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Soil test-based nutrient balancing improved crop productivity and rural livelihoods: case study from rainfed semi-arid tropics in Andhra Pradesh, India

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Widespread multinutrient deficiencies in the semi-arid tropics (SAT) are among major factors for large gaps between farmers' current crop yields and potential yields. In this study, we adopted a stratified soil sampling method to assess soil fertility-related constraints in farmers' fields in eight districts of Andhra Pradesh in the semi-arid tropics of India. Most of the fields across all eight districts were critical in sulfur (61%–98% deficient fields); and up to six districts each in boron (83%–98% deficient fields), zinc (50–85% deficient fields), and soil organic carbon (55–97% deficient fields). Low soil organic carbon specifically indicates nitrogen deficiency. Phosphorus deficiency was critical in three districts (60–84%) while potassium in general was adequate. Soil test-based nutrient balancing through the application of sulfur, boron, and zinc in addition to farmers' practice of adding only nitrogen, phosphorus, and potassium increased crop productivity by 8%–102%. Benefit–cost ratio (1.60–28.5) proved favourable to scale-up balanced nutrition. Better post-harvest soil health and residual benefits of sulfur, boron, and zinc up to four succeeding seasons indicated sustainability of the practice. Results showed that balanced nutrition is a way forward for sustainably improving farm productivity and livelihoods.

Keywords: balanced plant nutrition; crop productivity; farm income; nutrient uptake; production system resilience; soil fertility

Introduction

Rainfed agriculture is practiced worldwide in 80% of the agricultural area and most countries in the world depend primarily on rainfed agriculture for their grain food (Wani, Rockström, et al. 2011). Despite great strides made in improving productivity, a large number of families in Africa and Asia who practice rainfed agriculture, still face poverty, hunger, food insecurity, and malnutrition. In India, 89 million ha (two-thirds of the agricultural area) is under rainfed agriculture and contributes to 44% of national food production (Wani et al. 2012). In context of irrigated regions in India having reached productivity plateau, rainfed regions offer hope to increase food production to 290 million tons by 2025 to meet the food requirement of the burgeoning population (Amarasinghe et al. 2007; Wani, Sreedevi, et al. 2008). The rainfed semi-arid tropics (SAT) in India are the hot spot of land degradation, low crop yields, and poverty. Out of the 852 million poor and malnourished people in the world, 221 million are in India. Rural areas in Andhra

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Pradesh in India represent a typical gloomy scenario of SAT. In Andhra Pradesh, agriculture contributes to about 20% of the gross domestic product, but provides employment and livelihood to more than 70% of the rural population. Agriculture plays a key role in economic development (World Bank 2005) and poverty reduction (Irz & Roe 2000), with evidence indicating that increase in agricultural yields can translate to a decrease in the percentage of absolute poor (Thirtle et al. 2002). Growth in agricultural productivity also accounts for a large share of economic growth. Agricultural development is feasible in these rainfed regions by upgrading agriculture with scientific knowledge to increase crop productivity and farmers' income.

An analysis of major rainfed crops in semi-arid regions in Andhra Pradesh revealed large yield gaps between farmers' current yields and the achievable potential yields. The farmers' current yields are 2–4 times lower than the potential yields (Wani, Rockström, et al. 2011). The historic trends show a growing yield gap between farmers' practices (FPs) and farming systems with improved management (Wani, Pathak, et al. 2003). Results from long-term experiments at the heritage watershed site at ICRISAT (International Crops Research Institute for the Semi-Arid Tropics), Patancheru, Andhra Pradesh, have shown that integrated watershed interventions, which focus on balanced nutrient management along with crop, land, and water management practices can sustainably increase rainfed crop yield five folds as compared to that under traditional FPs (Wani, Pathak, et al. 2003; Wani, Dixin, et al. 2011; Wani, Rockström, et al., 2011).

In the rainfed production systems, the importance of water shortage and associated stress cannot be overemphasized especially in the semi-arid tropical regions (Pathak et al. 2009; Rockström et al. 2010; Sahrawat et al. 2010). However, apart from water shortage, soil infertility is also a constraint for crop production and productivity enhancement in most regions of the SAT of the world (Sahrawat et al. 2011) and is a stumbling block for utilization of the available scarce water. In general, very little attention has been devoted to determine the fertility status of farmers' fields and hence to diagnose the nutrient problems in the rainfed production systems. The information on the soil fertility status can help not only in enhancing crop productivity through balanced nutrient management but also promote judicious use of external inputs of nutrients (Wani, Joshi, et al. 2008). Various studies have found widespread deficiency of macro (N, P, K), micro, and secondary (Ca, Mg, S) nutrients in the rainfed areas (Wani, Singh, et al. 2003; Rego et al. 2005; Sahrawat et al. 2010; Chander et al. 2012). On-farm trials in some regions of the Indian SAT have shown that non-application of deficient secondary and micronutrients leads to significant yield losses, and such nutrient deficiencies apparently inhibit the realization of productivity potential in the SAT (Sahrawat et al. 2010; Chander et al. 2012, 2013).

Therefore, we hypothesized that through diagnosing soil fertility-related degradation and implementing soil test-based balanced nutrition (BN), yield gaps in rainfed rural areas in Andhra Pradesh could be bridged to increase crop productivity and improve farm-based livelihoods. The specific objectives of this study were to (1) assess nutrient status of farmers' fields in the target districts of Andhra Pradesh; and (2) conduct farmer participatory trials using soil test-based balanced nutrient management recommendations to assess effects on crop productivity, economic benefits, and sustainability.

Materials and methods

Study sites

The study sites were farmers' fields in clusters (blocks) of 3–9 villages in eight rainfed districts of Andhra Pradesh, India – Seethagondi cluster in Adilabad district, Pampanur in

Ananthapur, B. Yerragudi in Kadapa, Tummalachervu in Khammam, Jamistapur in Mahabubnagar, Dupahad in Nalgonda, Ibrahimpur in Rangareddy and Jaffergudem in Warangal district. Major crops grown in the area are cotton (*Gossypium* spp.), groundnut (*Arachis hypogaea*), castor (*Ricinus communis*), maize (*Zea mays*), chickpea (*Cicer arietinum*), sorghum (*Sorghum bicolor*), sunflower (*Helianthus annuus*), and rice (*Oryza sativa*). Other crops like cowpea (*Vigna unguiculata*) and green gram (*Vigna radiata*) are also sown to some extent as emergent short-duration crops. Crop productivity in general is very low. The soils of the region are predominantly red and black. Land degradation due to nutrient mining and wrong fertilization practices are apparent major constraints to higher productivity.

Diagnostic soil analysis

Soil samples were collected from 826 farmers' fields in the targeted clusters following the farmer participatory stratified soil sampling technique (Sahrawat et al. 2008). Under this technique, we divided target eco-regions in the districts into three topo-sequences. At each topo-sequence location, samples were taken proportionately from small, medium and large farm-holdings 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 topo-sequence, the samples were chosen carefully to represent all possible soil fertility variations as judged from soil colour, texture, cropping system, and agronomic management. At ultimate sampling unit in a farmer's field, we collected 8–10 cores of surface (0–0.15 m) soil samples and mixed together to make a composite sample. Surface soil samples were taken because most of the effective root biomass of agricultural crops is confined in surface soil and it represents the nutrient supply to crop plants. The collected samples were air-dried in the shade, ground with wooden pestle and mortar and sieved through a 2-mm sieve for general analysis. Soil samples for organic carbon (C) were ground to pass through a 0.25-mm sieve. Soil organic C was determined by Walkley–Black method (Nelson & Sommers 1996). Available phosphorus (P) was extracted using sodium bicarbonate ($NaHCO_3$) extractant (Olsen & Sommers 1982) and determined using molybdenum blue colorimetric method. Exchangeable potassium (K) was extracted using ammonium acetate (Helmke & Sparks 1996) and determined on atomic absorption spectrophotometer (SavantAA, GBC Scientific Equipment, Braeside, VIC, Australia). Plant available sulfur (S) was extracted with 0.15% calcium chloride ($CaCl_2$) (Tabatabai 1996), available zinc (Zn) by diethylene triamine pentaacetic acid (DTPA) reagent (Lindsay & Norvell 1978), and available boron (B) by hot water (Keren 1996) while their estimations were made using the inductively coupled plasma atomic emission spectrophotometer (SavantAA, GBC Scientific Equipment, Braeside, VIC, Australia).

Deduction of fertilizer recommendations

Based on the results of the analysis done on sampled soils and variable soil fertility across the region, fertilizer recommendations were developed at the level of cluster of villages called block, a lower administrative unit in a district. In India, blanket fertilizer recommendations involve, in general, nitrogen (N), P and K at the state (comprising of some districts) level which rarely match the soil fertility need and totally ignore secondary and micronutrients. In this study, fertilizer recommendations were designed at the block level by considering practical aspects like available infrastructure, human power and economics in research for impact for smallholders in the Indian SAT. Soil test-based recommendations were developed for all limiting nutrients, i.e., N, P, K, S, B and Zn. The critical values for delineating deficiency/sufficiency were 11,200 kg ha^{-1} for organic C, 11.2 kg ha^{-1} for P, 112 kg ha^{-1} for K, 22.4 kg ha^{-1} for S, 1.30 kg ha^{-1} for B and 1.68 kg ha^{-1} for Zn (Sahrawat et al. 2010). In soil test-based recommendations, full dose of a nutrient was added if <50% fields had adequate levels of the nutrient and half dose if >50% fields had adequate level of that nutrient. This way of nutrient recommendation was adopted by considering other existing risks in rainfed agriculture in the SAT while targeting optimum yields to improve livelihoods of poor farmers in the SAT. The state fertilizer recommendations for N, P and K were modified based on this principle to address varying soil fertility needs at the block level. The state recommended dose of nutrients per ha was 75–120 kg N, 17–26 kg P and 25–50 kg K for non-legumes and 10–20 kg N, 11–22 kg P and 0–41 kg K for legumes. For legumes, the amount of K varied and was 0 kg ha^{-1} in greengram and cowpea, 17 kg ha^{-1} in chickpea and 41 kg ha^{-1} in the groundnut. Similarly, for the diagnosed deficiencies of S, B and Zn, a general recommendation per ha (practiced in alternate years) of 30 kg S ha^{-1} (through gypsum), 10 kg Zn ha^{-1} and 0.5 kg B standardized earlier (Rego et al. 2005) was adjusted to meet varying soil fertility needs.

On-farm trials

Based on soil test results, on-farm participatory trials were conducted with all prominent crops in the targeted clusters (blocks) to evaluate the effects of BN in different rainy (June–September) and post-rainy (October–January) season crops during 2008/2009–2011/2012. For each test crop in the targeted cluster/district during a season, trials were replicated in 3–15 farmers' fields (Table 1). There were two treatments: (1) Farmers' practice (FP, application of N, P, and K) and (2) balanced nutrition (BN, application of N, P, K plus S, B, and Zn). Nutrients in both FP and BN were added as per fertilizer recommendations deducted and explained in the previous section. All the nutrients except N in non-legumes were added by basal fertilizer application. Nitrogen in non-legumes was added in three equal splits at sowing, one month after sowing and two months after sowing. The fertilizers were urea (46% N) for N, DAP (diammonium phosphate; 20% P, 18% N) for P and N, MOP (muriate of potash; 50% K) for K, gypsum (15% S) for S, zinc sulfate (20% Zn) for Zn and borax (10% B) for B. The treatments were imposed on 2000 m^2 plots without replicates on a farmer's field, side by side and uniform crop management practices were ensured in both the treatments. At maturity, the crop yield was recorded from the three sub-plots, each measuring 3 m × 3 m, i.e., a total of 27 m^2 per treatment which was interpolated to get the final yield per ha. Each farmer's field in a targeted block in a district was considered a replication. Thus, in all trials conducted in farmers' fields, the FP was compared with the BN treatment. The rainwater use efficiency (RWUE) was also computed as kg of food grain produced per mm of rainwater per ha received during the growing season. The rainfall received during the growing seasons in 2008–2011 is given in Table 2.

In on-farm trials during rainy season 2010, nutrient uptake was worked out under FP and BN treatments with sorghum crop in Adilabad district and groundnut crop in Nalgonda district. Plant nutrient uptake was worked out by multiplying dry matter yield of grain and straw with respective nutrient contents and summing-up grain and straw uptake.

The effects of nutrient management practices (FP and BN) were also assessed on post-harvest soil fertility in Nalgonga district. The soil samples were collected during 2010 after taking the rainy season groundnut crop and analysed for soil organic C, and available P, S, B and Zn.

Table 1. Number of farmers' fields evaluated for soil test-based balanced nutrition during 2008/2009–2011/2012 in Andhra Pradesh, India.

		2008/2009		2009/2010		2010/2011		2011/2012
District	Crop	Rainy season	Post-rainy season	Rainy season	Post-rainy season	Rainy season	Post-rainy season	Rainy season
Adilabad	Cotton (*Gossypium hirsutum*)	–	–	13	–	–	–	6
	Sorghum (*Sorghum bicolor)*	–	–	–	–	4	–	–
	Chickpea (*Cicer arietinum*)	–	14	–	8	–	5	–
Ananthapur	Groundnut (*Arachis hypogaea)*	9	4	3	9	5	5	5
Kadapa	Groundnut (*Arachis hypogaea)*	13	–	11	6	–	6	3
	Sunflower (*Helianthus annuus*)	–	8	–	7	–	–	–
Khammam	Cotton (*Gossypium hirsutum*)	13	–	–	–	5	–	4
	Greengram (*Vigna radiata)*	–	–	–	–	–	5	–
Mahbubnagar	Castor (*Ricinus communis)*	–	–	–	–	–	–	5
	Groundnut (*Arachis hypogaea)*	–	4	–	–	–	4	–
Nalgonda	Groundnut (*Arachis hypogaea)*	–	3	5	4	5	8	8
	Tomato (*Solanum lycopersicum)*	–	–	–	6	–	–	–
Rangareddy	Cowpea (*Vigna unguiculata)*	–	–	–	–	–	–	4
	Groundnut (*Arachis hypogaea)*	–	–	–	5	–	–	–
Warangal	Cotton (*Gossypium hirsutum*)	13	–	15	–	4	–	6
	Maize (*Zea mays*)	–	–	–	15	–	–	–
	Tomato (*Solanum lycopersicum)*	–	4	–	–	–	–	–

Table 2. Rainfall received in different districts of Andhra Pradesh, India, during 2008–2011.

	Rainfall received (mm)						
	Rainy season (June–September)				Post-rainy season (October–January)		
District	2008	2009	2010	2011	2008/2009	2009/2010	2010/2011
Adilabad	838	594	1227	855	27	88	170
Ananthapur	488	365	432	286	175	160	241
Kadapa	259	369	505	392	282	167	328
Khammam	1288	538	1378	793	97	145	233
Mahabubnagar	421	456	646	393	46	258	79
Nalgonda	604	343	729	464	58	133	210
Rangareddy	628	608	926	430	49	124	136
Warangal	1060	504	1123	795	49	136	161

In addition to trials on application of BN, the residual effects of S, B and Zn added were evaluated for crop production in succeeding seasons. In three trials, each of rainy season 2010, rainy season 2011 and post-rainy season 2011–12 applied with S, B, and Zn, cotton yields were studied during rainy season 2012 in Warangal district.

Plant chemical analysis

To estimate plant N, P and K contents, plant materials were digested with sulfuric acid–selenium mixture, while N and P in the digests were analysed using autoanalyzer and K using atomic absorption spectrophotometer (Sahrawat, Ravi Kumar, and Murthy 2002). Zinc in the plant materials was determined by digesting them with triacid (nitric acid: sulphuric acid:perchloric acid::9:2:1, v/v) and then using atomic absorption spectrophotometer (Sahrawat, Ravi Kumar, and Rao 2002). Total S and B in plant samples were determined by digesting the samples with nitric acid and then using inductively coupled plasma emission spectrophotometer (Mills & Jones 1996).

Economic and statistical analysis

To work out economic feasibility at the farm level, additional cost of BN was calculated for gypsum at Rs 2 kg^{-1}, zinc sulfate at Rs 30 kg^{-1} and borax at Rs 50 kg^{-1}. Additional returns were worked out at a farm-gate price of at Rs 37.50 kg^{-1} for cotton, at Rs 15 kg^{-1} for sorghum, at Rs 28 kg^{-1} for groundnut, at Rs 39 kg^{-1} for castor, at Rs 20 kg^{-1} for cowpea, at Rs 22 kg^{-1} for chickpea, at Rs 25 kg^{-1} for sunflower, Rs 50 kg^{-1} for green gram and at Rs 10 kg^{-1} for maize. The benefit–cost ratios of adopting the technology were worked out by dividing additional returns with additional costs over and above FP. The currency conversion factor is 1Rs = 0.016 US$ (31 July 2013).

The data collected were subjected to statistical analysis with ANOVA to test the least significant difference of treatment means at 5% probability level ($p \leq 0.05$) using the Genstat 13th edition (Ireland 2010). The experimental design was completely randomized and each farmer's field in cluster target villages in a district was treated as replication for statistical analysis of the data.

Table 3. Surface (0–0.15 m) soil carbon and nutrient content status of fields in the targeted village clusters (block) in eight districts of Andhra Pradesh, India.

		% fields sufficient in available nutrients					
District	No. of fields	Soil organic C	P	K	S	B	Zn
Adilabad	63	73 (13,888)	**40** (15.5)	98 (459)	**24** (27.3)	**13** (0.83)	**29** (1.48)
Ananthapur	82	**34** (10,080)	68 (18.8)	91 (260)	**15** (22.4)	**12** (0.72)	**39** (1.97)
Kadapa	83	**3** (5824)	**16** (5.60)	**46** (137)	**2** (14.8)	**12** (0.90)	**15** (1.37)
Khammam	102	75 (15,680)	**40** (19.0)	98 (403)	**33** (23.7)	**13** (0.87)	55 (2.44)
Mahabubnagar	133	**38** (9856)	**57** (19.5)	82 (235)	**27** (26.0)	**17** (0.81)	52 (2.15)
Nalgonda	142	**32** (10,304)	62 (19.3)	86 (199)	**39** (38.1)	64 (1.90)	**49** (2.28)
Rangareddy	121	**45** (11,200)	61 (19.9)	83 (206)	**2** (8.29)	**2** (0.58)	**24** (1.43)
Warangal	100	**19** (9184)	86 (35.8)	95 (264)	**23** (21.1)	77 (2.11)	**50** (2.15)

Notes: Data in parentheses indicate mean available nutrient contents (kg ha^{-1}); data represented as bold indicate critical situation with only few fields sufficient in respective nutrients.

Results and discussion

Soil analysis

Fields in eight districts of Andhra Pradesh, India showed widespread multinutrient deficiencies including those of secondary and micronutrients (Table 3). Adilabad and Khammam had most fields with adequate levels of soil organic C while it was deficient in most (55–97%) fields in the remaining districts. Low levels of soil C indicate general poor soil health and specifically N deficiency. Phosphorus level was adequate in most fields in the five districts thereby indicating the potential to reduce the cost of phosphorous fertilizers. In the remaining three districts of Adilabad, Kadapa and Khammam, however, most fields (60–84%) were deficient in P. Soil K level was generally adequate in most (82–98%) farmers' fields across different districts except in Kadapa where only 40% fields had adequate level. In addition to primary macronutrient deficiencies, the analysis showed relatively few fields with adequate levels of secondary and micronutrients mainly S, B, and Zn which farmers and other stakeholders were not aware of and do not include in their soil fertilization practices. Most of the fields in all eight districts were rather deficient in sulfur (61–98% fields) while most fields in the six districts were deficient in boron (83–98%) and zinc (50–85%). Critical levels of B were recorded in Adilabad, Ananthapur, Kadapa, Khammam, Mahabubnagar and Rangareddy while Zn levels were critical in Adilabad, Ananthapur, Kadapa, Nalgonda, Rangareddy and Warangal. The mining of nutrients through continuous cropping without adequate additions of required fertilizers and manures have impoverished the soils in the SAT over the years (Rego et al. 2005). In view of essentiality of nutrients, apparently S, B and Zn deficiencies along with that of N and P are inhibiting the realization of productivity potential.

Table 4. Effect of farmers' practice (FP) balanced nutrition (BN) on crop yield during rainy seasons 2008–2011.

District	Crop	2008 FP (kg ha^{-1})	2008 BN (kg ha^{-1})	2008 LSD (5%)	2009 FP (kg ha^{-1})	2009 BN (kg ha^{-1})	2009 LSD (5%)	2010 FP (kg ha^{-1})	2010 BN (kg ha^{-1})	2010 LSD (5%)	2011 FP (kg ha^{-1})	2011 BN (kg ha^{-1})	2011 LSD (5%)
Adilabad	Cotton	–	–	–	1060	1350* (5.1)	94	–	–	–	1610	1840 (4.0)	314
	Sorghum	–	–	–	–	–	–	2270	2770 (3.5)	1457	–	–	–
Ananthapur	Groundnut	600	760* (2.1)	44	380	500 (1.6)	129	330	570 (3.1)	361	500	740 (3.1)	655
Kadapa	Groundnut	510	740* (3.0)	109	620	1250* (8.2)	234	–	–	–	510	670 (2.1)	694
Khammam	Cotton	1920	2410* (13.1)	465	–	–	–	1670	2070* (10.7)	213	1440	1740 (8.0)	388
Mahbubnagar	Castor	–	–	–	–	–	–	–	–	–	690	830 (3.9)	381
Nalgonda	Groundnut	–	–	–	1320	1780 (6.4)	471	1400	1750* (4.8)	334	670	920* (3.5)	119
Rangareddy	Cowpea	–	–	–	–	–	–	–	–	–	1220	1420* (1.9)	180
Warangal	Cotton	1160	1360* (3.7)	103	2470	4010* (28.5)	568	1730	2430* (13.0)	132	2190	2670* (8.9)	268

Notes: Data in parentheses are benefit–cost ratios. *significant at $p \leq 0.05$.

Effects of balanced nutrition on rainy season crops

In on-farm trials with important rainy season crops during 2008–2011, significantly higher yields were recorded under the BN treatment as compared with the FP (Table 4). In Adilabad, Khammam and Warangal districts, the cotton yield with FP was 1060–2470 kg ha^{-1}. The application of BN significantly increased cotton yield by 14–62%. In Ananthapur, Kadapa and Nalgonda districts, groundnut yield with FP was 330–1400 kg ha^{-1}. The application of BN increased groundnut yield by 11–102%. Similarly, the application of BN increased yields of castor (8–20%) in Mahabubnagar, sorghum (22%) in Adilabad and cowpea (16%) in Rangareddy districts. Rainfed crops in other parts of India have also shown beneficial response to BN (Rao et al. 2009; Sahrawat et al. 2010; Chander et al. 2012, 2013). The results from on-farm studies showed that the productivity of the rainfed systems can be enhanced through management of various nutrient deficiencies. As the area under rainfed production is very large, even a modest increase in yield would substantially contribute to the global food pool, apart from providing source of income and livelihoods to the rural poor (Sahrawat et al. 2011).

Pooled data for four seasons indicated low water productivity with FP and varied in different districts: 1.2–2.4 kg mm^{-1} ha^{-1} for groundnut, 1.51–2.57 kg mm^{-1} ha^{-1} for cotton, 1.85 kg mm^{-1} ha^{-1} for sorghum, 1.76 kg mm^{-1} ha^{-1} for castor and 2.84 kg mm^{-1} ha^{-1} for cowpea. Plants are not able to utilize properly the available water resources because of constraints to growth due to low soil fertility caused by deficiencies of secondary and micronutrients. Under BN, the RWUE in the targeted districts increased to 1.71–3.19 kg mm^{-1} ha^{-1} for groundnut, 1.85–3.69 kg mm^{-1} ha^{-1} for cotton, 2.26 kg mm^{-1} ha^{-1} for sorghum, 2.11 kg mm^{-1} ha^{-1} for castor and 3.30 kg mm^{-1} ha^{-1} for cowpea. The results showed that soil fertility management to increase the proportion of water balance as productive transpiration is one of the most important rainwater management strategies to improve yields and water productivity (Rockström et al. 2010).

An economic analysis showed viability of the BN technology for scaling-up at the farm level. The adoption of soil test-based BN in farms in the target districts brought additional cost of Rs 1400–2150 ha^{-1} in cotton, Rs 2025–2150 ha^{-1} in groundnut, Rs 2150 ha^{-1} in sorghum, Rs 1400 ha^{-1} in castor and Rs 2150 ha^{-1} in cowpea. However, the additional benefits were far higher than additional costs – Rs 7500–57,750 ha^{-1} in cotton, Rs 3360–18,375 ha^{-1} in groundnut, Rs 7500 ha^{-1} in sorghum, Rs 5460 ha^{-1} in castor and Rs 4000 ha^{-1} in cowpea. In simple terms, per rupee invested on balanced nutrition brought additional returns to the tune of Rs 3.70–28.50 in cotton, Rs 1.60–8.20 in groundnut, Rs 3.50 in sorghum, Rs 3.90 in castor and Rs 1.90 in cowpea (Table 4).

Effects of balanced nutrition on post-rainy season crops

As in the rainy season crops, the benefits of BN were also obtained in post-rainy season crops like groundnut, chickpea, sunflower, green gram and maize (Table 5). In participatory trials with groundnut in Ananthapur, Kadapa, Mahabubnagar, Nalgonda and Rangareddy districts during three consecutive seasons (2008/2009–2010/2011), yield in FP was 480–1940 kg ha^{-1}, thus showing higher groundnut yields during post-rainy season in comparison to rainy season. The application of BN in different districts and seasons, however, increased groundnut yields over FP by 11–86%. Similar increase in productivity was also recorded in other crops like chickpea (38–97%) in Adilabad, sunflower (27–61%) in Kadapa, green gram (50%) in Khammam and maize (20–57%) in Warangal.

Table 5. Effect of farmers' practice (FP) and balanced nutrition (BN) on crop yield during post-rainy seasons 2008/2009–2010/2011.

		2008/2009			2009/2010			2010/2011		
District	Crop	FP (kg ha^{-1})	BN (kg ha^{-1})	LSD (5%)	FP (kg ha^{-1})	BN (kg ha^{-1})	LSD (5%)	FP (kg ha^{-1})	BN (kg ha^{-1})	LSD (5%)
Adilabad	Chickpea	610	1200* (6.0)	151	2130	2950 (8.4)	921	1760	2460* (7.2)	696
Ananthapur	Groundnut	480	750* (3.5)	259	1820	2220 (5.2)	929	1800	2970* (15.2)	839
Kadapa	Sunflower	1590	2020 (5.0)	793	360	580 (2.6)	506	–	–	–
	Groundnut	–	–	–	1030	1800* (10.0)	731	1330	1860* (6.9)	374
Khammam	Green gram	–	–	–	–	–	–	200	300* (3.6)	88
Mahabubnagar	Groundnut	1940	2590 (13.0)	989	–	–	–	750	880 (2.6)	168
Nalgonda	Groundnut	1610	1790* (2.5)	67	1470	2270 (11.1)	810	860	1600* (10.2)	482
Rangareddy	Groundnut	–	–	–	1800	2160* (4.7)	??	–	–	–
Warangal	Maize	–	–	–	5810	6550* (3.7)	455	5540	7320* (8.8)	377

Notes: Data in parentheses are benefit–cost ratios; *significant at $p \leq 0.05$.

The additional cost of soil test-based BN varied in different districts and was Rs 1400–2150 ha^{-1} in case of groundnut crop, Rs 1400 ha^{-1} in green gram, Rs 2025 ha^{-1} in maize and Rs 2150 ha^{-1} each in chickpea and sunflower crops. The additional returns were higher in all districts: Rs 3640–32,760 ha^{-1} in groundnut, Rs 12,980–18,040 ha^{-1} in chickpea, Rs 500–10,750 ha^{-1} in sunflower, Rs 5000 ha^{-1} in green gram and Rs 7400–17,800 ha^{-1} in maize. Thus, per rupee invested on BN returned Rs 2.50–15.20 in groundnut, Rs 6–8.40 in chickpea, Rs 2.60–5 in sunflower, Rs 3.60 in green gram and Rs 3.70–8.80 in maize, thereby proving it a profitable proposition.

Effects of balanced nutrition on vegetable crops

The agronomic challenge in dryland tropics in Andhra Pradesh is targeted at not only low crop productivity but also at restriction to growing traditional crops of low value. Therefore, demand-driven crop diversification into high value crops is promoted among the rural poor to generate more income. In Warangal and Nalgonda districts, farmers cultivated tomato and harvested 4710 kg ha^{-1} in Warangal and 21,940 kg ha^{-1} in Nalgonda by following their own management practice (Figure 1). In the plots where BN was followed, they obtained higher productivity of 21%–36%. In BN plots, farmers incurred an additional cost of Rs 2025 ha^{-1} on the application of deficient S, B, and Zn but obtained far higher additional returns of Rs 4950 ha^{-1} in Warangal and Rs 39,800 ha^{-1} in Nalgonda with a favourable benefit–cost ratio of 2.44–19.7. The cultivation of vegetable crops in watersheds in Dharwad, Haveri and Chitradurga districts of Karnataka during 2006/2007 season has also showed an impressive yield response to BN as compared to FP and the growing of these vegetables under BN was economically viable and remunerative (Srinivasarao et al. 2010).

Plant nutrient uptake

Under FP, data recorded on nutrient removal in harvested grain and straw together were 114 kg N ha^{-1}, 23 kg P ha^{-1}, 104 kg K ha^{-1}, 8 kg S ha^{-1}, 35 g B ha^{-1} and 284 g Zn ha^{-1} in sorghum crop in Adilabad district, and 138 kg N ha^{-1}, 13 kg P ha^{-1}, 86 kg K ha^{-1}, 10 kg S ha^{-1}, 230 g B ha^{-1} and 188 g Zn ha^{-1} in groundnut crop in Nalgonda district (Figure 2). Balanced nutrition in both the crops increased uptake by 41–48% in N, 37% in P, 47–62% in K, 43–50% in S, 39–66% in B and 26–77% in Zn. Nutrient uptake is a

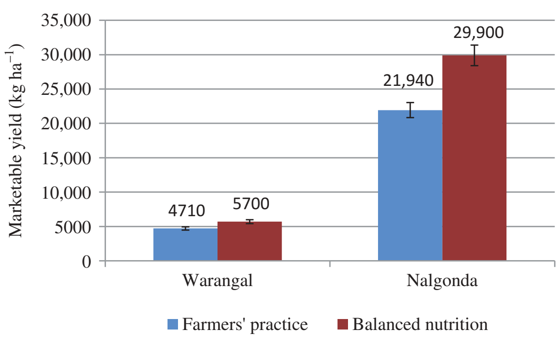

Figure 1. Effect of farmers’ practice (FP) and balanced nutrition (BN) on tomato marketable yield in Warangal during post-rainy season 2008/2009 and Nalgonda during post-rainy season 2009/2010.

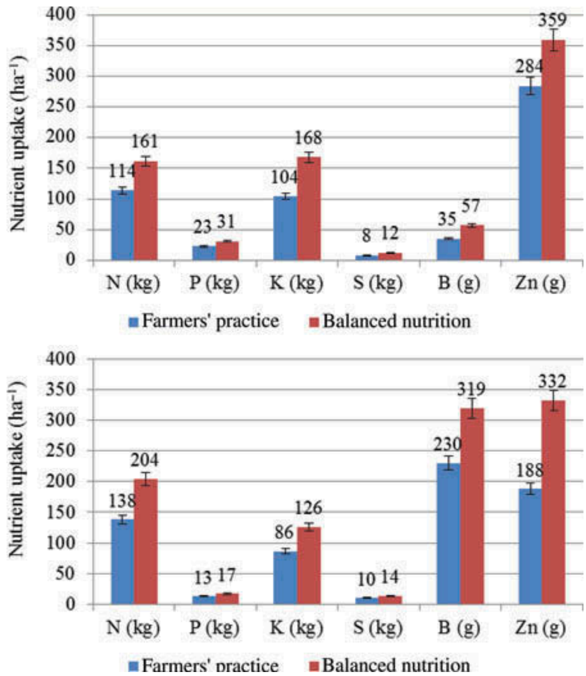

Figure 2. Effects of farmers' practice (FP) and balanced nutrition (BN) on nutrient uptake during rainy season 2010 – (top) sorghum crop in Adilabad and (bottom) groundnut crop in Nalgonda.

function of plant composition and harvested yield. Balanced nutrition while increasing crop yields maintained plant nutrient composition (data not shown) and so, this increase in nutrient uptake resulted because of increased growth and yield due to optimization of growing conditions through balancing of deficient nutrients. Development of extensive root biomass or root length density under BN probably led to absorption of nutrients from deeper soil layers and thereby enhancing uptake use efficiency of nutrients. Applied S, B and Zn in BN apparently increased their availability in soil and uptake by the plants. The synergistic interaction between B and P due to borate–phosphate exchange mechanism in soil may be one reason for more P uptake under BN treatment (Saha & Haldar 1998). In addition, there is documented evidence of the role of B and Zn in maintaining functional integrity of biological membranes (Cakmak et al. 1995; Alloway 2008) and hence enhanced ability of membranes to transport vital nutrients leading to higher uptake.

It is important that with FP mining of significant amounts of secondary and micronutrients was also observed and these amounts become very high in the long run. This explains the growing gap between farmers' yields and achievable potential yields due to soil fertility-related degradation over the years and a need for nutrient balancing for sustained higher productivity.

Soil carbon and nutrient balances

An evaluation of soil health status after 2010 rainy season crop (groundnut) harvest in Nalgonda district showed higher contents of soil organic C and available nutrients like P, S, B and Zn in plots with BN as compared with FP (Figure 3), which apparently are responsible for residual benefits in the succeeding seasons. Better root growth and more shoot biomass addition under balanced nutrient management apparently accounted for

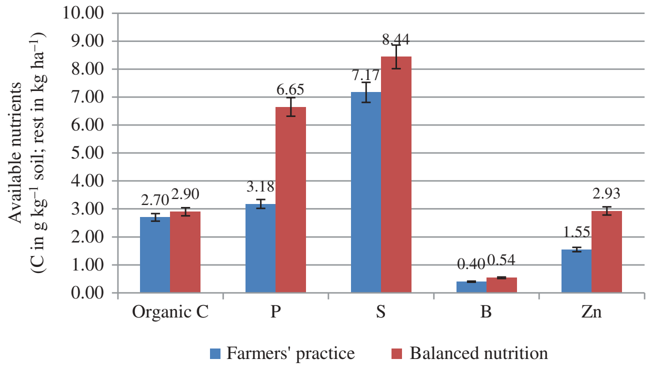

Figure 3. Effect of farmers' practice (FP) and balanced nutrition (BN) on post-harvest soil fertility status under rainy season groundnut in Nalgonda district during 2010.

higher soil organic C. Further, microbial biomass C is another pool which responds more rapidly to changes in soil management, and earlier studies have shown significant higher values of biomass C under improved management over the FP (Wani, Pathak, et al. 2003). A positive relationship of soil organic C with available P explains higher available P content in soil (Wani, Pathak, et al. 2003). Higher contents of S, B and Zn in BN plots are as expected due to their addition.

Residual effect of secondary and micronutrients

During rainy season 2012, one, two and four seasons residual effects of S, B and Zn, added during the post-rainy season of 2011–2012, rainy season of 2011 and rainy season of 2010 were recorded in cotton crop yields in Warangal district. Yield under FP was 2040–2050 kg ha^{-1}, but the plots with added S, B and Zn in previous seasons recorded additional residual benefits of 15%–24%. The soil test-based BN thus not only benefits farmers during the season of application but also leads to resilience-building of production systems.

Conclusions

Soil fertility depletion due to low levels of S, B, Zn P and soil organic C has been recognized as the major biophysical cause of low crop productivity in smallholder farmers' fields in SAT of Andhra Pradesh, India. Large number of on-farm trials proved soil test-based balanced fertilizer management as an effective strategy for significant and economic crop productivity improvement to address the issues of food security and smallholders livelihood improvement. Therefore, any program aimed at reversing the trend in declining agricultural productivity and improving farm livelihoods must begin with addressing soil fertility-related risks. However, majority of the farmers and stakeholders in general are unaware of the widespread deficiencies of secondary and micronutrients like S, B and Zn and do not include these nutrients in their fertilizer management practices. In absence of BN, farmers are apparently losing 8%–102% of current yield levels in season one and 15%–24% in each of the succeeding three to four seasons. The smallholders in the rainfed SAT in India or elsewhere are not in a position to implement the science-led strategy. So, there is a strong need for desired policy orientation by the respective governments to promote soil test-based BN strategies through appropriate economic and technological support for poor smallholders. For large-scale impact on farmers' fields, awareness building and convergence of different stakeholders like knowledge institutions, extension agencies and input companies are other important issues to be addressed. Establishment of centralized district level state of the art laboratories equipped to precisely diagnose the soil fertility constraints and to design appropriate BN management strategies should also receive desired attention in all the SAT regions. Taking the lead from such on-farm trials, the government of Andhra Pradesh has initiated a flagship initiative with the help from ICRISAT-led consortium to support the smallholders to improve productivity through soil test-based BN throughout the 22 districts in the state. However, to improve productivity and livelihoods of poor smallholders on a sustainable basis, such initiatives need to be replicated in other parts of the SAT worldwide.

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