in yearly application and 50% costing in application once in 2 years; * significant at $p \leq 0.05$.

Table 5. Effects of balanced nutrient management strategies on growth characteristics in maize and soybean at ICRISAT, Patancheru, India, rainy season 2010.

Treatment	Maize			Soybean			
	Plant height (m)			Plant height (m)			Nodules plant^{-1} at 60 DAS
	30 DAS	45 DAS	60 DAS	30 DAS	45 DAS	60 DAS	
Control	0.75	0.84	1.24	0.42	0.45	0.51	77
NP	1.08*	1.2*	2.04*	0.45	0.51*	0.62*	82
NP + SBZn (every year)	1.23*	1.36*	2.2*	0.52*	0.56*	0.64*	95
NP + 50%SBZn (every year)	1.21*	1.46*	2.26*	0.54*	0.61*	0.79*	134*
NP + SBZn (every second year)	1.28*	1.43*	2.32*	0.47*	0.58*	0.73*	120*
NP + 50%SBZn (every second year)	1.29*	1.53*	2.12*	0.52*	0.69*	0.77*	107
LSD (5%)	0.23	0.15	0.21	0.05	0.04	0.06	37

Note: * significant at $p \leq 0.05$.

The significant benefits of balanced nutrition were recorded at different stages in plant height of maize and soybean and nodule number in soybean, which apparently contributed to enhanced crop yields (Table 5).

Plant nutrient uptake

The applied NP fertilizers as compared with the control significantly increased macronutrient and micronutrient uptake in maize, while in spite of minor increments like yield trends, it was statistically at par in the case of soybean (Table 6). The inclusion of SBZn

Table 6. Effects of balanced nutrient management strategies on nutrient uptake in maize and soybean at ICRISAT, Patancheru, India, rainy season 2010.

Treatment	Macronutrients (kg ha^{-1})				Micronutrients (g ha^{-1})	
	N	P	K	S	B	Zn
Maize						
Control	14.2	5.1	14.2	2.11	13.1	162
NP	42.8*	15.1*	30.4*	4.64*	27.4*	233
NP + SBZn (every year)	51.1*	12.1*	32.5*	5.88*	41.8*	287*
NP + 50%SBZn (every year)	56.6*	15.1*	32.9*	6.75*	39.7*	329
NP + SBZn (every second year)	53.8*	16.4*	33.5*	5.81*	38.5*	267*
NP + 50%SBZn (every second year)	48.2*	13.5*	32.7*	5.04*	31.3*	269*
LSD (5%)	11.9	4.53	7.89	1.45	10.4	82.1
Soybean						
Control	118	7.79	45.7	4.36	136	153
NP	127	9.40	46.4	4.36	136	148
NP + SBZn (every year)	143*	11.2*	52.9	6.33*	150	187
NP + 50%SBZn (every year)	156*	12.7*	60.0*	6.85*	174*	202
NP + SBZn (every second year)	155*	11.4*	59.3*	6.01*	176*	172
NP + 50%SBZn (every second year)	152*	10.9*	54.3	5.58*	167*	192
LSD (5%)	17.8	1.87	9.28	1.02	25.7	55.1

Note: * significant at $p \leq 0.05$.

along with NP, however, brought also in general a significant increase in nutrient uptake over the control in soybean crop. More nutrient uptake in maize and soybean crops under balanced fertilization practice accrued mainly due to better crop growth and yield. The strategy of adding NP + 50%SBZn (every year) was significantly better than NP fertilization alone in terms of increased N, S and micronutrients uptake in maize and macronutrients and B uptake in soybean.

Nitrogen use efficiency indices

NUpE reflects the efficiency of the crop in obtaining N from the soil (Rahimizadeh et al. 2010). Uptake of supplied N is the first crucial step and an issue of concern worldwide, and hence, increased NUpE has been proposed as a strategy to increase NUE by Raun and Johnson (1999). Under absolute control in the absence of any N fertilizer, the N uptake is taken as the index of N supply from soil, and hence, the NUpE, which is the ratio of total N uptake with N supply, is unity in control. The applied NP fertilizers in maize crop recorded NUpE of 0.37, while it varied from 0.42 to 0.51 with NP + SBZn (every year), and the option of adding NP + 50%SBZn (every year) recorded the highest NUpE (Table 7). NUpE is positively correlated with plant dry matter and grain yield (Lee et al. 2004; Rahimizadeh et al. 2010), which were favourably affected under S, B and Zn addition and explains the increase in NUpE. The findings showed that balanced nutrition is the best strategy to increase cereal N uptake efficiency and thereby minimize N loss and environmental damage. N is really not an issue in legumes like soybean crop, but this study showed that the added S, B and Zn not only stimulated the crop to absorb all supplied N but also increased N uptake besides supply probably through enhanced N_2

Table 7. Effects of balanced nutrient management strategies on nitrogen efficiency indices in maize and soybean at ICRISAT, Patancheru, India, rainy season 2010.

Treatment	NUpE (kg N uptake kg^{-1} N supply)	NUtE (kg grain yields kg^{-1} N uptake)	NUE (kg grain yields kg^{-1} N supply	NHI (%)
Maize				
Control	1.00	60.2	60.2	46.8
NP	0.37*	80.7*	30.1*	67.3*
NP + SBZn (every year)	0.46*	78.5*	36.0*	60.5*
NP + 50%SBZn (every year)	0.51*	92.5*	47.3*	65.8*
NP + SBZn (every second year)	0.47*	84.4*	39.7*	69.3*
NP + 50%SBZn (every second year)	0.42*	80.8*	34.1*	67.0*
LSD (5%)	0.11	17.4	8.85	11.3
Soybean				
Control	1.00	17.4	17.4	78.3
NP	0.87	16.5	14.4	77.7
NP + SBZn (every year)	0.98	17.0	16.6	80.5
NP + 50%SBZn (every year)	1.06	17.3	18.4	80.6
NP + SBZn (every second year)	1.05	16.9	17.7	80.2
NP + 50%SBZn (every second year)	1.03	16.4	17.0	77.0
LSD (5%)	0.18	2.24	3.60	8.36

Note: * significant at $p \leq 0.05$; NUpE, nitrogen uptake efficiency; NUtE, nitrogen utilization efficiency; NUE, nitrogen use efficiency; NHI, nitrogen harvest index.

fixation mechanism along with better root proliferation. The treatment NP + 50%SBZn (every year) recorded the highest NUpE in soybean, which was significantly higher as compared with only N and P fertilizers added plot.

NUtE reflects the ability of the plant to translocate N into grain (Delogu et al. 1998). Interestingly, the conjoint application of N and P fertilizers was seen even a better strategy to significantly increase NUtE of maize crop as compared with no fertilizer addition (Table 7). The balanced fertilization comprising NP + 50%SBZn (every year) recorded the highest utilization efficiency followed by NP + SBZn (every second year). In soybean crop, however, different fertilization practices caused significant differences in NUtE.

The NP fertilized plots recorded NUE of 30.1 kg GY per kg N supply in maize crop (Table 7). A lower NUE in NP fertilized plot as compared with the control (60.2) plot indicates the problem associated with the efficient use of N supplied through chemical fertilizers. The fertilizer management practice of NP + 50%SBZn (every year) recorded the highest NUE of 47.3 kg GY per kg N supply in maize, followed by NP + SBZn (every second year) with NUE of 39.7 kg GY per kg N supply, both of which were significantly higher (32–57%) than that observed under only NP fertilized plot. The study proved here that balancing N with other nutrients (Potarzycki 2010), which in current context are deficient S, B and Zn along with P in the SAT soils, is an important strategy to improve NUE. Soybean, a leguminous crop, also showed a significantly higher NUE with application of NP + 50%SBZn (every year) in comparison to only NP fertilization.

NHI, defined as N in grain to total N uptake, is an important consideration in cereals. NHI reflects the grain protein content and thus the grain nutritional quality (Hirel et al. 2007). All fertilization practices involving only application of NP or in combination with S, B and Zn significantly increased NHI in maize as compared with the unfertilized control plot (Table 7). In soybean, however, the control and fertilized plots were at par with each other.

Phosphorus use efficiency indices

Along with N, the deficiencies of P are common in the SAT soils (Sahrawat et al. 2007, 2010), and P is the next nutrient added in large quantities (Table 1). On these soils, it can be necessary to apply up to fivefold more P as fertilizer than is exported in products (Simpson et al. 2011) due to extensive fixation in the soil. Phosphorus fertilizer is expensive for smallholder farmers, and given the finite nature of global P sources, it is important that such inefficiencies should be addressed. In fertilized plots of the current study, the estimation of phosphorus uptake efficiency (PUpE) in line with NUpE reflected values less than 1.0 kg P uptake per kg P supply, which indicated the challenges with P in its uptake due to fixation in soil. PUpE ranged from 0.41 to 0.53 kg P uptake per kg P supply in maize and from 0.28 to 0.36 kg P uptake per kg P supply in soybean with highest value under plot receiving NP + 50%SBZn (every year) or NP + SBZn (every second year) (Table 8). The differences were, however, statistically at par in maize fertilized plots.

Similarly, PUtE reflects the ability of the plant to translocate P into grain. Interestingly, the application of NP + SBZn in maize was a better strategy than adding NP alone to significantly increase PUtE over the control treatment (Table 8). The application of NP + 50%SBZn (every year) was the best strategy in terms of PUtE in maize. The different fertilizer management practices in soybean did not significantly influence the PUtE.

Table 8. Effects of balanced nutrient management strategies on phosphorus efficiency indices in maize and soybean at ICRISAT, Patancheru, India, rainy season 2010.

Treatment	PUpE (kg P uptake kg^{-1} P supply)	PUtE (kg grain yields kg^{-1} P uptake)	PUE (kg grain yields kg^{-1} P supply)	PHI (%)
Maize				
Control	1.00	172	172	60.4
NP	0.49*	228	111*	83.5*
NP + SBZn (every year)	0.41*	328*	134	83.9*
NP + 50%SBZn (every year)	0.51*	343*	176	87.9*
NP + SBZn (every second year)	0.53*	281*	146	90.1*
NP + 50%SBZn (every second year)	0.44*	299*	125*	84.9*
LSD (5%)	0.15	83.7	38.6	9.40
Soybean				
Control	1.00	268	268	74.4
NP	0.28*	225	62*	72.8
NP + SBZn (every year)	0.32*	218	69*	74.9
NP + 50%SBZn (every year)	0.36*	212*	77*	69.6
NP + SBZn (every second year)	0.34*	230	77*	72.6
NP + 50%SBZn (every second year)	0.32*	228	74*	70.7
LSD (5%)	0.04	52.3	39.0	15.8

Note: * significant at $p \leq 0.05$; PUpE, phosphorus uptake efficiency; PUtE, phosphorus utilization efficiency; PUE, phosphorus use efficiency; PHI, phosphorus harvest index.

PUE had lower values in fertilized plots than unfertilized control plot indicating the problem of reduced P efficiency with fertilization due to fixation in soil (Table 8). The conjoint application of NP + 50%SBZn (every year) resulted in the highest PUE both in maize and in soybean. The findings proved precisely that the balanced fertilization through including deficient S and micronutrients B and Zn is fundamental to efficient P use.

As regards PHI, defined as P in grain to total P uptake, the conjoint application of only NP was even a better strategy in maize to significantly increase PHI (Table 8). The application of NP alone or in combination with S, B and Zn were, however, statistically at par with each other. Different fertilizer management practices in soybean did not bring significant differences in PHI.

Rainwater use efficiency

Given the competition for water faced by the agricultural sector, and the uncertainties associated with climate change, improving the efficiency of water use in both rainfed and irrigated systems is the main challenge for food security (Fereres et al. 2011). Balanced fertilizer use in this study produced more food with less water and significantly increased RWUE in maize and soybean crops by channelizing unproductive evaporation loss into productive transpiration (Figure 1). The strategy to apply recommended NP + 50%SBZn (every year) recorded the highest RWUE of 5.33 kg mm^{-1} ha^{-1} in maize and 2.75 kg mm^{-1} ha^{-1} in soybean as against 3.50 kg mm^{-1} ha^{-1} in maize and 2.15 kg mm^{-1} ha^{-1} in soybean under a common practice of only application of NP fertilizers. The results proved that the balanced plant nutrient management with a purpose to increase proportion of water balance as productive transpiration is one of the best rainwater management strategies to improve yields and water productivity (Rockström et al. 2010).

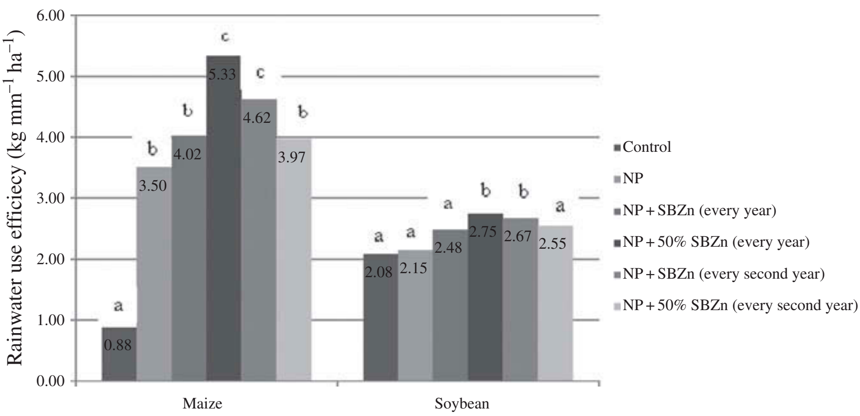

Figure 1. Effects of balanced nutrient management strategies on rainwater use efficiency in maize and soybean, rainy season, 2010; different letters indicate significant differences at $p \leq 0.05$.

Conclusions

The application of Zn, B and S is needed along with N and P to unlock the potential of rainfed agriculture and improve livelihoods in the SAT. The adoption of balanced nutrition is economically a viable option, which also significantly increased N and P fertilizer use efficiency indices and enhanced efficient utilization of available water resources. A better strategy is to apply 5 kg Zn, 0.25 kg B and 15 kg S ha^{-1} every year than to add 10 kg Zn, 0.5 kg B and 30 kg S ha^{-1} every second year.

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