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Balanced Nutrient Management for Crop Intensification and Livelihood Improvement: A Case Study from Watershed in Andhra Pradesh, India

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Soil health assessment of farmers' fields in watershed villages in Medak district, Andhra Pradesh, India showed widespread deficiencies of sulfur (S), boron (B), and zinc (Zn) in addition to organic carbon and phosphorus (P). Participatory on-farm trials on soil test-based application of deficient Zn, B, and S along with nitrogen (N) and P during 2009 to 2012 significantly increased crop yields over farmers' practice (FP)—by 31% to 45% in chickpea, 15% to 16% in cotton, 12% to 15% in paddy, and 8% to 9% in sugarcane. Total soluble sugars in sugarcane under balanced nutrition (BN) increased by 13%. Residual benefits of S, B, and Zn were observed in succeeding chilly crop (12% higher yield). Benefit to cost (B:C) ratios of BN ranged between 2.8 to 8.5 in chickpea, 2.6 to 4.4 in cotton, 2.3 to 2.9 in paddy, and 7.1 to 11.4 in sugarcane, indicating economic feasibility for scaling-up.

Keywords Balanced nutrition, boron, crop productivity, soil health, sulfur, zinc

Introduction

Studies have indicated large yield gaps (two- to fivefold) between farmers' practice (FP) and achievable potential yields in rain-fed agriculture in India and different developing countries in Asia and Africa (Rockstrom et al. 2007, 2010; Wani et al. 2011, 2012). The productivity of crops in these areas is comparatively very low as compared to those in irrigated agriculture. Low crop yields on farmers' fields are largely attributed to low resource (water and nutrients) use efficiencies due to inappropriate management practices adopted by the farmers (Wani et al. 2009). The soils of semi-arid tropics (SAT) are generally marginal with low inherent fertility and further degradation due to inappropriate management, thus posing difficulty in combating soil fertility related degradation, and increasing productivity. In Indian SAT, the deficiencies of major nutrients, especially nitrogen (N) and phosphorus (P) are considered important for the SAT soils (El-Swaify et al. 1985) and hence little research effort has been devoted to determine the role of secondary nutrients such as S and micronutrients in crop production and productivity. Globally, sulfur (S) and

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micronutrient deficiencies have been reported with increasing frequency, especially from intensive, irrigated agricultural production systems; and Indian agriculture is no exception (Takkar et al. 1989; Pasricha and Fox 1993; Scherer 2001; Fageria et al. 2002; Katyal and Rattan 2003). In India, micronutrient deficiencies have been reported as one of the main causes for yield plateau or even yield decline, especially in irrigated intensified systems (Takkar et al. 1989; Takkar 1996).

While soil and plant testing for diagnostic purposes have been more frequently employed in intensive, irrigated systems, and micronutrient deficiencies have been reported with increasing frequencies (Takkar 1996), little attention, however, has been paid to diagnose the deficiencies of S and micronutrients in the fields under dryland farming in the SAT regions of India. In the SAT regions, productivity increase and sustainability can be achieved when holistic approach for the soil and water conservation measures are implemented along with nutrient management, and choice of crops and their management options (Wani et al. 2003, 2012).

Based on this strategy, experience from Andhra Pradesh Rural Livelihood Program (APRLP) revealed that the extent of micronutrient deficiencies particularly zinc (Zn) and boron (B) along with S were widespread and large scale yield benefits were recorded with the application of these nutrients along with N and P (Rego et al. 2007). Analyses of 1617 soil samples collected from farmers' fields in 14 districts of SAT India showed that most of the soil samples were low to medium in organic carbon (C) content, Zn deficiency ranged from 2 to 100%, B deficiency ranged from 0 to 100% and S deficiency ranged from 40 to 100% across the districts. and significant yield responses were recorded with the application of Zn, B, and S (Srinivasarao et al. 2008).

In this context, it was hypothesized that in four benchmark villages (Fasalwadi, Shivampet, Chakriyal, and Venkatakishtapur) within a watershed in Medak district, Andhra Pradesh, the on-farm productivity can be improved through soil test-based nutrient management to showcase an example for the farmers of the region. The on-going farmer-participatory integrated watershed management program in four villages provided the opportunity to implement nutrient management along with soil and water conservation practices in farmers' fields in the Indian SAT. This paper presents the results of farmer participatory on-farm research cum demonstration trials conducted under "ICRISAT-SAB Miller India project on improved livelihoods through community water resources management in community watersheds" from 2009 to 2012 in farmers' fields that showed widespread deficiency of S, B, and Zn in four villages in Medak district of Andhra Pradesh, India, and on-farm responses of field crops to the application of these plant nutrients.

Materials and Methods

Watershed Villages and Site Description

The community water resources management initiative was started during 2009 with an objective to improve agricultural productivity and livelihoods in selected four villages in Madak district in Andhra Pradesh, India. These villages namely Fasalvadi (Latitude 17° 38′ 24.9″ and Longitude 078° 07′ 26.7″) in Sanga Reddy mandal and Venkatakishtapur (Latitude 17° 41′ 09.3″ and Longitude 078° 07′ 05.1″), Shivampet (Latitude 17° 40′ 20.5″ and Longitude 078° 06′ 16.9″), and Chakriyal (Latitude 17° 40′ 37.6″ and Longitude 078° 05′ 29.2″) in Pulkal mandal are located at about 10-15 km distance from Sangareddy town, headquarter of Medak district and fall under semi-arid agro-ecological southern region of India. Four villages together have a total area of 3313 ha with 1880 ha under rainfed and 1035 ha under irrigation. Number of households are 2526 with total population of 12940. The number of farmers cultivating arable land varies across the villages. Area of arable land in the villages range from 300-1000 ha. The farm holding size within a village also varies (from about 0.5 to >5 ha). However, farmers in the four villages are primarily dependent on agriculture for their livelihoods. The area receives an average annual rainfall of 800 mm. The villages are characterized by undulating topography with an average slope of about 2.5%. Soils are predominantly Vertisols with medium to high (150-200 mm) water holding capacities. In general, the soils are low in fertility because of imbalanced use of plant nutrient inputs through external sources and very low inputs of organic matter over the years.

Soil Sampling and Soil Analysis

Soil samples were collected from farmers' fields following a stratified random sampling methodology (Sahrawat et al. 2008). As a first step, a rapid rural appraisal was conducted during first week of June 2009 in the watershed villages. For soil sampling, we divided watershed into three groups based on the position of the fields on a topo-sequence - top, middle, and bottom, depending on the elevation and drainage pattern. Different soil types were separated in each category. The farmers were grouped into large (>5 ha), medium (2 to 5 ha), and small holders (< 2.0 ha) in each village based on farmers' information. Farmers' fields were selected randomly from each topo-sequence in the proportion as needed to represent the farm size, crops, and soil type. In each selected farmer's field, 8 to 10 cores of surface (0–15 cm depth) soil samples were collected by the trained farmers themselves from different positions, mixed, and sub-sampled to form a composite soil sample from a field. Composite soil samples were collected from Fasalvadi (20 numbers), Shivampet (23), Chakriyal (19), and Venkatakishtapur (15) watershed villages. The soil samples were processed – air-dried and powdered with wooden hammer to pass through a 2 mm sieve. For organic C, the soil samples were finely powdered to pass through a 0.25 mm sieve. Prepared soil samples were analyzed in the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) analytical services laboratory. Soil pH was measured by a glass electrode using a soil to water ratio of 1:2; electrical conductivity (EC) was determined by an EC meter using a soil to water ratio of 1:2. Organic C was determined using the Walkley-Black method (Nelson and Sommers 1996). Exchangeable potassium (K) was determined using the ammonium acetate method (Helmke and Sparks 1996). Available S was measured using 0.15% calcium chloride ($CaCl_2$) as an extractant (Tabatabai 1996); available P was measured using the sodium bicarbonate ($NaHCO_3$) test (Olsen and Sommers 1982). Available Zn was extracted by diethylene triamine penta acetic acid (DTPA) reagent (Lindsay and Norvell 1978) and available B was extracted with hot water (Keren 1996). The critical limits in the soil used for separating deficient fields from non-deficient were 0.5% for organic C, 5 mg kg^{-1} for P, 50 mg kg^{-1} for K, 10 mg kg^{-1} for S, 0.58 mg kg^{-1} for B, and 0.75 mg kg^{-1} for Zn. Soil samples lower than the critical limits were characterized as deficient in a particular nutrient (Sahrawat 2002).

On-Farm Trials

For crop response to soil test-based balanced fertilizer application studies, farmer participatory research trials cum demonstrations were conducted (Table 1) in watershed villages during 2009–2012. Each trial was conducted in 0.4 ha area with two treatments, each in 0.2 ha. The treatments comprised of – (1) Control based on farmers' nutrient inputs

Table 1
Detail of farmers' participatory research cum demonstration trials conducted in benchmark watershed in Medak district, Andhra Pradesh, India during 2009 to 2012

	2009–10	2010–11				2011–12		
Village	Chickpea	Chickpea	Cotton	Paddy	Sugarcane	Cotton	Paddy	Sugarcane
Fasalvadi	3	3	3	4	5	3	6	6
Shivampet	3	3	–	–	–	–	–	–
Venkatakishtapur	3	–	–	–	–	–	–	–
Chakriyal	–	–	–	–	–	–	4	–
Total	9	6	3	4	5	3	10	6

mainly N and P (termed as farmers' practice, FP) and (2) FP plus application of nutrient amendments of 50 kg ha^{-1} zinc sulfate (10 kg Zn ha^{-1}), 2.5 kg ha^{-1} agribor (0.5 kg B ha^{-1}), and 200 kg ha^{-1} gypsum (30 kg S ha^{-1}) (termed as balanced nutrition; BN). These nutrients were broadcasted uniformly on the plot before final land preparation. In all on-farm trials, farmers chose the crop and variety to be grown on their fields; however, similar crop management and cultural practices were followed at the field level across farmers and sites. Cost of 200 kg gypsum, 50 kg zinc sulfate, and 2.5 kg agribor together was ` 2250 (US$ 41.7)* during 2009 and 2010, and ` 2500 (US$ 46.3) during 2011. Farm gate price of chickpea was ` 23000 (US$ 425.9) $t^{-1}$ during 2009-10 and 2010–11, sugarcane was ` 2100 (US$ 38.9) t^{-1} during 2010–11 and 2011–12, paddy was ` 9000 (US$ 166.7) $t^{-1}$ during 2010–11 and 2011–12, and cotton was ` 40000 (US$ 740.7) t^{-1} during 2010–11 and ` 32000 (US$ 592.6) t^{-1} during 2011–12. In Shivampet village, the residual effects of sulfur and micronutrients applied during post rainy 2009–10 were also evaluated on rainy 2010–11 season chilly crop.

The project area received 578.4 mm rainfall during rainy season from June to October 2009 and 66.6 mm rainfall during post rainy season from November 2009 to January 2010. Amount of rainfall from June to October 2010 during rainy season was 1000.6 mm and from November 2010 to January 2011 during post rainy season was 14.0 mm. Rainfall during rainy season from June to October 2011 was 541.4 mm, whereas during the post rainy season from November 2011 to January 2012 it was 14.4 mm.

At maturity, crop yields were estimated from three representative spots in each treatment. For each spot, harvested area was 9 m^2. Thus in each trial, crop plants covering a total area of about 27 m^2 was harvested and the harvested plants were pooled. Economic parts of the plants were separated from the vegetative parts and weighed separately. Sub-samples weights were recorded and brought them to ICRISAT center at Patancheru (India) for further processing. The sub-samples were dried at 60 °C for 48 hours and dry weights of grain and straw samples were recorded to interpolate yields to t ha^{-1}. The data was subjected to statistical analysis using the Genstat 7th edition package (VSN International, Oxford, UK) (Ireland 2010).

Crop Quality and Post-Harvest Soil Health Analysis

During the year 2010–11, the sugarcane samples were collected to determine the effects of balanced nutrient management on total soluble sugar content. To study the effects on soil

* 1 US$ = `54.

health and sustainability, post-harvest surface (0 to 0.15 m) soil samples were also collected from under the FP and balanced nutrient management treatments. In each treatment, the soil samples were collected from 4 to 5 spots and mixed together to make a composite sample for analysis.

Results and Discussion

Fertility Status of Farmers' Fields

A summary of the chemical analysis of soil samples from farmers' fields in four villages in a benchmark watershed of Medak district in Andhra Pradesh, India during 2009 showed that the fields had a wide range of pH (6.3 to 8.5) and EC (0.1 to 4.1 dS m^{-1}) (Table 2). Soils were low in organic C (0.19% to 1.13%), low to medium in Olsen-P, and generally adequate in exchangeable K. The low levels of soil organic C (and thereby N) is not entirely surprising as the production systems are based on little or no inputs of organic matter to the soils (El-Swaify et al. 1985; Rego et al. 2003). Soil analysis results indicated that soil organic C content was low in most fields in three villages and percent deficiency of samples ranged from 67% to 83%; while in Chakriyal village the deficiency was in 47% fields and still majority fields were on sufficient side. Available P in the fields was not critically deficient in the villages and percent deficiency of samples ranged from 5 to 35%; and thus majority fields had sufficient P to reduce use and cost of phosphatic fertilizers by just having a maintenance dose. Similarly, K was not a problem in any field and thus indicated scope to also reduce use and cost of potash fertilizers. However, the most revealing results on soil chemical analysis are the levels of available S, B, and Zn in the samples. Available S was low in majority fields in Fasalvadi and Shivampet villages and percent deficiency of samples ranged from 50% to 74%. Available B was critically deficient in most fields (70% to 80%) in three villages except Chakriyal village, whereas available Zn was deficient in most fields (55 to 83%) in all the villages (Table 2). Results of soil samples analysis for chemical fertility parameters thus indicated a wide spread deficiency of S, B, and Zn in farmers' fields in the Medak, Andhra Pradesh. The extensive Zn, B, and S deficiencies are probably due to poor organic C status of soils (Srinivasarao et al. 2006) and continuous cropping without S, B and Zn application, exhausting these plant nutrients from the SAT soils (Rego et al. 2007; Wani et al. 2013). The extent of deficiency of S, B, and Zn, as revealed by soil testing, are comparable to those reported from well endowed and intensive, irrigated production systems (Takkar et al. 1989; Takkar 1996; Srinivasarao et al. 2008).

Response of Crops to Applied Nutrients

The Zn, B, and S application along with N, P under BN over the FP (only N and P) showed significant increased yield responses in all the crops across the watershed villages (Tables 3 and 4). The BN treatment yielded 45% more grain yield in chickpea crop across the watershed during post-rainy season 2009–10, and 31% during post-rainy season 2010–11. The yield increase was relatively less during 2010–11 probably due to less amount of rainfall from November 2010 to January 2011 (14.0 mm) as compared to the previous post-rainy season (66.6 mm) (Table 3).

The BN treatment yielded 16% more cotton yield during the rainy season 2010–11 and 15% during the rainy season 2011–12. In paddy crop, the BN treatment yielded 14% more grain yield during the rainy season 2010–11 and 15% during the rainy season 2011–12 in

Table 2
Chemical characteristics of soil samples collected from farmers' fields in four villages of benchmark watershed in Medak district, Andhra Pradesh, India, 2009

Village	No. of fields		pH	EC (dS m^{-1})	Organic C (%)	Olsen P (mg kg^{-1})	Exch. K (mg kg^{-1})	Extractable nutrient elements (mg kg^{-1})		
								S	B	Zn
Fasalvadi	20	Range	6.4–8.5	0.1–4.1	0.19–0.83	2.0–75.1	61–978	4.2–431.0	0.08–1.14	0.40–1.92
		Mean	7.4	0.6	0.43	18.0	187	39.1	0.36	0.80
		% deficient[a]			75	35	0	50	80	55
Venkatakishtapur	15	Range	6.5–8.3	0.2–1.6	0.28–0.90	1.6–35.3	50–310	3.6–258.0	0.12–1.84	0.24–1.96
		Mean	7.8	0.5	0.49	13.2	163	48.5	0.47	0.62
		% deficient			67	20	0	27	73	80
Shivampet	23	Range	6.3–8.5	0.1–0.4	0.22–0.69	1.4–40.5	92–338	3.7–41.6	0.17–1.14	0.20–1.34
		Mean	7.8	0.2	0.38	10.5	199	10.2	0.49	0.53
		% deficient			83	26	0	74	70	83
Chakriyal	19	Range	7.0–8.5	0.1–2.1	0.22–1.13	2.4–44.0	46–208	6.2–464.0	0.14–2.00	0.20–1.56
		Mean	7.9	0.6	0.52	21.2	130	62.1	0.89	0.69
		% deficient			47	5	5	26	26	63

[a]The critical limits used were 0.5% for organic C, 5 mg kg^{-1} for P, 50 mg kg^{-1} for K, 10 mg kg^{-1} for S, 0.58 mg kg^{-1} for B and 0.75 mg kg^{-1} for Zn.

Table 3

Effects of soil test-based balanced nutrition on chickpea crop in benchmark watershed, Medak district, Andhra Pradesh, India, 2009–10 to 2010–11

Village	Grain yield (t ha^{-1}) and economics (`) during 2009–10						Grain yield (t ha^{-1}) and economics (`) during 2010–11					
	Farmers' practice (FP)	FP + SBZn	LSD (5%)	Additional income	Additional cost	B:C ratio	Farmers' practice (FP)	FP + SBZn	LSD (5%)	Additional income	Additional cost	B:C ratio
Fasalvadi	1.57	2.06	0.39	11270	2250	5.0	0.71	0.98	0.13	6210	2250	2.8
Shivampet	1.28	2.11	0.50	19090	2250	8.5	1.38	1.74	0.18	8280	2250	3.7
Venkatakishtapur	0.99	1.40	0.36	9430	2250	4.2	–	–	–	–	–	–

Table 4
Effects of soil test-based balanced nutrition on yield of cotton, paddy and sugarcane crops in benchmark watershed of Medak district, Andhra Pradesh, India, 2010 to 2012

		Grain/economic yield (t ha^{-1}) and economics (`) during 2010–11						Grain/economic yield (t ha^{-1}) and economics (`) during 2011–12					
Village	Crop	Farmers' practice (FP)	FP + SBZn	LSD (5%)	Additional income	Additional cost	B:C ratio	Farmers' practice (FP)	FP + SBZn	LSD (5%)	Additional income	Additional cost	B:C ratio
Fasalvadi	Cotton	1.55	1.80	0.18	10000	2250	4.4	1.35	1.55	0.11	6400	2500	2.6
Fasalvadi	Paddy	4.80	5.47	0.50	6030	2250	2.7	5.33	6.13	0.24	7200	2500	2.9
Chakriyal	Paddy	–	–	–	–	–	–	5.47	6.10	0.49	5670	2500	2.3
Fasalvadi	Sugarcane	146.0	158.2	3.53	25620	2250	11.4	107.8	116.3	7.20	17850	2500	7.1

Fasalvadi village; where as in Chakriyal, grain yield increase was 12% over FP during the rainy season 2011–12. The BN treatment yielded 9% more cane yield during the year 2010–11 and 8% during the year 2011–12 (Table 4).

Our results clearly demonstrated significant yield responses of different rainfed as well as irrigated crops to application of Zn, B, and S under BN over the FP. The crop responses to applied nutrients greatly vary with seasonal rainfall and its distribution during the cropping season (El-Swaify et al. 1985). The responses of crops to the application of Zn, B, and S varied across crops; the crop yields responses are significant and are of similar magnitude to those reported for field crops under irrigated agriculture (Takkar 1996; Scherer 2001; Fageria et al. 2002; Katyal and Rattan 2003) and rainfed agriculture also (Rego et al. 2007; Srinivasarao et al. 2008). The deficiencies of Zn, B, and S clearly assume critical importance for increasing and sustaining crop productivity of rainfed systems in the Indian SAT. Results from on-farm trials conducted during 2009-2012 in the villages clearly demonstrated that under rainfed as well as irrigated conditions, the application of Zn, B, and S is essential to increase the productivity.

Benefits of Zn, B, and S Application

Economics of Zn, B, and S application was calculated for all the crops by considering the cost of additional inputs used, additional income generated due to yield enhancement, and benefit cost (B:C) ratio for each rupee of additional investment made. In case of chickpea, the additional income due to the adoption of soil test-based fertilizer application ranged between ` 9430 (US$ 174.6) to ` 19090 (US$ 353.5) during 2009-10, and between ` 6210 (US$ 115.0) to ` 8280 (US$ 153.3) during 2010–11. The returns to per rupee invested were quite high as evident from B:C ratios of 4.2 to 8.5:1 during 2009–10 and 2.8 to 3.7:1 during 2010–11(Table 3). The B:C ratio of cotton crop was 4.4:1 with the additional income of ` 10000 (US$ 185.2) during the rainy season 2010–11, whereas the B:C ratio was 2.6:1 with the additional income of ` 6400 (US$ 118.5) during the rainy season 2011–12. Similarly, the B:C ratio for paddy grain yield was 2.7:1 with the additional income of ` 6030 (US$ 111.7) during the rainy season 2010–11, where as the B:C ratio of paddy grain yield ranged from 2.3 to 2.9:1 with the additional income in the range of ` 5670 (US$ 105.0) to ` 7200 (US$ 133.3) during the rainy season 2011–12. The B:C ratio of sugarcane was 11.4:1 with the additional income of ` 25620 (US$ 474.4) during the year 2010–11, where as the additional income from sugarcane crop was ` 17850 (US$ 330.6) with the B:C ratio of 7.1:1 during the year 2011–12 (Table 4). Significant increase in additional income due to small additional investment made in balanced nutrition and favorable B:C ratios indicate that application of Zn, B, and S were economical and this practice can be recommended for large scale adoption where Zn, B, and S are deficient. Similar B: C ratios were also reported with the application of secondary and micronutrients on soils deficient in these nutrients (Sakal et al. 1996; Srinivasarao et al. 2008; Chander et al. 2012, 2013).

Residual Effects of Zn, B, and S

Farmers are diversifying their field crops with high-value crops like chilly and vegetables to improve their livelihoods and incomes. After seeing the response of chickpea crop to soil test-based balanced fertilizers application during post-rainy season 2009–10, two farmers in Shivampet village planted rain-fed chilly crop in the same fields and observed positive yield response due to the residual effect of gypsum, zinc sulfate and agribor during the rainy season 2010. On average, farmers harvested 6.5 t ha^{-1} of red chilly on dry weight

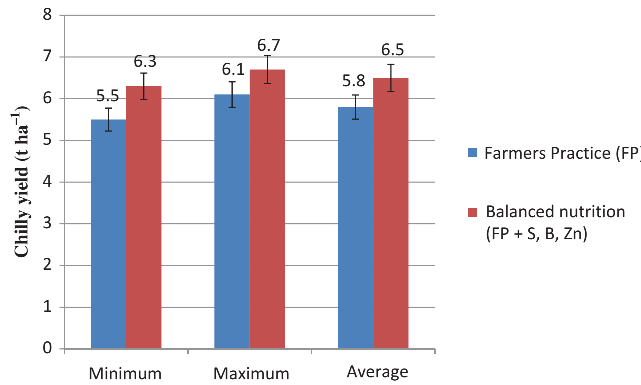

Figure 1. Residual effects of Zn, B and S application on chilly crop in Shivampet village in Medak district, Andhra Pradesh, India during 2010–11.

basis from the plots with the residual effect of Zn, B, and S and 5.8 t ha^{-1} from the plots where FP was adopted (Figure 1). The residual effect of Zn, B, and S yielded 12% more dry chillies yield during the year as compared to FP.

Earlier studies have also reported that besides direct effects of these nutrients, there was considerable residual effect on succeeding crops (Srinivasarao et al. 2008; Chander et al. 2013). Results emphasize the need for better management strategies to utilize residual effects more efficiently under farmers' conditions. Thus, the present results show that for sustained increase in productivity, the agricultural crops should be fertilized with Zn, B, and S along with N and P.

Produce Quality

The application of nutrients based on soil test-based results by including S, B, and Zn not only benefited crop productivity, but crop quality also. Total soluble sugars (%) in sugarcane juice increased by 13% under balanced nutrition as compared with the

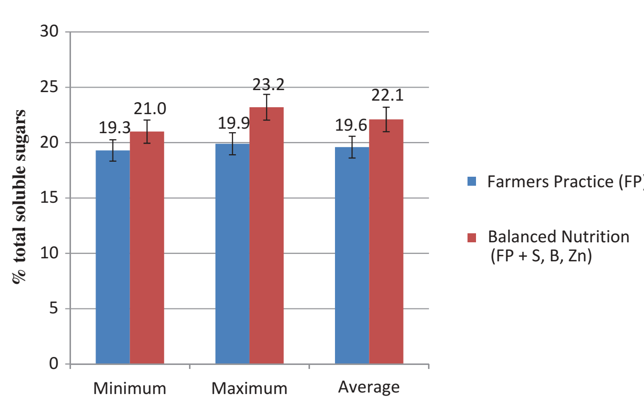

Figure 2. Effects of farmers' practice and balanced nutrition treatments on total soluble sugars in sugarcane in Fasalvadi village in Medak district, Andhra Pradesh, India during 2010–11.

Table 5
Post-harvest soil health status under farmers' practice and balanced nutrition trials in different crops in benchmark watershed villages, Medak district, Andhra Pradesh, India during 2010–11

		Organic C (%)		Olsen P (mg kg^{-1})		Extractable S (mg kg^{-1})		Extractable B (mg kg^{-1})		Extractable Zn (mg kg^{-1})	
Crop	Village	Farmers' practice (FP)	FP + SBZn	Farmers' practice (FP)	FP + SBZn	Farmers' practice (FP)	FP + SBZn	Farmers' practice (FP)	FP + SBZn	Farmers' practice (FP)	FP + SBZn
Paddy	Fasalvadi	0.24	0.28	3.60	3.40	25.2	48.9	0.46	0.72	0.64	0.78
Chickpea	Fasalvadi	0.28	0.24	7.9	7.5	35.9	33.2	0.37	0.51	1.05	3.36
Sugarcane	Fasalvadi	0.30	0.48	2.2	27.2	19.3	17.7	0.45	0.97	0.92	2.22
Chilly	Shivampet	0.26	0.32	11.8	15.2	17.6	19.5	0.30	0.42	0.84	3.28

FP (Figure 2). The increased sugar content under balanced nutrition is likely due to applied Zn and B. Zinc is structural component of enzymes regulating carbohydrate metabolism (Robson 1993), while B is reported to control different reactions in carbohydrate metabolism such as α-amylase, glucose 6-phosphate dehydrogenase, β-amylase and reactions of uridine diphosphate glucose (UDGP)-synthesis (Goldbach 1997). There is evidence that applied Zn and B tend to increase cane sugar content (Singh et al. 2002; Pawar et al. 2003).

Post-Harvest Soil Health Analysis

Post-harvest soil analysis in paddy, chickpea and sugarcane fields during 2010–11 showed in general better soil health in terms of plant nutrient contents under the balanced nutrient management treatment as compared with the FP (Table 5). Soil organic C, an indicator of general soil health, tended to increase under the balanced nutrient management practice. Better root growth and more shoot biomass addition under the balanced nutrient management apparently accounted for higher soil organic C. The available contents of nutrients like P, S, Zn, and B under the balanced nutrition were either at par or higher than that under the FP. A positive relationship between soil organic C and available P (Wani et al. 2003) implies the role of increased organic matter in enhancing soil P in legume-based systems. Higher contents of S, B, and Zn in balanced nutrition plots are on expected lines due to their addition under soil test-based fertilizer management strategy. Even in the plots where chilly crop was taken on residual S, B and Zn the next season, the soil available contents of organic C, P, S, B, and Zn were higher than those in the plots where FP was followed (Table 5). The results proved precisely that the soil test-based balanced nutrition is the way forward to sustainably intensify food production through maintenance of soil productivity.

Conclusions

Soil analysis results clearly demonstrated the widespread deficiencies of S, B, and Zn in addition to the well-known deficiencies of N and P in the SAT soils, and hence observed response of crops to the application of these nutrients.

Soil test-based balanced fertilizers application trials clearly demonstrated that the deficiencies of S, B, and Zn assume critical importance for increasing and sustaining crop productivity of the rain-fed as well as irrigated crops in the Indian SAT. On average, chickpea grain yield was increased by 38% with a mean B:C ratio of 4.6, cotton yield was increased by 16% with B: C ratio of 3.5, paddy grain yield was increased by 14% with B:C ratio of 2.6, and sugarcane yield was increased by 9% with a mean B:C ratio of 9.3. Residual effect of these nutrients was observed in succeeding season on chilly crop as 12% yield increase in addition to direct benefit in previous crop. In addition to increased yields and B:C ratios, total soluble sugars in sugarcane increased by 13% under balanced nutrition as compared with the FP.

Post-harvest soil analysis in paddy, chickpea, and sugarcane crops showed in general better soil health under the balanced nutrient management treatment as compared with the FP. These results clearly demonstrated that for sustained increase in productivity, produce quality and better soil health, SAT soils need applications of not only major nutrients such as N and P, but also nutrients such as S, B, and Zn.

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References

Chander, G., S. P. Wani, K. L. Sahrawat, and L. S. Jangawad. 2012. Balanced plant nutrition enhances rainfed crop yields and water productivity in Jharkhand and Madhya Pradesh states in India. *Journal of Tropical Agriculture* 50:24–29.

Chander, G., S. P. Wani, K. L. Sahrawat, P. J. Kamdi, C. K. Pal, D. K. Pal, and T. P. Mathur. 2013. Balanced and integrated nutrient management for enhanced and economic food production: case study from rainfed semi-arid tropics in India. *Archives of Agronomy and Soil Science* 59(12):1643–1658.

El-Swaify, S. A., P. Pathak, T. J. Rego, and S. Singh. 1985. Soil management for optimized productivity under rainfed conditions in the semi-arid tropics. *Advances in Soil Science* 1:1–64.

Fageria, N. K., V. C. Baligar, and R. B. Clark. 2002. Micronutrients in crop production. *Advances in Agronomy* 77:185–268.

Goldbach, H. E. 1997. A critical review on current hypotheses concerning the role of boron in higher plants: Suggestions for further research and methodological requirements. *Journal of Trace Microprobe Techniques* 15:51–91.

Helmke, P. A., and D. L. Sparks. 1996. Lithium, sodium, potassium, rubidium, and cesium. In *Methods of soil analysis. Part 3. Chemical methods—Soil Science Society of America Book Series no. 5*, ed. D. L. Sparks, 551–574. SSSA and ASA: Madison, WI.

Ireland, C. 2010. *Experimental statistics for agriculture and horticulture*. Chemsford: Essex, UK.

Katyal, J. C., and R. K. Rattan. 2003. Secondary and micronutrients: Research gaps and future needs. *Fertilizer News* 48(4):9–14, 17–20.

Keren, R. 1996. Boron. In *Methods of soil analysis. Part 3. Chemical methods— Soil Science Society of America Book Series no. 5*, ed. D. L. Sparks, 603–626. SSSA and ASA: Madison, WI.

Lindsay, W. L., and W. A. Norvell. 1978. Development of a DTPA test for zinc, iron, manganese and copper. *Soil Science Society of America Journal* 42:421–428.

Nelson, D. W., and L. E. Sommers. 1996. Total carbon, organic carbon, and organic matter. In *Methods of soil analysis. Part 3. Chemical methods—Soil Science Society of America Book Series no. 5*, ed. D. L. Sparks, 961–1010. SSSA and ASA: Madison, WI.

Olsen, S. R., and L. E. Sommers. 1982. Phosphorus. In *Methods of soil analysis. Part 2.* 2nd edition. *Agronomy Monograph 9*, ed. A. L. Page, 403–430. ASA and SSSA: Madison, WI.

Pasricha, N. S., and R. L. Fox. 1993. Plant nutrient sulfur in the tropics and subtropics. *Advances in Agronomy* 50:209–269.

Pawar, M. W., S. S. Joshi, and V. T. Amodkar. 2003. Effect of foliar application of phosphorus and micronutrients on enzyme activities and juice quality in sugarcane. *Sugar Tech* 5(3):161–165.

Rego, T. J., V. N. Rao, B. Seeling, G. Pardhasaradhi, and J. V. D. K. Kumar Rao. 2003. Nutrient balances—a guide to improving sorghum and groundnut based dryland cropping systems in semi-arid tropical India. *Field Crops Research* 81:53–68.

Rego, T. J., K. L. Sahrawat, S. P. Wani, and G. Pardhasaradhi. 2007. Widespread deficiencies of sulfur, boron and zinc in Indian semi-arid tropical soils: On-farm crop responses. *Journal of Plant Nutrition* 30:1569–1583.

Rockström, J., N. Hatibu, T. Oweis, and S. P. Wani. 2007. Managing water in rain-fed agriculture. In *Water for Food, Water for Life: a Comprehensive Assessment of Water Management in Agriculture*, ed. D. Molden, 315–348. Earthscan, London, UK and International Water Management Institute (IWMI): Colombo, Sri Lanka.

Rockstrom, J., Louise Karlberg, S. P. Wani, Jenni Barron, Nuhu Hatibu, Theib Oweis, Adriana Bruggeman, Jalali Farahani, and Zhu Qiang. 2010. Managing water in rainfed agriculture – The need for a paradigm shift. *Agricultural Water Management* 97:543–550.

Sahrawat, K. L. 2002. Plant nutrient sufficiency and requirements. In *Encyclopedia of soil science*, ed. R. Lal, 1000–1004. Marcel Dekker, Inc.: New York, NY.

Sahrawat, K. L., T. J. Rego, S. P. Wani, and G. Pardhasaradhi. 2008. Stretching soil sampling to watershed: Evaluation of soil-test parameters in a semi-arid tropical watershed. *Communications in Soil Science and Plant Analysis* 39(19–20):2950–2960.

Sakal, R., A. P. Singh, R. B. Sinha, and N. S. Bhogal. 1996. *Twenty five years of research on micro and secondary nutrients in soils and crops of Bihar*. RAU: Pusa, Bihar.

Scherer, N. W. 2001. Sulfur in crop production. *European Journal of Agronomy* 14:81–111.

Singh, A., A. K. Gupta, R. N. Srivastava, K. Lal, and S. B. Singh. 2002. Response of zinc and manganese to sugarcane. *Sugar Tech* 1&2:74–76.

Srinivasarao, Ch., K. P. R. Vittal, G. Ravindra Chary, P. N. Gajbhiye, and B. Venkateswarlu. 2006. Characterization of available major nutrients in dominant soils of rainfed crop production systems of India. *Indian Journal of Dryland Agricultural Research and Development* 21:105–113.

Srinivasarao, Ch., S. P. Wani, K. L. Sahrawat, T. J. Rego, and G. Pardhasaradhi. 2008. Zinc, boron and sulphur deficiencies are holding back the potential of rainfed crops in semi-arid India: Experiences from participatory watershed management. *International Journal of Plant Production* 2:89–99.

Tabatabai, M. A. 1996. Sulfur. In *Methods of soil analysis. Part 3. Chemical methods—Soil Science Society of America Book Series no. 5*, ed. D. L. Sparks, 921–960. SSSA and ASA: Madison, WI.

Takkar, P. N. 1996. Micronutrient research and sustainable agricultural productivity. *Journal of the Indian Society of Soil Science* 44:563–581.

Takkar, P. N., I. M. Chhibba, and S. K. Mehta. 1989. *Twenty years of coordinated research on micronutrients in soils and plants* (1967–1987). Bulletin no.1, Indian Institute of Soil Science: Bhopal, India.

Wani, S. P., G. Chander, K. L. Sahrawat, Sreenath Dixit, and B. Venkateswarlu. 2013. *Improved crop productivity and rural livelihoods through balanced nutrition in the rainfed semiarid tropics*. Resilient Dryland Systems Report no. 58. International Crops Research Institute for the Semi-Arid Tropics (ICRISAT): Patancheru, Andhra Pradesh, India: 36 pp.

Wani, S. P., P. Pathak, L. S. Jangawad, H. Eswaran, and P. Singh. 2003. Improved management of Vertisols in the semiarid tropics for increased productivity and soil carbon sequestration. *Soil Use and Management* 19:217–222.

Wani, S. P., T. K. Sreedevi, J. Rockström, and Y. S. Ramakrishna. 2009. Rain-fed agriculture - Past trend and future prospects. In *Rain-fed agriculture: Unlocking the Potential. Comprehensive Assessment of Water Management in Agriculture Series*, eds. S. P. Wani, J. Rockström, and T. Oweis, 1–35. CAB International: Wallingford, UK.

Wani, S. P., J. Rockstrom, B. Benkateswarlu, and A. K. Singh. 2011. New paradigm to unlock the potential of rainfed agriculture in the semi-arid tropics. World soil resources and food security. In *Advances in Soil Science*, eds. Rattan Lal, and B. A. Stewart, 419–469. CRC Press: Boca Raton, FL.

Wani, S. P., Y. Dixin, Z. Li, W. D. Dar, and G. Chander. 2012. Enhancing agricultural productivity and rural incomes through sustainable use of natural resources in the SAT. *Journal of the Science of Food and Agriculture* 92:1054–1063.