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Soil-Test-Based Balanced Nutrient Management for Sustainable Intensification and Food Security: Case from Indian Semi-arid Tropics

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*In the semi-arid tropics (SAT), there exists large yield gaps (two- to four-fold) between current farmers' yields and achievable yields. Apart from water shortages, soil degradation is responsible for the existing gaps and inefficient utilization of whatever scarce water resource is available. On-farm soil fertility testing across different states in Indian SAT during 2001–2012 showed widespread new deficiencies of sulfur (46–96 percent), boron (56–100 percent), and zinc (18–85 percent) in addition to already known phosphorus (21–74 percent) and nitrogen (11–76 percent, derived from soil carbon). Based on these results, a new fertilizer management strategy was designed to meet varying soil fertility needs at the level of a cluster of villages by applying a full nutrient dose if >50 percent fields were deficient and a half dose in the case of fields <50 percent deficient. Improved nutrient management significantly increased crop productivity in groundnut (*Arachis hypogaea*) (17–86 percent), sorghum (*Sorghum bicolor*) (30–55 percent), soybean (*Glycine max*) (10–40 percent), and maize (*Zea mays*) (10–50 percent) with favorable benefit-cost ratios (1.43–15.2) over farmers' practice. Nutrient balancing improved nitrogen-fertilizer-use efficiency in respect of plant uptake from soil, transport into grain, use efficiency in food production, and grain nutritional quality. Balanced-nutrient-managed plots showed better postharvest soil fertility. Residual benefits of sulfur, boron, and zinc were observed in up to three succeeding seasons. Results of soil-test-based nutrient-management trials have sensitized policy makers in some states for desired policy orientation to benefit millions of smallholders in the Indian SAT.*

Keywords Crop productivity, fertilizer-use efficiency, micronutrients, natural resource management, soil health, sulfur

Introduction

The world population is expected to increase up to 9.2 billion people by 2050, most of whom are expected in developing countries in Asia (5.3 billion) and Africa (1.7 billion), raising serious issues of food security (Sreedevi et al. 2006). In the context of food production, 80 percent of agriculture globally is rainfed and contributes 60 percent to the world's food basket (Wani, Rockström, and Oweis 2009). The current productivity levels

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in farmers' fields in the rainfed tropics are less than the achievable yields by two- to fourfold (Rockström et al. 2010; Wani et al. 2003, 2009, 2012). To achieve food security and reduce rampant poverty in these regions, it is essential to increase productivity of rainfed systems by harnessing existing potential (Wani et al. 2003).

Rainfed agriculture in India constitutes about 60 percent of the net cultivated area and accounts for nearly 44 percent of the national food basket (Sharma 2011). Though India has made major strides in food production since 1960s, the gains have come mainly from the irrigated agriculture with large-scale cultivation of high-yielding varieties of cereals and increased application of fertilizers and pesticides. However, the green revolution bypassed rainfed agriculture and the productivity of the major rainfed crops and the socioeconomic conditions of the farmers remained unchanged. The demand for food would continue to rise as the population of India increases from the current 1.21 billion in 2011 (Ministry of Agriculture, Government of India 2013) to the expected 1.69 billion by 2050 (FAOSTAT 2013). Rainfed agriculture in India accounts for nearly 80 percent of oilseeds, 65 percent of cotton, and 90 percent each of pulses and coarse cereals (CRIDA 1997). These data show the importance of rainfed agriculture in India's food security, and furthermore, in the context of near saturation productivity levels in irrigated agriculture, there is a growing realization that further gains in productivity of crops and livestock will have to emanate from the rainfed regions. Moreover, it is estimated the irrigation expansion, a major thrust of the growth in the crop area in the past decade, is likely to continue and irrigation coverage is expected to increase from 41 to 55 percent over the period 2000–2050; thus, around 45 percent of the area in the year 2050 will continue to remain rainfed (Amarasinghe et al. 2007). Hence, it will be necessary to increase the productivity levels of the major rainfed crops to meet the ever-increasing demand of food, which emphasizes the critical importance of rainfed agriculture in Indian economy and food security.

A long-term study, started in 1976 at the International Crops Research Institute for the Semi-arid Tropics (ICRISAT) center based at Patancheru, India, demonstrated a virtuous cycle of persistent yield increases through improved soil, crop, and water management in rainfed agriculture. An improved system of sorghum/pigeonpea intercropping produced 5.1 t ha^{-1} grain yield, which we can say is an achievable potential yield as compared with 1.1 t ha^{-1} with sole sorghum in the farmers' practice (Wani et al. 2012). Both management practices are sustainable in the long run, but have different carrying capacities—farmers' practice has a low carrying capacity of 5 persons ha^{-1}, whereas improved management gives a carrying capacity of 21 persons ha^{-1}, which is urgently needed for feeding the burgeoning population. The study validated the need for knowledge-based management in the dry lands to bridge yield gap for future food security and improved farm incomes and livelihoods for smallholders in the SAT.

Apart from water shortages, the productivity in rainfed systems of semi-arid tropics (SAT) of India is low due to poor fertility status of the soils (Sahrawat et al. 2010; Chander et al. 2012, 2013). Poor and degraded soils are major stumbling blocks, resulting in inefficient utilization of available water and other resources. However, no attempt has been made to diagnose the nutrient problems in these areas and the usual practice of applying only nitrogen (N), phosphorus (P), and potassium (K) continues over widespread areas. For a sustainable increase in rainfed productivity, the issues related to soil fertility needs to be addressed. So, the objectives of this communication are to (1) diagnose and highlight rampant soil-fertility-related degradation in terms of new deficiencies of secondary and micronutrients along with primary nutrients, and which are not included in current fertilization practices in the Indian SAT, and (2) to show how soil-test-based fertilizer management practice can sustainably increase crop productivity to ensure food security in the SAT regions of India.

Materials and Methods

Diagnosis of Soil Fertility Issues and Designing of Fertilization Strategies

The target regions for this study were predominantly rainfed semi-arid tropics in seven states in India (Figure 1). Specifically, it comprised eleven districts (Adilabad, Ananthapuram, Kadapa, Khammam, Kurnool, Mahabubnagar, Medak, Nalgonda, Prakasam, Rangareddy, and Warangal) in Andhra Pradesh; one district (Junagarh) in Gujarat; all thirty districts in Karnataka state; three districts (Kollam, Pathanamthitta, and Thiruvananthapuram) in Kerala; twelve districts (Barwani, Dewas, Guna, Indore, Jhabua, Mandla, Raisen, Rajgarh, Sagar, Sehore, Shajapur, and Vidisha) in Madhya Pradesh; nine districts (Alwar, Banswara, Bhilwara, Bundi, Dungarpur, Jhalawar, Sawai

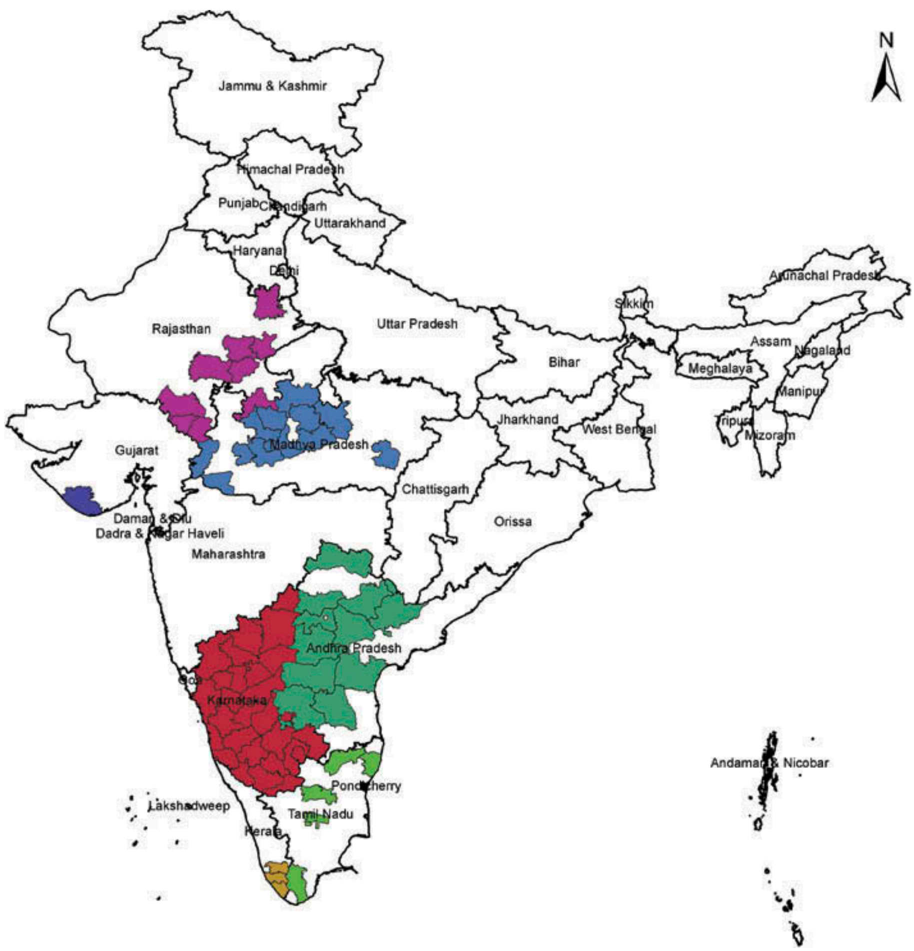

Figure 1. Study sites across seven states in Indian semi-arid tropics (SAT).

Madhopur, Tonk, and Udaipur) in Rajasthan; and five districts (Kanchipuram, Karur, Salem, Tirunelveli, and Vellore) in Tamil Nadu. To diagnose soil-fertility-related constraints in Indian SAT, 95,187 composite surface (0–0.15 m) soil samples were collected from farmers' fields during the period 2001–2012: 3650 samples in Andhra Pradesh, 82 in Gujarat, 90,546 in Karnataka, 28 in Kerala, 341 in Madhya Pradesh, 421 in Rajasthan, and 119 in Tamil Nadu. The samples were collected following the stratified random sampling method (Sahrawat et al. 2008) to address all factors apparently leading to variable soil fertility. Under this method, we divided target ecoregions into three toposequences. At each toposequence location, samples were taken proportionately from small, medium, and large farm-holding sizes to address the variations that may arise due to different managements because of different economic status in each farm-size class. Within each farm-size class in a toposequence, the samples were chosen carefully to represent all possible soil fertility variations as judged from soil color, texture, cropping system, and agronomic management. From each sampled field, we collected eight to ten cores of surface (0–0.15 m) soil samples and mixed them together to make a composite sample. The samples were processed and analyzed for organic carbon (C), available sulfur (S), boron (B), zinc (Zn), P, and K in Charles Renard Analytical Laboratory, ICRISAT (see details in the "soil and plant chemical analysis" section).

Based on soil analysis results, fertilizer management strategies were designed at the level of a cluster of villages (referred to as a block, a lower administrative unit in a district). This is in contrast to the existing approach followed generally in India, in which blanket fertilizer recommendations for N, P, and K are made only at the state (comprising some districts) level. The critical values for delineating deficiency of available nutrients are 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 (Sahrawat et al. 2010). Similarly for soil organic C, which was used as a proxy for available N, 5.0 g kg^{-1} was used as a critical limit to delineate farms having low levels of soil organic C (Sahrawat et al. 2010). We recommended application of a full dose of a particular nutrient if its deficiency was in >50 percent farms in a block and a half dose of a nutrient as a maintenance dose if its deficiency was in <50 percent farms. This strategy of fertilizer management was designed to effectively manage existing risks in rainfed agriculture in the SAT while targeting optimum yields to improve the livelihoods of poor SAT farmers. The state fertilizer recommendations for N, P, and K were modified based on this principle to meet varying soil fertility needs at the block level. Similarly, for newly emerged deficiencies of S, B, and Zn, the per-ha general recommendations of 30 kg S (through gypsum), 5 kg Zn, and 0.5 kg B, which were to be added once every 2 years, evaluated, and standardized earlier (Rego et al. 2005), were also adjusted based on the aforementioned principle of deficiency to meet varying soil fertility needs.

On-Farm and On-Station Experimentation

Based on the soil-test results, on-farm trials were conducted during the rainy season (June–September) 2010 with prominent regional crops such as maize (*Zea mays*) in five districts of Rajasthan, soybean (*Glycine max*) in six districts of Madhya Pradesh, and sorghum (Sorghum bicolor) in three districts of Karnataka. Another set of trials were conducted after the rainy season (October/November to January/February) in 2010–2011 with groundnut (*Arachis hypogaea*) crop in four districts of Andhra Pradesh. During and after the rainy season of 2010–2011, trials were conducted in four to seventy-five farmers' fields in each of the districts with an average of around thirty trials per district. There were two treatments: (1) farmers' practice (FP, application of recommended N, P, and K only) and (2) balanced nutrition (BN, applications of recommended N, P, and K plus deficient S, B, and Zn). The state-recommended rates of nutrients on per hectare basis were 50–60 kg N and 30–35 kg P_2O_5 for nonlegume sorghum and maize crops, whereas 20 kg N, 40–60 kg P_2O_5, and 20–50 kg K_2O for legume soybean and groundnut crops. As explained in the previous section, the state fertilizer recommendations for N, P, and K were modified based on the principle of percentage deficiency to address varying soil fertility needs at the block level. Recommendations of 30 kg S, 10 kg Zn, and 0.5 kg B in alternate years were also modified on similar lines. All the nutrients except N in nonlegumes were added as basal. Nitrogen in nonlegumes was added in three equal splits at sowing, 1 month after sowing, and 2 months after sowing. The fertilizer sources for nutrients were urea for N, DAP (di-ammonium phosphate) for P, N and muriate of potash (MOP) for K, gypsum for S, zinc sulfate for Zn, and borax for B. The treatments were imposed on 2000-m^2 plots, side by side, and uniform crop management practices were ensured in both treatments. At maturity, the crop yields were recorded from three subplots measuring 3 m × 3 m, the average of which was converted into final yield. To evaluate the effects on soil health under FP and BN, postharvest soil samples were collected from postrainy groundnut crop in Andhra Pradesh.

An on-station study to evaluate the effects on N-efficiency indices in maize during the rainy season of 2010 was also conducted at the ICRISAT center at Patancheru. In addition to FP and BN treatments, an absolute control was also maintained for calculation of N-efficiency indices as described in the following section. All the treatments were applied in plots 9 m × 8 m in size and replicated three times. At maturity, the yields were recorded in all plots representing different treatments and were converted into kg ha^{-1}. Plant samples comprising grain and straw parts were also collected for chemical analysis with regard to N contents.

Soil and Plant Chemical Analysis

The soil samples collected were air dried, ground, and passed through a 2-mm sieve. For organic C, the soil samples were ground to pass through a 0.25-mm sieve. Soil organic C was analyzed following the Walkley-Black method (Nelson and Sommers 1996). Available nutrients were extracted using the sodium bicarbonate for P (Olsen and Sommers 1982), ammonium acetate for K (Helmke and Sparks 1996), 0.15 percent calcium chloride for S (Tabatabai 1996), hot water for B (Keren 1996), and diethylene triamine pentaacetic acid (DTPA) reagent for Zn (Lindsay and Norvell 1978). Available P was determined using a colorimetric method, and K was measured by atomic absorption spectrophotometry (AAS). Analyses of S, B, and Zn were made using inductively coupled plasma–atomic emission spectroscopy (ICP-AES).

Plant samples collected from on-station study were separated into grain and straw, ground, and analyzed for N contents. Total N in plant materials was determined by digesting with sulfuric acid–selenium mixture and analyzed using an auto-analyser (Sahrawat, Ravi Kumar, and Murthy 2002).

Nitrogen-Use Efficiency Indices

Nitrogen input efficiency was calculated in terms of different standards such as N-uptake efficiency, N-utilization efficiency, N-use efficiency, and N harvest index parameters (Delogu et al. 1998; Lopez-Bellido and Lopez-Bellido 2001).

Nitrogen-uptake efficiency (NUpE) was calculated by dividing total plant N uptake with N supply. Total plant N uptake was determined by multiplying dry weight of plant parts by N concentration and summing over parts for total plant uptake. The N supply was defined as the sum of N applied as fertilizer and total N uptake in control, that is, 0 N applied (Limon-Ortega, Sayre, and Francis 2000). Nitrogen-utilization efficiency (NUtE) was calculated by dividing grain yield with total plant N uptake. Nitrogen-use efficiency (NUE) was estimated by dividing grain yield with N supply, and N harvest index (NHI) was determined by dividing total grain N uptake with total plant N uptake and multiplying by 100.

Economic and Statistical Analysis

To calculate economic feasibility at a farm level, the additional cost of BN was calculated for gypsum at Rs. 2/- per kg, zinc sulfate at Rs. 30/- per kg, and borax at Rs. 50/- per kg. Additional returns were calculated at per kg farm gate price of Rs. 28/- for groundnut, Rs. 13/- for sorghum, Rs. 17/- for soybean, and Rs. 10/- for maize. The benefit-to-cost (B/C) ratios of adopting the technology were calculated by dividing additional returns with additional costs over and above the farmers' practice. The currency conversion factor is Rs. 1 = US $ 0.0180.

The data collected were subjected to statistical analysis and the test of significance between FP and BN with any crop in targeted region in a district was conducted at the 5 percent probability level using Genstat, thirteenth edition (Ireland 2010). Each farmer's field for any crop in a targeted region in a district received uniform nutrient application and so was treated as a replication for statistical analysis of the data.

Results and Discussion

Soil Fertility

Soil analysis results of farmers' fields in semi-arid regions of India showed that majority of fields were low in soil organic C in Andhra Pradesh, Karnataka, and Tamil Nadu states (Table 1). Soil organic C is an indicator of general soil health and specifically of available N. Similarly, P tested low in a majority of fields in Gujarat, Madhya Pradesh, and Tamil Nadu. Across all states, the majority of fields were generally adequate in K (Table 1). However, widespread deficiencies of secondary and micronutrients, mainly S, B, and Zn, were also detected in the Indian SAT regions. Soils testing low in S were critical in all the states except Gujarat and those low in Zn were in all states except Kerala and Rajasthan. Boron deficiencies were critical in all the states, with the majority of fields testing low in it. The percentage of fields testing low in S ranged from 46 to 96 percent. Similarly, the percentage of fields testing low in B ranged from 56 to 100 percent and for Zn from 18 to 85 percent (Table 1). The diagnostic soil fertility assessment clearly pointed out that multinutrient deficiencies of secondary nutrients such as S and micronutrients such as B and Zn are apparently holding back realization of greater yields in farmers' fields in semi-arid India (Sahrawat et al. 2010; Chander et al. 2012, 2013).

Crop Productivity

Balanced nutrient application as compared to the farmers' input treatment increased crop yields during and after the rainy season across the districts in Andhra Pradesh, Karnataka, Madhya Pradesh, and Rajasthan (Table 2; Figure 2). During the rainy season, crop productivity increased by 10 to 50 percent in maize in Rajasthan, 10 to 40 percent in soybean

Table 1
Percent of farm field soil samples found deficient in available nutrients and having low levels of soil organic C

State	Samples with low levels of soil organic C (%)	Samples deficient in available nutrients (%)				
		P	K	S	B	Zn
Andhra Pradesh[a]	76	38	12	79	85	69
Gujarat[c]	12	60	10	46	100	85
Karnataka[b]	52	41	23	52	62	55
Kerala	11	21	7	96	100	18
Madhya Pradesh[a]	22	74	1	74	79	66
Rajasthan[a]	38	45	15	71	56	46
Tamil Nadu[c]	57	51	24	71	89	61

[a]Wani, Chander, and Sahrawat (2012).
[b]Wani et al. (2011).
[c]Sahrawat et al. (2007).

in Madhya Pradesh, and 30 to 55 percent in sorghum in Karnataka. Similarly, during the postrainy season, groundnut productivity in Andhra Pradesh increased by 17 to 86 percent. The B/C ratios of BN ranged between 1.43 to 5.86 for maize, 1.66 to 3.32 for soybean, 3.27 to 4.76 for sorghum, and 2.60 to 15.2 for groundnut, thereby indicating it is a remunerative option for scaling up at the farm level. Rainfed crops in SAT India have also shown beneficial response in other studies to BN application (Sahrawat et al. 2010; Chander et al. 2012, 2013). As the area under rainfed production is very large, even a modest increase in yield would contribute in a big way to the global food pool, apart from providing a source of income and livelihoods to the rural poor (Sahrawat et al. 2011).

Taking leads from earlier findings of soil-test results and benefits of soil-test-based BN, the state government in Karnataka, India, has implemented an ICRISAT consortium-led initiative to revive the entire state agricultural lands in a phased manner through technical and financial support to poor smallholder farmers (ICRISAT 2013a, 2013b, 2013c). This soil-test-based strategy has shown dramatic growth in agriculture sector at the state level, 5.9 percent during 2010–2011 and 11.2 percent during 2011–2012 against a static or negative growth rate earlier. The spectacular success in Karnataka has led to the initiation of similar programs in Andhra Pradesh, the adjoining state in India, and also another Asian country (Philippines). The benefits of BN in crop productivity trials presented in this study and successful scaling up as in Karnataka has proved the soil-test-based management as the way forward for food security in the SAT.

Nitrogen-Use Efficiency

With added S, B, and Zn along with N and P under BN treatment in the on-station study, the N-efficiency indices increased significantly over the FP without S, B, and Zn (Figure 3). Nitrogen-uptake efficiency (NUpE) reflects the efficiency of the crop in obtaining N from the soil (Rahimizadeh et al. 2010). Under the absolute control, total plant N uptake is equal to N supply (N applied as fertilizer + total N uptake in control) and so, as per definition,

Table 2
Effects of balanced nutrition on crop yield and benefit-to-cost ratios during rainy season 2010

District	Grain yield ($kg\ ha^{-1}$) FP	Grain yield ($kg\ ha^{-1}$) BN	Additional cost ($Rs\ ha^{-1}$)	Additional benefit ($Rs\ ha^{-1}$)	B/C
Maize (*Zea mays*) in Rajasthan					
Banswara[a]	1980	2450*	2150	4700	2.19
Bhilwara	2960	3590*	1075	6300	5.86
Tonk[a]	1730	2590*	2150	8600	4.00
Sawai Madhopur	1940	2140	1400	2000	1.43
Maize in ICRISAT, Patancheru, Andhra Pradesh					
Medak[b]	3440	4540*	2150	11000	5.12
Soybean (*Glycine max*) in Madhya Pradesh					
Raisen	1280	1490*	2150	3570	1.66
Sagar	1500	1740*	1400	4080	2.91
Shajapur	1990	2200*	1200	3570	2.98
Indore	1550	1710*	1075	2720	2.53
Sehore	2290	2650*	2150	6120	2.85
Vidisha	1060	1480*	2150	7140	3.32
Sorghum (Sorghum bicolor) in Karnataka					
Bidar	1630	2290*	2150	8580	3.99
Davangere	1780	2320*	2150	7020	3.27
Chamrajnagara	1428	2215*	2150	10231	4.76

Notes. FP, farmers' practice (application of N, P, K only); BN, balanced nutrition (FP inputs plus S + B + Zn); B/C, benefit-to-cost ratio.
[a]Chander et al. (2011).
[b]Chander et al. (2015).
*Significant at 5 percent level.

NUpE is unity. A lower NUpE in FP treatment shows the problem associated with efficient use of applied N fertilizers. The BN treatment significantly enhanced it over the FP treatment, indicating the roles of added S, B, and Zn in contributing to the first crucial step in enhancing N-use efficiency, that is, uptake of supplied N. The NUtE reflects the ability of the plant to transport the N uptake into grain (Delogu et al. 1998). This study showed that fertilizer management under FP was even a better practice to enhance NUtE; however, the BN treatment recorded the greatest NUtE. A lower NUE (a ratio of grain yield by N supply) in fertilized plots as compared with absolute control again shows the problem associated with efficient use of applied N fertilizers. With the same amount of added N, the BN treatment recorded a significantly greater NUE over the FP, indicating clearly the roles of deficient S, B, and Zn to improve NUE. The NHI, which reflects the grain protein content or the grain nutritional quality (Hirel et al. 2007), is also greatest under the BN treatment. The findings showed that the BN is the best strategy to increase NUE, the ability of the plant to transport the N uptake into grain, NUE of applied and native N, and grain nutritional quality through enhanced protein content.

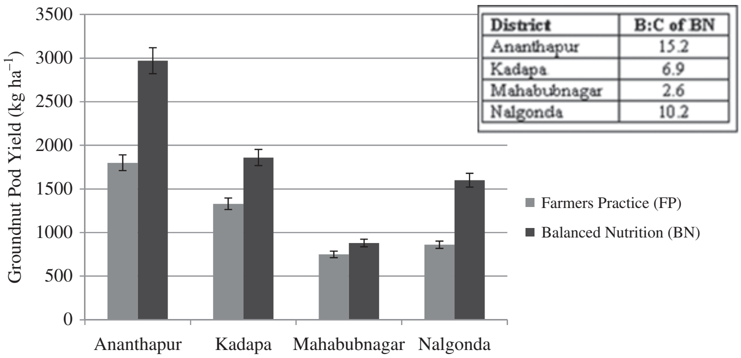

Figure 2. Effects of balanced nutrition on groundnut (*Arachis hypogaea*) pod yield in Andhra Pradesh, India, post-rainy seasons 2010–2011. B:C, benefit-to-cost ratio of balanced nutrition.

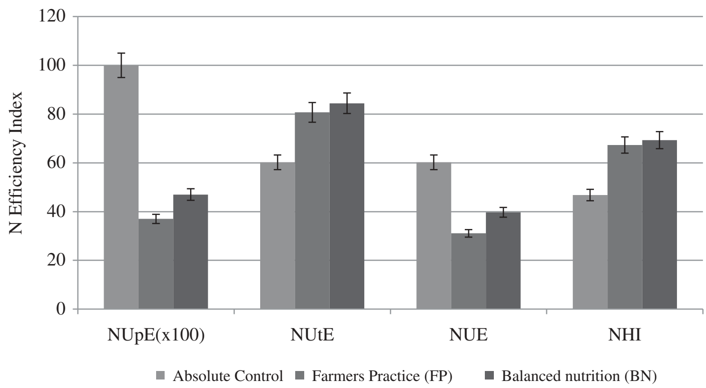

Figure 3. Effects of balanced nutrition on N-efficiency indices in maize (*Zea mays*) at ICRISAT, Patancheru, India, rainy season 2010. NUpE, nitrogen-uptake efficiency (total plant N uptake / N applied as fertilizer + N uptake in control); NUtE, nitrogen-utilization efficiency (grain yield / total plant N uptake); NUE, nitrogen-use efficiency (grain yield / N applied as fertilizer + N uptake in control); and NHI, nitrogen harvest index (total grain N uptake / total plant N uptake × 100).

Postharvest Soil Fertility

The study conducted to evaluate the soil fertility status after the 2010–2011 postrainy season crop (groundnut) harvest in Nalgonda District showed greater available contents of P, S, B, Zn, and soil organic C in the BN-managed plots than in those of FP (Figure 4). The results clearly showed that soil-test-based fertilization practice not only results in increased economic crop yields but also renders an ecosystem service in terms of improved soil fertility required for sustainable intensification.

Residual Benefits of Secondary and Micronutrients

The study in Vidisha District in Madhya Pradesh showed that the fields where S, B, and Zn were applied during rainy season 2010 not only increased soybean crop yield (40 percent increase) in that season but also benefitted the succeeding three season crops grown in BN plots due to residual effects of S, B, and Zn. During the postrainy season 2010–2011,

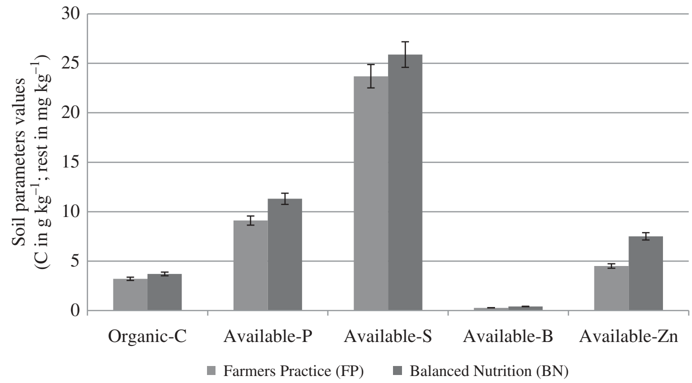

Figure 4. Soil fertility status after 2010–2011 postrainy season trials with balanced nutrition of groundnut (*Arachis hypogaea*) in Nalgonda, Andhra Pradesh.

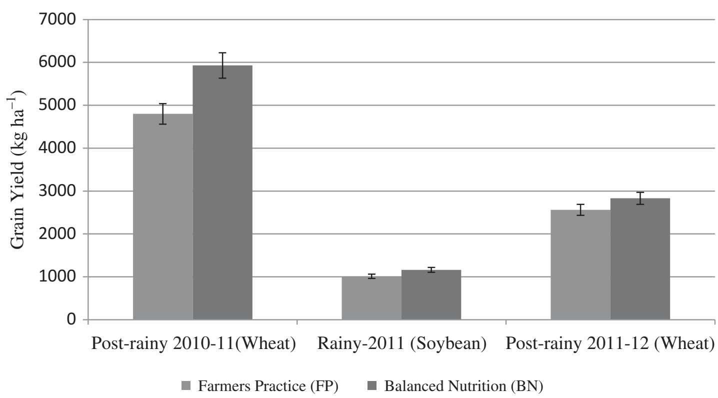

Figure 5. Residual effects of S, B, and Zn applied in 2010 on the succeeding three seasons of wheat (Triticum *aestivum*) and soybean (*Glycine max*) crop grain yields in Vidisha, Madhya Pradesh.

wheat yields in BN plots as compared with the FP plots were greater by 24 percent, and the during rainy 2011 season, soybean yields were greater by 15 percent (Figure 5). Similarly, during postrainy season 2011–2012, the wheat grain yields were still greater by 11 percent in the BN plots as compared with the FP plots. The wheat yields in general were lower during postrainy season of 2011–2012 than those during the postrainy season of 2010–11, probably because no rainfall was received during the active growth period in October to December, whereas during the postrainy season of 2010–2011, about 56 mm of rainfall was received at critical stages during the same period. So it is evident that the benefits of balanced nutrition in terms of B/C ratios as presented in earlier section in this study for the season of application are thus not the only benefits; this management of nutrients also leads to resilience building of production systems for benefits in future (Chander et al. 2013).

Conclusions

Soil-fertility-related degradation due to mining from soil by crops over a period resulted in newly emerging deficiencies of secondary nutrient S and micronutrients such as B and Zn, which apparently act as stumbling blocks to realize greater productivity in the Indian semi-arid tropics. Farmers should consider and include these deficient secondary and micronutrients in their fertilizer-management strategies every alternate year. The apparent yield losses in absence of soil-test-based balanced nutrition through addition of S, B, and Zn are between 10 to 86 percent of current crop yield levels in the season 1. Failure to realize residual benefits of S, B, and Zn as documented in the next three succeeding seasons creates additional losses under farmers' management practice. Balanced nutrition is economically remunerative in season 1 to adopt at a farm level and is much more remunerative if residual benefits in yield improvement through resilience building are also considered. The on-farm evaluation results of this study prove precisely the need to promote balanced nutrition for sustainable food production and greater net returns. Rural farmers in the rainfed semi-arid tropics in India are unaware of soil health issues and are entrapped in poverty, so not in a position to implement the science-led strategy of their own. There is a strong need for desired policy orientation by the respective governments to promote capacity strengthening and soil-test-based balanced nutrition strategies through appropriate incentives for poor smallholders in the semi-arid tropics in India. Findings of nutrient balancing trials in the past decade have sensitized policy makers in some states such as Karnataka, where soil-test-based fertilizer management strategy has been picked and scaled up to 5.5 million hectares, benefitting more than 3.6 million smallholder farm families. The government in Andhra Pradesh has also implemented the desired policy orientation to scale up the science-led strategy in a phased manner to benefit millions of smallholders in the state. The study concludes there is need in all states in the Indian semi-arid tropics and other parts of the world to follow these examples and adopt soil-test-based fertilization as part of food production to ensure future food security.

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