Macro-benefits from Boron, Zinc and Sulfur Application in Indian SAT

A Step for Grey to Green Revolution in Agriculture

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Introduction

The mandate of the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) is to enhance the livelihoods of poor farmers in the semi-arid tropics (SAT) through integrated genetic and natural resource management (IGNRM) strategies. Majority of the people in the SAT depend on subsistence agriculture for livelihood. The productivity of crops in these areas is low as compared to those in irrigated agriculture. The major constraints for low productivity in the SAT regions are shortage of water and low soil fertility. Hence the soils in SAT are often referred to as thirsty and hungry soils.

Earlier research and development work in the SAT emphasized mainly increasing the availability of water to crops as well as reduction of soil erosion through various soil and water conservation structures in the watersheds. This structure-driven watershed developmental work neither impacted the productivity nor encouraged the farmers to participate in development and management of watersheds and maintain these structures once the implementing agency withdrew the support mainly because only a few resourceful farmers in the watershed benefited (Wani et al. 2003a). ICRISAT (Patancheru, India) in collaboration with the national agricultural research systems (NARSs), non-government organizations (NGOs), government departments and farmers developed a consortium model for development of sustainable watersheds, wherein the emphasis was shifted from mere conservation of soil and water to increased use efficiency of conserved resources such as water and soil through enhanced crop productivity and incomes, in partnership with farmers (Wani et al. 2003b).

In this approach, community-based soil and water conservation interventions were taken up in a participatory mode with farmers. Also farm-level interventions for conserving rainwater in situ and translating the benefits by overcoming constraints to individual farmers' crop productivity were implemented. Lack of appropriate soil, water and nutrient management practices at farm level were identified as the most important constraint for increasing crop productivity.

Reasons for Low Fertility in SAT Soils

The SAT soils are generally marginal compared to those in the irrigated or assured rainfall regions. Poor soils are brought under cultivation due to population pressure. The reserves of nutrients in these soils are low. Secondly, these soils have been under cultivation without much external input of nutrients for a long time, resulting in mining and depletion of scanty stocks of nutrients. Farmers avoided external nutrient inputs because of the risk of crop failure due to erratic rainfall in these regions unlike in the irrigated or assured rainfall regions where risks of crop failure are nil or minimal. Further, the rate of organic matter degradation in the SAT is relatively higher than in the temperate region due to prevailing high temperatures. These soils are prone to severe wind and water erosion, which take away nutrient rich fine top fertile soil layer.

In irrigated or assured rainfall regions, farmers used high-yielding cereal varieties (responsive to higher inputs) along with adequate nitrogen (N), phosphorus (P) and potassium (K) fertilizers, which ultimately resulted in the Green Revolution. The father of Green Revolution, Dr Norman Borlaug while accepting the Nobel Peace Prize in 1970 aptly said: "If the dwarf wheat varieties developed (by him) was the vehicle, the fertilizers were the fuel which produced high yields and triggered the Green Revolution in many developing countries including India." This synergy between improved genetic resources and adequate nutrient supply forms the basis of sustained increased productivity of rice and wheat for nearly three decades. In recent years the high productivity in irrigated agriculture is stagnating or declining in spite of supplying increasing NPK fertilizers. One of the major factors for this situation has been identified as inadequate supply of micronutrients.

Micronutrient deficiencies in irrigated production systems

In irrigated intensive crop production systems, use of high-yielding varieties along with increasing use of fertilizers containing major nutrients (N, P, K) but without micronutrients through inorganic or organic fertilizers dramatically increased crop production. As a result, this system depleted micronutrient reserves in the soil and caused a number of nutrient disorders and associated nutrient imbalances. A sharp decline in the available micronutrient status of soils is reported in irrigated agricultural production systems under continuous cropping with recommended rates of only major nutrients. For example, field-scale deficiencies of zinc (Zn) in rice and wheat on alluvial soils, iron (Fe) deficiency in sugarcane, upland rice, chickpea and groundnut on sandy calcareous soils, manganese (Mn) deficiency in wheat in rice-wheat systems on sandy soils and boron (B) deficiency in chickpea and rice on high pH calcareous soils have been reported, mostly in intensified production systems. The deficiencies of micronutrients are of critical importance for sustaining high productivity in some areas of India. Among these, Zn deficiency is most prevalent in intensively cropped light-textured, alkaline soils. Boron deficiency has become more critical for cropping systems on highly calcareous soils, sandy leached soils, limed acid soils and reclaimed soil (Takkar, 1996). As an example, the amounts of micronutrients removed in one year in a few major cropping systems under intensified production system are given in Table 1. It is clear that the micronutrient removal by various cropping systems varies with crops. Soil analysis of major soil series in India clearly indicated that Zn is the most limiting micronutrient. According to estimates made on the total and available micronutrient status, it is suggested that the soil Zn reserves would be just enough for 165 to 384 years. It is assumed that there is no loss of surface soil by erosion because most micronutrients are in the topsoil layer. The soil reserve of B should last for 266 to 558 years and that of molybdenum (Mo) for 419 years.

The Indian soils have been under intensive cultivation for hundreds of years and the deficiencies of various micronutrients are not surprising. However, in the case of irrigated production systems deficiencies have been appearing gradually as they were monitored by soil and plant analysis. Thus, the deficiencies of different micronutrient elements are now visible.

Micro and secondary nutrient deficiencies in drylands of SAT India

Under dryland agriculture, especially in the SAT regions with subsistence agriculture, the situation differs from that under irrigated, intensified systems. Most of the soils are marginal and frequent droughts of various intensities result in low yields. Farmers have noticed responses to small quantities of N, P and K fertilizers and most of the farmers do apply some amount of fertilizers for comparatively high-value crops like groundnut, maize, castor and sorghum. Thus, these crops mine the limited stocks

Table 1. Amount of micronutrients removed by major intensified production systems in India.

Cropping system	Total grain yield (t ha^{-1})	Nutrients removed (g ha^{-1})					
		Zn	Fe	Mn	Cu	B	Mo
Rice-rice	8.0	320	1224	2200	144	120	16
Rice-wheat	8.0	384	3108	2980	168	252	16
Maize-wheat	8.0	744	7296	1560	616	-	-
Soybean-wheat	6.5	416	3362	488	710	-	-
Pigeonpea-wheat	6.0	287	4356	493	148	-	-

Source: Takkar (1996).

of micronutrients and secondary elements from the marginal soils, resulting in their decline in these soils. Table 2 gives the amounts of micro and secondary nutrients removed by various crops under rainfed dryland conditions. Even though the quantities of nutrients removed are small when compared to irrigated crops because of low yields, deficiencies do occur due to relatively small reserves in these marginal soils. Further, the application of farmyard manure (FYM) was a common practice both in irrigated and dryland agriculture as a source of nutrients before the widespread use of NPK fertilizers. The FYM and other organic manures supply small quantities of micro and secondary nutrients. In recent years, the availability of FYM and organic manures and the quantity applied have declined drastically resulting in micronutrient deficiencies. The problem of secondary and micronutrients is severe in drylands, as farmers preferentially apply whatever available small quantities of organic manure to irrigated rice, vegetables and cash crops like cotton and horticultural crops. Low-value crops like sorghum, millet, etc receive small quantities of FYM, once in 3 to 4 years in some cases. Dryland farmers apply small quantities of N, P and K fertilizers to complement nutrients from other sources. Policy distortions also led to imbalanced use of fertilizers. For example, subsidy on N containing urea and diammonium phosphate (DAP) resulted in more use of these fertilizers instead of single super phosphate (SSP) containing sulfur (S), leading to widespread S deficiency. Improper crop management in drylands due to inadequate supply of nutrients and other inputs results in poor growth of crops which in turn results in poor canopy development and more soil erosion due to downpour during the rainy season. Thus the nutrient-rich topsoil is eroded resulting in various nutrient deficiencies.

Table 2. Mean yield and uptake of nutrients by crops grown in APRLP watersheds, Andhra Pradesh, India in 2002.

	Stover yield ($t\ ha^{-1}$)		Grain yield ($t\ ha^{-1}$)		Total nutrients removed ($g\ ha^{-1}$)					
					Control			Treated		
Crop	Control	Treated	Control	Treated	S	B	Zn	S	B	Zn
Mung bean	0.73	1.00	0.77	1.11	2325	20	46	4009	30	68
Maize	3.46	4.29	2.73	4.56	4536	16	112	7014	19	192
Groundnut	1.99	2.49	0.70	0.94	4355	40	50	6418	52	81
Pigeonpea	1.31	2.10	0.54	0.87	1619	22	27	2649	36	45
Castor	0.82	1.19	0.59	0.89	2216	18	40	3550	26	62

Approach to Tackle Micro and Secondary Nutrient Deficiencies

As a part of an innovative farmer participatory consortium model for integrated watershed management, we used Decision Support System (DSS) crop simulation model to estimate the yield gap for selected crops (Piara Singh et al. 2002). Based on the yield gap for soybean between the existing farmers' crop yields and potential achievable yields with simulation studies, appropriate soil, water and nutrient management (SWNM) options were evaluated in partnership with the farmers. To scale-up the evaluation of technologies and benefits from research watershed (15–20 ha) to community watershed (500 ha) and to the agroecoregion level, we adopted the approach of benchmark watersheds in the target ecoregion. Further scaling-up within the district and ecoregion was done through nucleus and satellite watersheds approach under the Andhra Pradesh Rural Livelihoods Programme (APRLP) and Tata-ICRISAT-ICAR project in selected states of India (Wani et al. 2003b, 2003c) (Figs. 1 and 2). In the process of scaling-up the nucleus watershed, NGOs and farmers acted as trainers for their respective peer groups with technical support from the consortium partners.

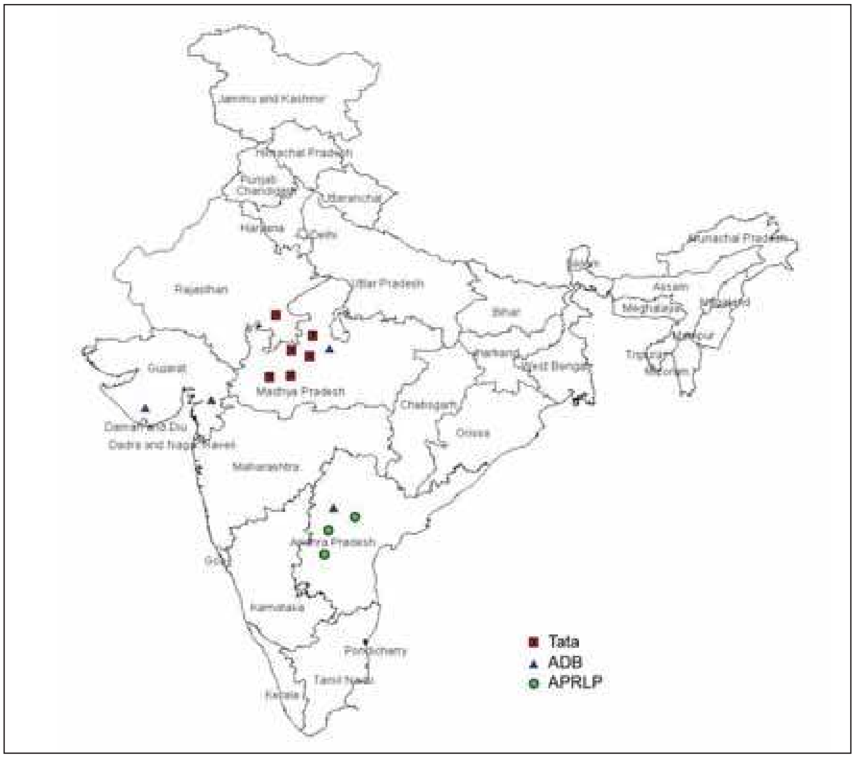

Figure 1. Watershed locations in India.

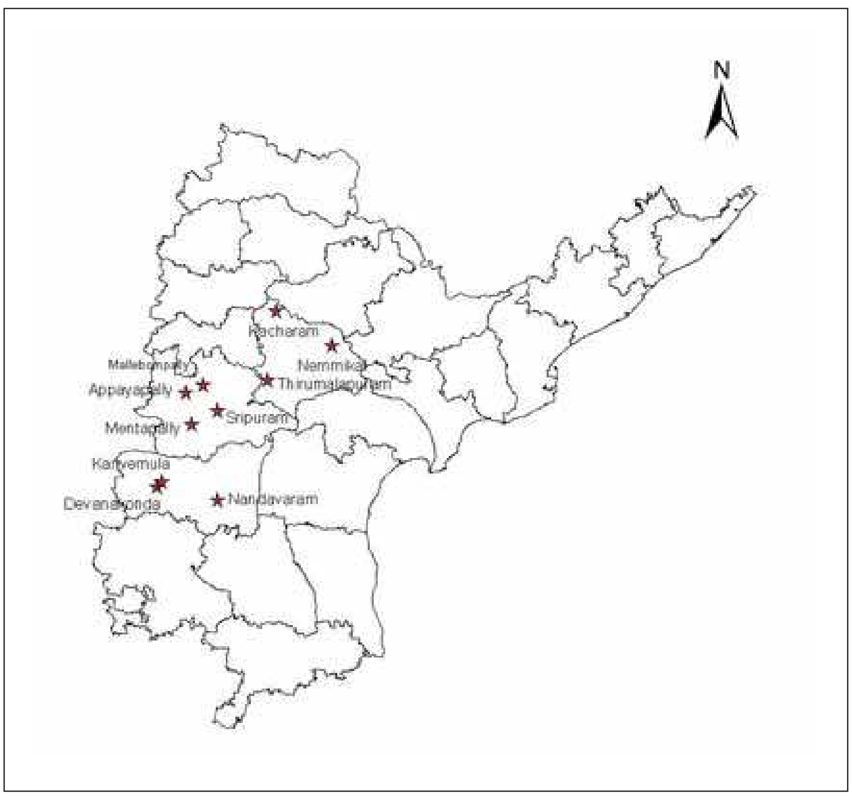

Figure 2. APRLP watersheds in Andhra Pradesh, India.

During 1999, a large yield gap of 2 t ha^{-1} for soybean was observed in Madhya Pradesh, India between predicted potential yield (using crop model) and actual yield on farmers' fields (Piara Singh et al. 2002). We selected Lalatora in Vidisha district of Madhya Pradesh and Adarsha watershed, Kothapally, Ranga Reddy district of Andhra Pradesh, India as benchmark watersheds to scale-up our findings from on-station research watershed at ICRISAT to community watersheds. During the participatory rural appraisal (PRA) with the farmers of Lalatora and Adarsha watersheds, the potential yields in their fields versus actual yields obtained by them were discussed. Farmers informed that more and more nutrient inputs, mainly fertilizers, are required even to get current yields year after year. This provided first hand information on the extent of soil degradation through nutrient-depletion. To confirm and quantify the extent of nutrient depletion in the watersheds, baseline soil characterization was conducted. The analysis of soil samples from a few representative fields in the microwatersheds (500–750 ha) indicated deficiencies of B and S. The results of soil analysis, its implication on crop productivity and possible solutions through amendments were discussed with the farmers in group meetings. Such discussions enabled the farmers to take decisions for undertaking evaluation trials on the fields. As the approach adopted no free inputs, the users have to pay the costs and no underwriting of evaluation trials was done. Only farmers willing to adopt the approach were encouraged to undertake trials. This approach helped to identify genuinely interested farmers and also avoided the criticism of favoritism in the community for so called demonstration trials. The results of these participatory evaluation trials showed 18 to 53% more grain yields of soybean, maize and sorghum in Lalatora and Adarsha watersheds.

Besides farmers' inputs 30 kg S ha^{-1} as gypsum (200 kg ha^{-1}) and 1.0 kg B ha^{-1} (10 kg borax ha^{-1}) were applied in farmers' fields at Lalatora watershed. Farmer input plots served as control. Soybean responded to the application of B and S during 2000, 2001 and 2002. The first year (2000) was a normal rainfall year and 26% increase in grain yield was observed for a combined application of B and S. During the second year (2001), a less favorable rainfall year, yield increase was only 18% while during 2002, it was maximum (53%) (Table 3). The residual effects of these micronutrients were quite significant in the following wheat crop during 2000 where 18% increase in grain yield of wheat was observed. But in the drought year of 2001, the response was less than 5%. As an example of the magnitude of response and net profit during 2000, the average of all on-farm trials on soybean-wheat system is given in Table 4. It is clear from the data that soybean grain yield for combined application of B+S treatment was 1.77 t ha^{-1} while it was only 1.40 t ha^{-1} in control. Grain yield of the following wheat crop was 3.7 t ha^{-1} in treated plots while control plot yielded 2.7 t ha^{-1} of wheat grain. The net profit from soybean-wheat system was Rs 26,450 ha^{-1} in treated plots compared to Rs 17,760 ha^{-1} in control plot.

During the same period similar research work was also carried out in Adarsha watershed. The major cereal crops, sorghum and maize, grown by farmers responded to B and S application. Increase in sorghum grain yield ranged from 13 to 29% while increase in maize grain yield was 20 to 39% over

Table 3. Soybean grain yield response to applied boron (B) and sulfur (S) in farmers' fields at Lalatora watershed in Madhya Pradesh, India during 2000–02.

	Grain yield (t ha^{-1})			
Year	Control (Farmers' input)	B	S	B+S
2000	1.40	1.73 (23)[1]	1.74 (24)	1.77 (26)
2001	1.24	1.39 (12)	1.38 (12)	1.47 (18)
2002	1.18	1.44 (22)	1.54 (31)	1.79 (53)

1. Figures in parentheses indicate percentage increase over control.

Table 4. On-farm performance of soybean and wheat to applied boron (B) and sulfur (S) in Lalatora watershed in Madhya Pradesh, India during rainy season 2000.

	Grain yield (t ha^{-1})			Net profit
Treatment	Soybean	Wheat	Soybean + wheat	(Rs ha^{-1})
B (1 kg ha^{-1})	1.73	3.60	5.03	26610
S (30 kg ha^{-1})	1.74	3.50	5.24	25960
B + S	1.77	3.70	5.47	26450
Control (Farmers' input)	1.40	2.70	4.10	17760

Table 5. Total productivity of sorghum and maize with boron (B) and sulfur (S) amendments at Adarsha watershed, Kothapally, Andhra Pradesh, India during 2001.

	Sorghum yield (t ha^{-1})			Maize yield (t ha^{-1})		
Treatment	Gain	Straw	Total productivity	Gain	Straw	Total productivity
Control	1.46	2.80	4.26	1.96	2.36	4.32
B	1.65	3.03	4.68	2.36	2.64	5.00
S	1.89	3.32	5.21	2.73	2.84	5.56
B + S	1.80	3.49	5.29	2.58	3.06	5.64

control. Table 5 gives the increase in productivity of sorghum and maize due to the application of B and S.

Based on the impressive overall results from the benchmark watersheds in Kothapally, Lalatora, Than Ha (Vietnam) and Tad Fa (Thailand), the funding support by the Asian Development Bank (ADB) was approved with another grant to scale-up this work to other locations in the target ecoregion. Meanwhile APRLP, funded by the UK Department for International Development (DFID), also selected the Kothapally watershed model for scaling-up in Kurnool, Mahbubnagar and Nalgonda districts of Andhra Pradesh. Sir Dorabji Tata trust came forward to extend on-farm watershed experiences to two districts (Guna and Dewas) in western Madhya Pradesh and one district (Bundi) in eastern Rajasthan. In all these benchmark watersheds biophysical and social surveys were conducted as a first step to identify the constraints for increased crop productivity. As a part of this baseline survey, soil characterization was undertaken to identify any nutrient deficiencies as per our earlier experience in Lalatora and Kothapally. The stratified random sampling methodology was adopted to identify the deficient nutrients in the soil and these deficiencies were confirmed through on-farm trials.

Representative Soil Sampling in Community Watersheds

Most of the watersheds in India are about 500 ha (microwatershed) and the number of farmers cultivating the arable land varied across the watersheds. Even within a benchmark watershed, the size of farm holdings varied greatly. To have an efficient, cost-effective and representative sampling strategy, a stratified random sampling was developed for each watershed. We assumed that soil fertility of any given field mainly depends on two factors: (1) soil inherent fertility; and (2) input quantities by farmers. Further, in each watershed we assumed that the particular type of soil such as black soil or red soil or loamy soil should have similar inherent fertility because these soils were under cultivation for many years. Soil fertility might be dependent mainly on the farmer's inputs, which in turn depends on the resourcefulness of the farmer's status, ie, big or small landholder.

The landholding of a farmer was used as surrogate for socioeconomic study of the family. As a first step, through rapid rural appraisal (RRA), the watershed was divided into three groups based on the position of fields on a toposequence, ie, top, middle and bottom, and also on the elevation and drainage pattern. Further, farmers were categorized into big, medium and small holders in each watershed and the number in each group was recorded based on farmers' information. For example, in Andhra Pradesh small farmers had <2.0 ha, medium 2–5 ha and big >5 ha, while in Madhya Pradesh as the holding size was large, the area under each category was much larger (small <5 ha, medium 5–10 ha and large >10 ha). Considering farm-holding size in each category in the proportion of occurrence on each toposequence, 20% fields were randomly selected for sampling. In each farmer's field, we selected a major crop growing plot and collected 8 to 10 cores of samples from 0–15 and 15–30 cm depth (Fig. 3); two samples from each farmer were collected with details of soil type, crop, etc. These samples were air dried and powdered with a wooden hammer and passed through 2-mm sieve for analysis. Another lot of soil samples were finely powdered and passed through 100-mesh sieve for analysis. All the ground samples were analyzed in ICRISAT laboratory for parameters such as pH, EC, organic carbon (C), total N, Olsen P, available K, available S, available Zn and available B.

Table 6 gives the critical levels of different nutrient elements in soil and plant tissues below which level that particular element is considered deficient in the soil or plant. The nutrient status of soils from the benchmark watersheds of six states (Andhra Pradesh, Madhya Pradesh, Rajasthan, Gujarat, Haryana and Tamil Nadu) are summarized in Tables 7 and 8. Using the critical limits in the soil, it was observed that most of the soils were deficient in major nutrients like N, P and organic C. But the most revealing results are about micronutrients and secondary nutrients like S. In the watersheds of Nalgonda district of Andhra Pradesh, soil samples from 99% of farmers' fields were deficient in

Figure 3. Collection of soil samples in Mentepally watershed, Mahbubnagar district, Andhra Pradesh, India.

Table 6. Critical limits (CL) in the soil and plant issue (fully developed youngest leaf) for micronutrient deficiencies in field crops.

Element	Soil		Plant tissue
	Extractant	CL (µg g^{-1})	CL (µg g^{-1})
Zn	DTPA[1]	0.6	10–20
Mn	DTPA	2.0	15–25
Fe	DTPA	2.5–4.5	50
Cu	DTPA	0.2	2–5
B	Hot water	0.5	5–30
Mo	Ammonium oxide (pH 3.5)	0.2	0.03–0.15

1. DTPA = Diethylene triamine pentaacetic acid.
Source: Katyal and Rattan (2003).

available B, 94% of farmers' fields were deficient in available Zn and 89% of farmers' fields were deficient in available S. In Mahbubnagar district, soil samples from 98% of farmers' fields were deficient in available B, 83% of farmers' fields were deficient in available Zn and 89% of farmers' fields were deficient in available S. Similarly in Kurnool district, soil samples from 92% of farmers' fields were deficient in available B, 81% were deficient in available Zn and 88% in available S.

In Bundi district of Rajasthan, soil samples from 67% of farmers' fields were deficient in available Zn, 72% in available B and 72% in available S.

These results from soil analysis demonstrated a widespread deficiency of B, Zn and S in farmers' fields in the watersheds in six states of India. The deficiency is especially severe in the states of Andhra Pradesh, Madhya Pradesh and Gujarat. The sample size of Andhra Pradesh is large, and clearly indicates that the micronutrient deficiency in the drylands of other districts of the state with light-textured soil could indeed be as widespread. In Tamil Nadu too 100% deficiency of S, B and Zn was observed in a watershed in Tirunelvelli district where it was under grass without cultivation for 20 years. Clearly, there is a need to use these results for developing site-specific nutrient management strategies for increasing productivity of rainfed systems sustainably.

Following the baseline survey of soil samples for micronutrient status, simple on-farm trials to confirm these deficiencies and means to overcome them were designed. Farmer participatory meetings were conducted in each benchmark/nucleus watershed, where nutrient status of the fields was discussed and volunteer farmers were identified to conduct field trials.

Knowledge-based Entry Point in Watersheds

To build a rapport between the project implementing agency (PIA) and the villagers before initiating the watershed programs, an entry point activity is envisaged. The entry point intervention/activity is identified through PRA. The Government of India (GOI) watershed guidelines mention a specific budgetary allocation (Rs 80,000) for the entry point activity. In the innovative farmer participatory consortium model for watershed management by ICRISAT-led consortium, one of the important components is no subsidy for interventions on private farm lands. For scaling-up the benefits from benchmark watersheds to the target agroecoregional level we have adopted the nucleus and satellite watersheds approach. Consciously the consortium partners decided to use the results of baseline soil characterization as a knowledge-based entry point activity for rapport building in nucleus and satellite watersheds. This technique has been standardized since 1999 and was successfully applied during the scaling-up process under the APRLP-ICRISAT and Tata-ICRISAT-ICAR consortium projects.

Table 7. Results of soil analysis across three districts in Andhra Pradesh, India, 2002–03[1].

District	No. of farmers	pH	EC (dS m^{-1})	Total N (ppm)	Available nutrients (mg kg^{-1}) P	K	S	Zn	B	Organic C[2]
Mahbubnagar	262	7.1	0.12	342	8.6	104	4.5	0.52	0.15	0.3
		5.4–9.1	0.03–0.56	123–783	0.7–61.0	25–416	1.2–30.8	0.1–1.5	0.02–0.74	0.1–0.8
				100	37	7	89	83	98	59
Nalgonda	176	7.7	0.15	410	7.6	130	4.4	0.4	0.21	0.4
		5.7–9.2	0.02–0.58	144–947	0.7–35.2	34–784	1.4–50.5	0.1–2.2	0.02–0.80	0.1–1.0
				100	39	3	89	94	99	80
Kurnool	223	7.8	0.2	295	7.9	127	4.4	0.4	0.27	0.3
		5.9–9.7	0.03–1.84	26–966	0.4–31.5	33–335	1.4–24.7	0.1–1.2	0.04–1.48	0.1–0.8
				100	40	8	88	81	92	91
Critical limits			<0.8 (normal)				8–10	0.75	0.58	
Low				500–1200	<5	<50				<0.5
Medium				1200–2500	5–10	50–125				0.5–0.75
High				>2500	>10	>125				>0.75

1. Values for each district in a column represent mean, range and percentage of deficmient fields.
2. Data are percentage values.

Table 8. Extractable (available) zinc (Zn), boron (B) and sulfur (S) status of soil in farmers' fields in different locations in six states of India.

Location	No. of farmers' fields	Extractable Zn ($\mu g\ g^{-1}$)			Extractable B ($\mu g\ g^{-1}$)			Extractable S ($\mu g\ g^{-1}$)		
		Min		Max	Min		Max	Min		Max
Andhra Pradesh										
Nalgonda	176	0.08		2.20	0.02		0.8	1.4		50.5
(% deficient fields)			94			99			89	
Mahbubnagar	262	0.12		1.38	0.02		0.74	1.1		30.8
(% deficient fields)			83			98			89	
Kurnool	223	0.10		1.18	0.04		1.48	1.3		24.7
(% deficient fields)			81			92			88	
Madhya Pradesh										
Vidisha	12	0.16		0.96	0.65		1.2	3.2		5.35
(% deficient fields)			92			0			100	
Dewas	24	0.12		0.56	0.2		0.8	3.9		9.5
(% deficient fields)			100			96			100	
Guna	18	0.24		1.74	0.6		2.2	2.6		14.2
(% deficient fields)			78			0			89	
Rajasthan										
Bundi	36	0.20		1.8	0.1		0.98	3.2		50.9
(% deficient fields)			67			72			72	
Gujarat										
Bharuch Kutch	82	<0.2		2.45	0.06		0.49	1.1		150.4
(% deficient fields)			85			100			40	
Haryana										
Gurgaon	30	<0.2		0.87	0.09		0.85	<0.3		90.8
(% deficient fields)			89			93			60	
Tamil Nadu										
Tirunelvelli	12	<0.2		<0.2	0.08		0.26	<0.3		3.4
(% deficient fields)			100			100			100	

Following the stratified sampling procedure through PRA, the randomly selected farmers collected the soil samples along with the technical experts and the samples were analyzed. The results were tabulated in local language along with the necessary interpretation details and explained to the farmers in a group meeting (Fig. 4). The farmers from the nucleus watersheds explained the results of their evaluation trials to the satellite watershed farmers. This exercise led to building a strong trust with satellite watershed farmers. The rapport and trust starts building through a knowledge-based entry point delivering a key message that no subsidies would be flowing in this approach.

Andhra Pradesh

In the first year (2002) farmer participatory meetings were conducted in all the 9 nucleus watersheds in 3 districts in Andhra Pradesh. After discussing the nutrient status of their fields, 15 volunteer farmers from each nucleus watershed were identified for conducting on-farm trials. We had only two treatments, ie, control (farmers' nutrient inputs) and application of micronutrients (30 kg S ha^{-1},

Figure 4. Technical experts discuss soil analysis results with farmers in Nemmikal watershed, Nalgonda district, Andhra Pradesh, India.

0.5 kg B ha^{-1} and 10 kg Zn ha^{-1}) in addition to farmers' nutrient inputs (Fig. 5). We imposed these treatments in 0.2-ha plots side by side. Farmers' variety of crops and crop management were uniform in both the treatments. In all we had nearly 150 trials in 3 districts using different test crops like mung bean, maize, sorghum, groundnut, pigeonpea and castor. Each farmer for a particular crop was treated as a replication. Thus maize trials were conducted in 22 farmers' fields, groundnut in 19, mung bean in 9, pigeonpea in 43, and castor in 8 fields. Due to drought condition some trials were abandoned. Impressive responses of grain yield to applied nutrients were obtained in all crops (maize 65%, groundnut 33%, mung bean 43%, pigeonpea 63% and castor 50%). The grain yield of different crops in micronutrient-treated plots is given in Table 9. Farmers not only harvested more grain yields, but also benefited economically by spending only Rs 1750 ha^{-1} for these micronutrients over and above their other nutrient inputs (Figs. 6 and 7). For example, in Mahbubnagar, net economic gain for maize was Rs 8200 ha^{-1} while that for pigeonpea was Rs 2900 ha^{-1} in maize/pigeonpea cropping system. In

Figure 5. Mixing (left) and application (right) of micronutrients in on-farm trials in Kacharam watershed, Nalgonda district, Andhra Pradesh, India.

Table 9. Crop response to micronutrients in watersheds in Andhra Pradesh, India, 2002/03.

Watershed	Crop	Grain yield (t ha^{-1}) Control	Treated	Yield increase over control (%)
Mahbubnagar				
Sripuram	Maize	2.38	4.37	84
	Pigeonpea[1]	0.24	0.42	75
Malleboinpally	Maize	2.98	4.57	53
Mentepally	Maize	1.20	1.74	45
Nalgonda				
Tirumalapuram	Castor	0.43	0.64	49
	Pigeonpea[1]	0.41	0.46	12
Nemmikal	Mung bean	0.84	1.10	31
	Pigeonpea[1]	0.35	0.66	89
Kurnool				
Karivemula	Groundnut	1.44	1.96	36
	Pigeonpea[1]	0.13	0.33	154
Devanakonda	Groundnut	0.94	1.24	32
	Pigeonpea[1]	0.23	0.50	117
Nandavaram	Castor	0.86	1.29	50
	Pigeonpea[1]	1.63	2.64	62

1. Represents intercrop.

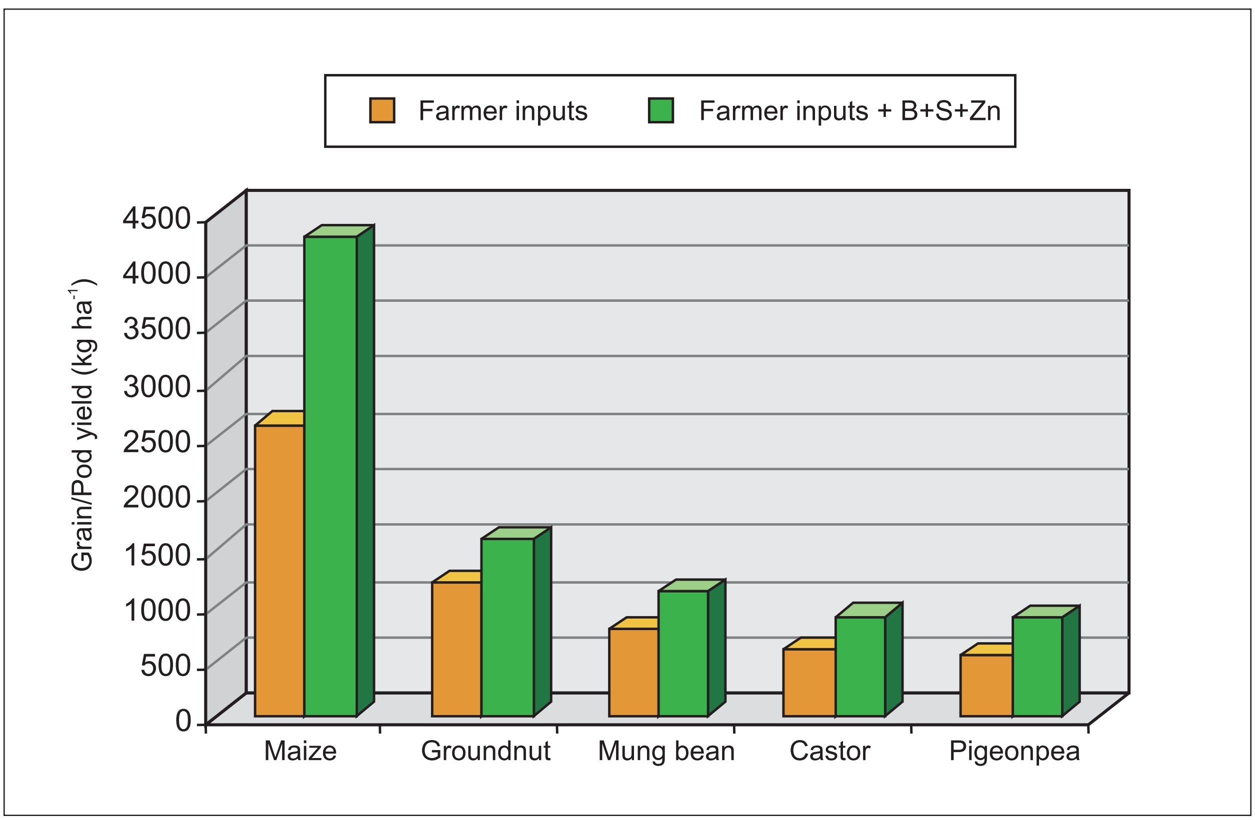

Figure 6. Grain/pod yields of various crops with micronutrients in the APRLP watersheds in three districts in Andhra Pradesh, India during 2002 rainy season.

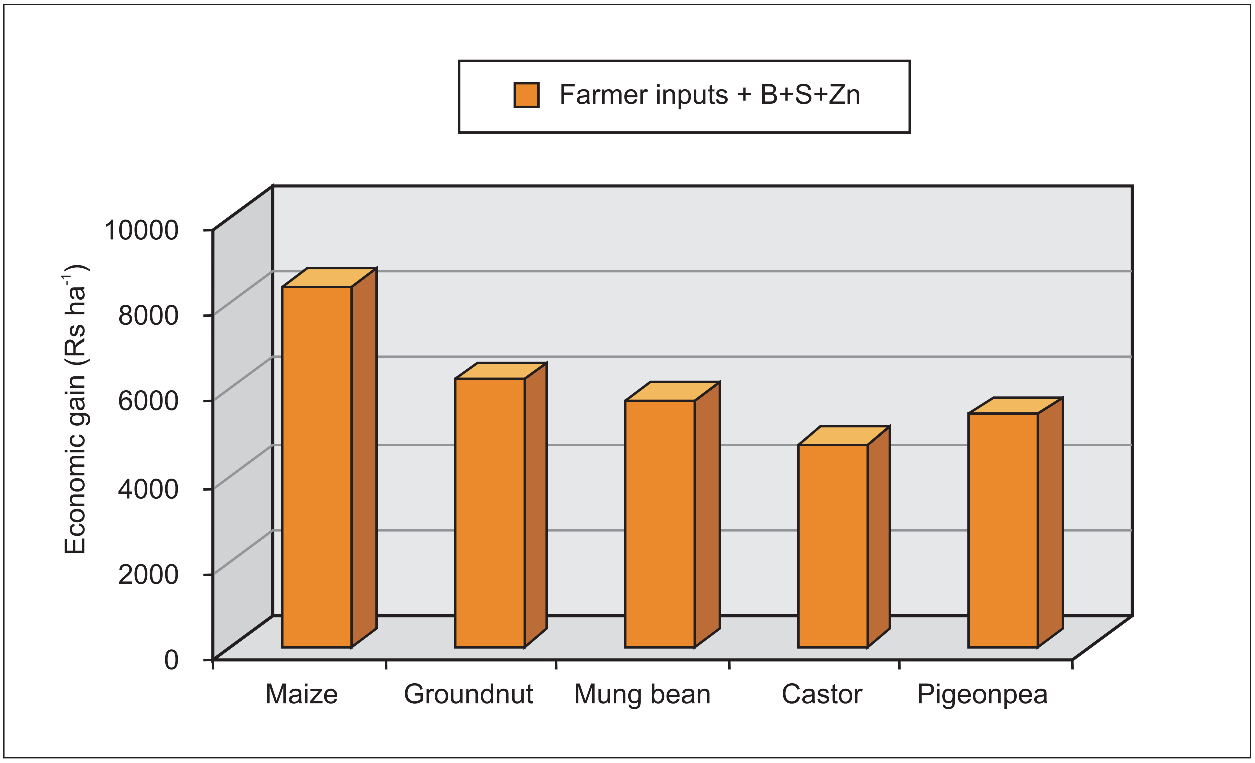

Figure 7. Economic gains due to micronutrient application to various crops in the APRLP watersheds in three districts in Andhra Pradesh, India during 2002 rainy season.

Nalgonda, net economic gain for castor was Rs 1600 ha^{-1} while that for mung bean was Rs 2700 ha^{-1}. In Kurnool net economic gain for groundnut was Rs 6500 ha^{-1} while that for pigeonpea was Rs 3200 ha^{-1} in groundnut/pigeonpea cropping system.

During 2003, in addition to 9 nucleus watersheds under the APRLP we scaled-up the watershed interventions for enhancing agricultural productivity to additional one nucleus and 40 satellite watersheds. Thus we had a total of 50 watersheds. Again, we collected stratified soil samples in the new watersheds and analyzed them for nutrient status. We conducted farmer participatory meetings in all the nucleus (10) watersheds. For each meeting we invited farmers from 4 satellite watersheds in each nucleus watershed. In the meeting we discussed the results of soil analysis from farmers' fields and the volunteer trial farmers shared their experiences with other farmers (Fig. 8). Following this approach, we identified 3 volunteer farmers from each watershed. Unlike the previous year we increased the treatments and reduced the plot size. In addition to previous two treatments we evaluated treatments with the application of only B, only Zn, only S, and B+Zn+S with and without optimum N and P. These treatments were given over and above farmers' nutrient inputs. In each treatment the plot size was about 0.2 ha. Our objectives were to find out the response to individual deficient element, combined application at farmers' nutrient input level and combined application at optimum N and P level. Combined application of micronutrients at optimum N and P level gave the maximum response and the additive response to each deficient element at this level was obtained. At farmer input level, the full potential of S, Zn and B would not have been obtained because of inadequate supply of N and P. This was proved by an increased response in yield of various crops to application of S, Zn and B along with N and P. Thus in maize 51% and 76%, in sorghum 41% and 61%, in groundnut 47% and 78%, in mung bean 41% and 61%, in pigeonpea 71% and 90% and in castor 54%

Figure 8. Technical experts discuss crop response to micronutrient application with farmers in Tirumalapuram watershed, Nalgonda district, Andhra Pradesh, India.

and 70% responses were obtained by combined application of B, Zn and S at farmer nutrient input level and at optimum N and P level (Figs. 9, 10 and 11; Table 10).

Madhya Pradesh

In Lalatora watershed (Vidisha district), soil analysis indicated that in addition to B and S, Zn was also deficient in many farmers' fields. In Guna watershed also S and Zn were found deficient and in Dewas watersheds S, B and Zn were deficient. Both in Dewas and Guna on-farm trials on the application of these deficient elements were conducted on volunteer farmers' fields. Based on our

Figure 9. Response of groundnut to micronutrients in Karivemula watershed, Kurnool district, Andhra Pradesh, India.

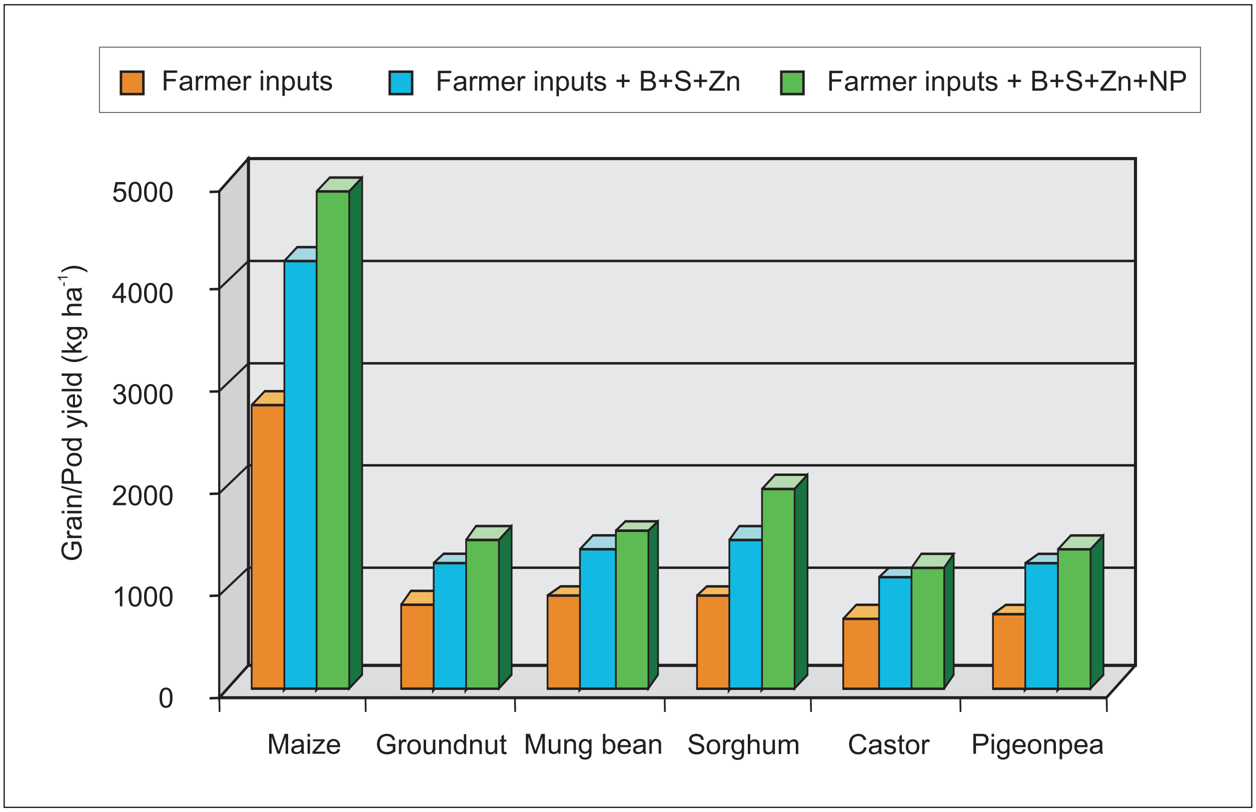

Figure 10. Yields of various crops with micronutrients and other inputs in the APRLP watersheds, Andhra Pradesh, India during 2003 rainy season.

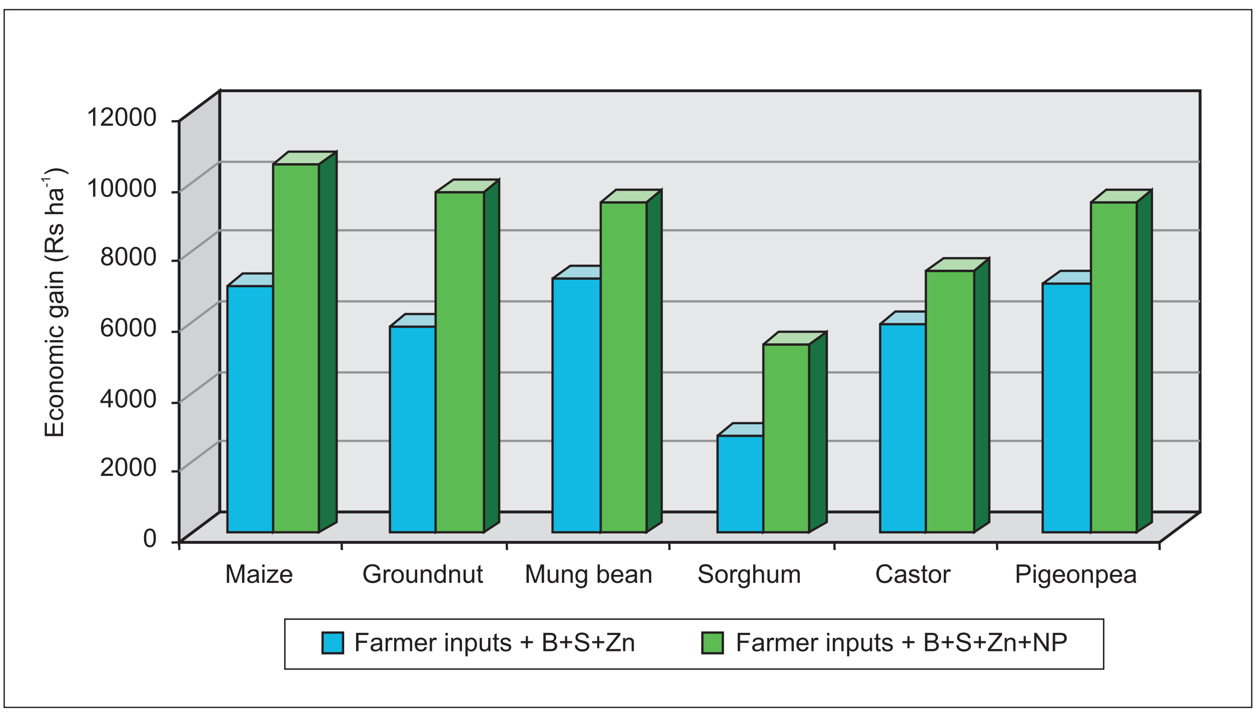

Figure 11. Economic gains due to micronutrient application to various crops in the APRLP watersheds in three districts in Andhra Pradesh, India during 2003 rainy season.

Table 10. Crop response to micronutrients in watersheds in Andhra Pradesh, India, 2003/04.

District	Crop	No. of farmers	Grain yield[1] (t ha^{-1}) Control	Control + MN		Control + MN + NP	
Mahbubnagar	Maize	14	3.34	4.58	(37)	5.17	(55)
	Sorghum	6	0.90	1.46	(62)	1.97	(119)
	Castor	8	0.94	1.38	(48)	1.65	(77)
	Pigeonpea	3	0.86	1.48	(71)	1.88	(118)
Nalgonda	Maize	10	2.01	3.60	(80)	4.46	(122)
	Mung bean	6	0.91	1.39	(54)	1.54	(70)
	Castor	9	0.48	0.76	(59)	0.78	(64)
	Groundnut (pod)	7	0.62	0.93	(49)	1.14	(84)
	Pigeonpea	5	0.65	1.21	(88)	1.22	(90)
Kurnool	Groundnut (pod)	23	0.90	1.32	(47)	1.59	(77)
	Pigeonpea	4	0.70	1.06	(50)	1.20	(70)

1. MN = Micronutrients; NP = Optimum nitrogen and phosphorus.
Figures in parentheses indicate percentage increase over control.

previous work, a large number of farmers in Lalatora have started using these micronutrients in addition to normal P fertilizers. In all the three microwatersheds (Kailashpur, Baroda Kala and Banjari Barri) in Guna district, application of B and S together significantly improved soybean grain and haulm yields (Table 11). The increase in grain yield was 83% and in haulm yield was 74% over control. Some farmers in Guna watersheds evaluated the residual benefits of B and S application on chickpea and wheat following soybean, which had received B and S amendments in the rainy season. Chickpea responded to residual S as well as to B. The highest response was observed to residual S, which was approximately 68% higher chickpea grain yield over control (Table 12). In the case of wheat also residual benefits of B and S were observed (Table 13). Significant net returns were obtained due to the residual benefits of rainy season amendments. Based on soil analysis results, on-farm trials were also conducted on chickpea and wheat during the postrainy season of 2002 in Guna watersheds. Results clearly showed the response of chickpea and wheat to direct application of Zn, S and Zn+S (Tables 14 and 15). These amendments not only increased chickpea yields up to 60% and wheat yields by 40% over control, but also improved net returns, resulting in higher benefit-cost ratio. These results demonstrated that widespread deficiencies of micro and secondary nutrients existed in rainfed areas. Further, amendments with deficient nutrients increased economic yields as well as economic benefits from the rainfed systems.

Table 11. Effect of boron (B) + sulfur (S) application on grain and haulm yields (t ha^{-1}) of soybean in Guna district, Madhya Pradesh, India 2002/03.

	Kailashpura		Baroda Kala		Banjari Barri		Pooled yield	
Treatment	Grain	Haulm	Grain	Haulm	Grain	Haulm	Grain	Haulm
Control[1]	0.66	0.92	0.84	1.05	0.71	0.96	0.74	0.98
B + S	1.08	1.63	1.35	1.58	1.59	1.88	1.34	1.70
SE ±	0.097	0.089	0.073	0.108	0.103	0.100	0.094	0.098
CD at 5%	0.28	0.25	0.22	0.31	0.30	0.29	0.261	0.28

1. In control plot farmer's own seed from previous year's harvest or seed procured from cooperative society was used whereas in other plots Mahyco seed was used.

Table 12. Residual effect of boron (B), sulfur (S) and B+S applied to soybean on grain and haulm yield of chickpea in Guna district, Madhya Pradesh, India during postrainy season 2002.

	Yield (t ha^{-1})		Yield increase (%) over control	
Treatment	Grain	Haulm	Grain	Haulm
B (1 kg ha^{-1})	1.61	1.66	54	10
S (30 kg ha^{-1})	1.76	1.92	68	27
B + S	1.55	1.79	48	18
Control	1.05	1.51	-	-

Table 13. Residual effect of boron (B), sulfur (S) and B+S applied to soybean on grain and straw yield of wheat and economic benefits in Guna disrict, Madhya Pradesh, India during postrainy season 2002.

	Yield (t ha^{-1})		Cost of cultivation	Gross returns	Net returns	Benefit-
Treatment	Grain	Straw	(Rs ha^{-1})	(Rs ha^{-1})	(Rs ha^{-1})	cost ratio
B	2.58	2.92	13170	29290	16425	2.24
S	2.98	3.25	13170	33720	20550	2.56
B + S	2.85	3.00	13170	31840	18670	2.41
Control	1.93	2.33	13170	22620	9450	1.71
SEm ±	0.069	0.077	-	108.1	73.0	0.068

Table 14. Effect of micronutrients and best-bet option treatments on grain and haulm yields and economics of chickpea in Guna district, Madhya Pradesh, India during postrainy season 2002.

	Yield (t ha^{-1})		Cost of cultivation	Gross returns	Net returns	Benefit-
Treatment	Grain	Haulm	(Rs ha^{-1})	(Rs ha^{-1})	(Rs ha^{-1})	cost ratio
Zinc (Zn)	1.87	2.12	12500	32050	19550	2.56
Sulfur (S)	1.75	2.13	12230	30130	17900	2.46
Zn + S	2.05	2.39	13570	35210	21640	2.59
Zn + S + SSP[1]	2.17	2.59	14210	37390	23180	2.63
Control	1.33	1.65	10480	22920	12440	2.18
SEm ±	0.069	0.051	-	94.59	71.66	0.052

1. SSP = Single superphosphate.

Table 15. Effects of micronutrient amendments and best-bet option treatments on grain and straw yield and economics of wheat in Guna district, Madhya Pradesh, India during postrainy season 2002.

	Yield (t ha^{-1})		Cost of cultivation	Gross returns	Net returns	Benefit-
Treatment	Grain	Straw	(Rs ha^{-1})	(Rs ha^{-1})	(Rs ha^{-1})	cost ratio
Zinc (Zn)	2.69	3.22	14460	31470	17010	2.17
Sulfur (S)	3.07	3.64	15220	35760	20540	2.34
Zn + S	2.89	3.67	15410	33900	18490	2.20
Zn + S + SSP[1]	3.15	4.13	16380	38100	21720	2.32
Control	2.24	2.83	13170	26700	13530	2.02
SEM ±	0.071	0.066	-	107.60	96.65	0.04

1. SSP = Single superphosphate.

In Dewas watersheds on-farm trials with micronutrients (B, Zn) and S were conducted with soybean, maize, sorghum and groundnut during rainy season and with chickpea during the postrainy season of 2003. As in Guna, good responses to these amendments were observed in all the trials.

Rajasthan

In the on-farm trials conducted on 6 maize farmers' fields, 60% increase in yield was observed with combined application of B and S over farmers' inputs (Table 16). A single trial on black gram also confirmed the deficiency of B and S.

Table 16. Response of maize and black gram to boron (B), sulfur (S) and B+S in Bundi watershed, Rajasthan, India during rainy season 2003.

		Grain yield (t ha^{-1})			
Crop	No. of farmers	Control	B	S	B + S[1]
Maize	6	1.89	2.59	2.36	3.02 (60)
Black gram	1	0.67	0.89	0.67	1.00 (49)

1. Figures in parentheses indicate percentage increase over control.

Increased Rainwater Use Efficiency

Rainfall use efficiency (RUE) indicates how best the precious rainfall is used for crop production. The RUE in simple terms is calculated as grain yield (kg) produced per unit (mm) of rainfall received during the season. During 2003 in three districts of Andhra Pradesh (Kurnool, Mahbubnagar and Nalgonda), the RUE was substantially higher where B, Zn and S were applied to all the crops tested in the study. The RUE for grain yield in maize was 5.2 kg mm^{-1} in farmer nutrient input conditions while it was 9.2 kg mm^{-1} with farmer nutrient input plus B, Zn and S; the respective values were 1.6 kg mm^{-1} and 2.8 kg mm^{-1} in groundnut; 1.7 kg mm^{-1} and 2.9 kg mm^{-1} in mung bean; and 1.7 kg mm^{-1} and 3.7 kg mm^{-1} in sorghum. The RUE in terms of net economic returns for the rainfed crops was substantially higher by 1.5 to 1.75 times in case of Zn, B and S amended plots as compared to only farmer nutrient input plots. During 2001 in Lalatora (Vidisha, Madhya Pradesh), the RUE of soybean grain yield was 1.6 kg mm^{-1} of rainwater under farmers' nutrient input condition while it was 2.0 kg mm^{-1} of rainwater with farmers' inputs plus micronutrient amendments which is 25% more productive. In soybean and wheat system the RUE increased substantially as was evident from the increased grain yields with additional micronutrients and S over the farmer nutrient input condition.

Integrated implementation of interventions in the watershed led to increased productivity for the same amount of rainfall in the given crop and place. Among the interventions, addition of micronutrients and S substantially increased the productivity of crops and resulted in increased RUE.

Future Research/Development Needs

- Standardization of soil samples collection method in the community watershed: Even though 20% of the farmers' fields in a watershed of roughly 500 ha are sampled by following stratified method based on farm size and toposequence position, there is a need to improve this methodology.

- Appropriate formulation: No proper formulation of micronutrients along with major nutrients are available in the market.
- Availability of micronutrients/secondary nutrients: Even though big farmers can buy the amendments from nearby towns or cities, it is difficult for a small landholder to procure these materials. Mechanisms have to be worked out to make available these materials at farmers' doorstep.
- Availability of credit: Extra credit requirement should be made available along with other credit requirement of farmers from different sources.
- Appropriate policies regarding fertilizers: The subsidy component in urea and DAP as opposed to SSP might have resulted in imbalanced application of urea and DAP. As a result, S deficiency has occurred in many farmers' fields. Such inappropriate policies have to be corrected.
- Decision Support System (DSS): Most of the agricultural decisions including nutrient management are site specific as well as farmer specific. A proper DSS is needed to identify the nutrient deficiencies and to apply appropriate quantities of these nutrients through different available sources as per requirement of crops and farmer's ability to spend money for purchasing the inputs. Targeted yield approach is a possible system.
- Research requirements:
  - How long do the residual effects of micro/secondary nutrient amendments last in different soils and for different crops?
  - Alternate sources of these micro/secondary nutrients need to be identified and evaluated.
  - Grain/straw quality as a consequence of growing crop on deficient nutrient soils should be studied.
  - Effect of micronutrient and S application on C sequestration through increased biomass and root production should be studied.
  - Quicker and cheaper methods of soil and plant analysis need to be developed or evaluated.

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