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MACRO-BENEFITS FROM MICRONUTRIENTS FOR GREY TO GREEN REVOLUTION IN AGRICULTURE

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ABSTRACT

The Semi-Arid Tropics (SAT), spread over 11.6 million sq km worldwide, is home to millions of poor people. Its soils are low in fertility and degraded to varying extents, with a climate characterized by undependable rainfall, high average temperatures and water stress situations for crop growth. The SAT is densely populated and a large number of its poor live off subsistence agriculture. The Green Revolution in Asia bypassed these large tracts of rainfed systems. ICRISAT is committed to improve livelihoods of millions of poor living in the SAT by undertaking agricultural research for impact in a partnership mode. Our new watershed model emphasizes the management of water as an entry point for improving livelihoods through convergence of natural resource-based activities. Our on-farm community watershed research in Asia revealed that the SAT's subsistence agricultural systems have depleted soils not only for macronutrients, but also for micronutrients such as Zn, B, and secondary nutrients like S beyond the critical limits. Wide spread (80-100%) deficiencies of micro and secondary nutrients were observed in farmers' fields in Andhra Pradesh, Madhya Pradesh and Rajasthan states of India. Substantial increase in yields by 20 to 80 percent due to micronutrient amendments, and a further increase at 70 to 120 percent micronutrient and adequate N and P amendments in a number of crops (maize, sorghum, greengram, pigeonpea, castor, chickpea, soybean and wheat) in the farmers fields were observed. Increased use efficiency of the inputs such as N and P fertilizers, as well as rainwater, resulted in increased profits and increasing productivity besides minimizing land degradation in the tropics. We are integrating these natural resource management (NRM) interventions with improved genotypes to harness the full benefits in the watershed. The integrated genetic and natural resource management (IGNRM) approach adopted in watersheds will thus make the Grey to Green revolution a reality.

INTRODUCTION

Semi-arid tropical (SAT) regions spread over 11.6 million sq km in the developing world are densely populated and poverty stricken largely as a result of dependence of the economy and livelihoods on subsistence agriculture. These regions did not benefit greatly from the green revolution for cereal production in well-endowed irrigated agriculture. Obviously, there is need for a 'Grey to Green Revolution' in the SAT to feed and provide proper nourishment to the ever-increasing population of the developing world.

ICRISAT's vision is guided by the seven planks of the new Consultative Group on International Agricultural Research (CGIAR) vision, its core competencies and thematic comparative advantages, strategic analysis of opportunities in the SAT, and how agricultural research and institutional environment and impacts affect the livelihoods of the poor. ICRISAT's vision is improved well being of the poor of the SAT through agricultural research for impact. ICRISAT's new mission is to help the poor of the SAT through science with a human face and partnership-based research for impact.

ICRISAT's mandate is to enhance the livelihoods of the poor in SAT farming systems through integrated genetic and natural resource management strategies. ICRISAT will strive to make major food crops in the SAT areas more productive, nutritious, and affordable to the poor; diversify utilization options for staple food crops; develop tools and techniques to manage risk and utilize the natural resource base in a sustained fashion, minimize land degradation, develop options to diversify systems and sources for income generation; and strengthen delivery systems to key clients. Partnership-based research for impact, gender sensitivity, capacity building and enhanced knowledge and technology flows are integral to this mandate.

Since water shortage is a key constraint to sustainable increased productivity (apart from the soil infertility problem), ICRISAT in partnership with national agricultural research systems (NARS) developed an innovative consortium model for sustainable development of watersheds. In this approach, the emphasis is shifted from mere soil and water conservation to efficient utilization of conserved resources for increasing productivity and incomes through convergence of activities. Watershed management is used as an entry point for improving livelihoods through sustainable use of natural resources and diversifying the systems (Wani et al. 2003). Apart from water shortage, low fertility is another major constraint to crop production and productivity in the SAT. The soils are not only thirsty but also hungry; and the hidden hunger often goes unnoticed. Better availability and utilization of water along with integrated nutrient management is the key to the farmers' well being. This will help to draw them out of the vicious circle of low productivity, low incomes and increased land degradation.

Optimum plant growth, crop production and productivity require a balanced use and availability of essential plant nutrients. Essential nutrients are those nutrients without which a plant cannot complete its life cycle. The absence of an essential nutrient or nutrients results in the death of the plant or decreased dry matter production, and partial to complete loss of economic yield of a crop.

Based on the quantity required, plant nutrients are grouped into macro- and micronutrients. As the name implies, macronutrients are required in large quantities by plants compared to micronutrients, which are required in small quantities. The micronutrients are also termed as minor or trace elements because their concentrations in plant tissues are minor or in trace amounts as compared to macronutrients. The essential micronutrient elements for crops include zinc (Zn), iron (Fe), manganese (Mn), copper (Cu), boron (B) and molybdenum (Mo). Other mineral nutrients such as nickel (Ni), cobalt (Co), chlorine (Cl) and silicon (Si) are considered agronomically beneficial to some plants and their universal essentiality has not been fully established (Marschner 1995).

A combination of high-yielding varieties of cereals such as rice and wheat along with adequate nutrients and optimum water supply paved the way for a green revolution in the production of these cereals. Dr Norman Borlaug while accepting his Noble peace prize in 1970 aptly said "if the dwarf wheat varieties developed (by him) were the vehicle, the fertilizers were the fuel which produced high yields and trigged the green revolution in many developing countries including India".

The synergy between improved genetic resources on the one hand, and adequate nutrient supply on the other, forms the basis of increased and sustainable productivity in lands under irrigated and assured rainfed agriculture. Moreover, the use of fertilizers as a major source of nutrients is also the means for land saving. Land saving is a very important consideration because the soil resource is becoming scarce especially in countries like India and China. Under these situations, the only way to increase crop production and productivity is through vertical growth or intensification of agriculture, as there is little scope to increase the net cultivated area, or horizontal expansion of agricultural production.

MICRONUTRIENT DEFICIENCIES IN IRRIGATED PRODUCTION SYSTEMS

The use of high-yielding cereal varieties along with the increasing use of fertilizers containing major nutrients (N, P, K), but without micronutrients through inorganic or organic fertilizers, dramatically increased food production under irrigated intensified systems. However, as a result of depleted micronutrient reserves in the soil, this practice resulted in 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 in India under continuous cropping with recommended rates of only major nutrients.

For example, field scale deficiencies of Zn in rice and wheat on alluvial soils, Fe deficiency in sugarcane, upland rice, chickpea and groundnut on sandy calcareous soils, Mn deficiency in wheat in rice-wheat systems on sandy soils and B deficiency in chickpea and rice on high pH, calcareous soils have been reported, mostly in intensified production systems. The deficiencies of micronutrients have assumed critical importance for sustaining high productivity in some areas of the country. Among these, zinc 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 soils (Takkar 1996).

The critical limits, gleaned from literature, at and below which a positive response to applied nutrient is expected in soil and plant tissue for various micronutrient elements, are summarized in Table 1 (Katyal and Rattan, 2003). The limits serve as a rough guideline because these differ not only among crop species but also among varieties in a crop species.

Table 1. Critical limits (CL) in the soil and plant tissue (fully developed youngest leaf) for micronutrient deficiencies in field crops.

Element	Soil		Plant tissue
	Extractant	CL ($\mu g\ g^{-1}$)	CL ($\mu g\ g^{-1}$)
Zn	DTPA	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	Am.ox.(pH 3.5)	0.2	0.03-0.15

Source: Katyal and Rattan (2003)

As an example, the micronutrient requirement and removal of a few major cropping systems in intensified production systems are given in Table 2. It is clear that the micronutrient removal by various cropping systems varies with crops.

Table 2. Amounts of micronutrients removed by major intensified production systems in India.

	Total yield	Nutrients removed ($g\ ha^{-1}$)					
Cropping systems	($t\ ha^{-1}$)	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)

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 of micronutrients are in the topsoil layer. The soil reserves of B should last for 266 to 558 years and that of 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 the deficiencies have been appearing gradually as they were monitored by soil and plant analyses. Thus, the deficiencies of different micronutrient elements have been seen coming.

MICRONUTRIENT DEFICIENCY 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. In the first place, yield levels are low. Secondly, soil erosion in some cases is severe resulting in the removal of top surface layers. Compounded with the low use of organic manures, which were the dominant sources of nutrients, micronutrients especially have dwindled in the recent past. Moreover, the recent emphasis on the use of micronutrient-free fertilizers such as urea (for N) and di-ammonium phosphate (DAP for N and P) has led to rather widespread deficiencies of micronutrient and secondary nutrient like S. Unlike under irrigated production systems, the monitoring of micronutrient status in the soil-crop system under dryland agriculture has not been carried out and the hidden hunger is not recognized in rainfed agriculture.

The initiation of the evaluation and scaling-up of new farmer-participatory watershed model in community watersheds by ICRISAT and its NARSs partners provided an opportunity to study the role of water harvesting and utilization practices along with nutrient management options on the yields of dryland crops in the watersheds of selected districts in the states of Andhra Pradesh, Gujarat, Madhya Pradesh and Rajasthan in India, NE-Thailand, north Vietnam and Southern China (Wani et al. 2003). The initial effort on nutrient management focused on the characterization of the fertility status including the micronutrient status of soils in farmers' fields. In this section the results of case studies on potential micronutrient deficiency in the three states of India and the effect of applications of micronutrients on crop yields on farmers' fields in the dryland districts of Andhra Pradesh, Madhya Pradesh and Rajasthan, are described to illustrate the important role of micronutrients in increasing the production and productivity of dryland crops through enhanced efficiency of nutrients and rainwater.

During 2002-2003, base line soil samples were collected from farmers' fields in watersheds in various districts of Andhra Pradesh, Madhya Pradesh, and Rajasthan by adopting a stratified sampling procedure considering toposequence positioning and land holding information. The soil samples were processed and analyzed for chemical properties including micronutrients.

The results of the micronutrient status of soils from the three states are summarized in Table 3. Using the critical limits in the soil, it was observed that in the watersheds of the Nalgonda district of Andhra Pradesh, soil samples from 99% of the farmers' fields were potentially deficient in available B (extracted by hot water) and 94% of the farmers' fields were deficient in available Zn (extracted by DTPA). In the Mahaboobnagar district watersheds, soil samples from 98% farmers' fields were deficient in B and 83% of the fields were deficient in available Zn; and in the Kurnool district, 92% of the farmers' fields were deficient in available B and 81% were deficient in available Zn. It was also noted that in addition to the deficiencies of B and Zn, the samples were also potentially deficient in available S (extracted by calcium chloride), and nearly 90% of the samples were found deficient in the three districts of Andhra Pradesh (Table 3).

In the three districts, Guna, Vidisha and Dewas of Madhya Pradesh, soil samples from farmers' fields showed a higher deficiency in Zn and S than B. The soil samples showed a wide range (0-100%) in potential deficiency of B (Table 3). In the Bundi district of Rajasthan, 67% soil samples from farmers fields were deficient in available Zn and 72% of the samples were deficient in available B. Sulfur deficiency was noted in 72% of the soil samples collected from farmers' fields in the Bundi district of Rajasthan (Table 3).

Table 3. Extractable (available) Zn, B and S status of the soil in farmers' fields in different locations of three states in India.

Locations	No.of farmers fields	Extractable Zn (μg g^{-1})		Extractable B (μg g^{-1})		Extractable S (μg g^{-1})	
		Min	Max	Min	Max	Min	Max
AndhraPradesh							
Nalgonda	176	0.08	2.20	0.02	0.8	1.4	50.5
% Deficient fields		94		99		89	
Mahaboobnagar	263	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	
MadhyaPradesh							
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	

These results demonstrated a widespread deficiency of B and Zn in the farmers' fields in watersheds of the three states of India. The deficiency is especially severe in the states of Andhra Pradesh and Madhya Pradesh. The sample size for Andhra Pradesh is large, and clearly indicates that the micronutrient deficiency in the drylands of other districts of the state with light-textured soils could indeed be as wide spread. 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 the soil samples for micronutrient status through farmer-participatory trials, scientists responded to the nutrient deficiency problem with evaluations and amendments to different crops in farmers' fields in the watersheds of Andhra Pradesh, Madhya Pradesh and Rajasthan. The objective was to evaluate the effects of micronutrient applications with and without sulfur, Nitrogen and Phosphorus application on the yields of dryland crops. The results of various treatments on the effects of Zn and B applications on the yields of maize, sorghum, groundnut and mungbean crops and the economics of the use of micronutrients are presented in Figures 1, 2 and 3. The treatments at several farmers' fields included: control (farmer's practice, mainly application of small amounts of N and P through di-ammonium phosphate, DAP) control plus Zn (10 kg Zn ha^{-1} as zinc sulfate) and control plus B (0.5 kg B ha^{-1} as borax).

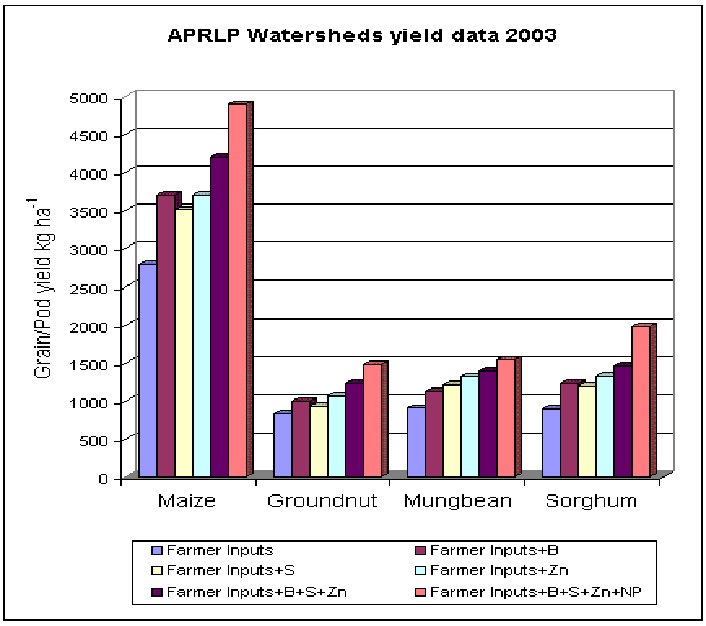

Figure 1. Effects of boron and zinc fertilization with and without application of sulfur, nitrogen and phosphorus on yields of crops in farmers' fields in three districts of Andhra Pradesh under dryland conditions in 2003. The results presented are averages of three districts.

The results from various treatment combinations clearly demonstrated the effects of B and Zn applications for increasing the crop yields by 20 to 80% under dryland conditions. The increase in yield of the crops were greater when micronutrients were added in conjunction with N, P and S (70 to 120%) (Figure 1). The economic returns also increased substantially following increase in economic yields with the application of B and Zn under various combinations of N plus P and S application (Figure 2).

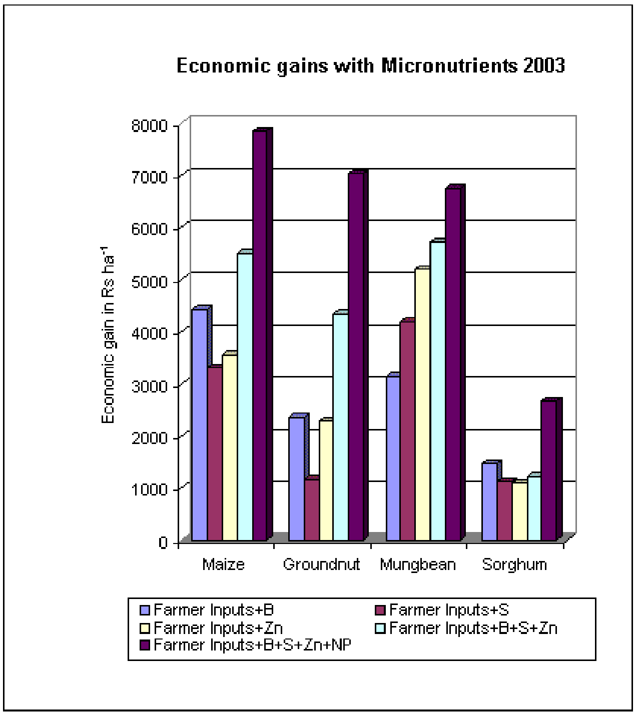

Figure 2. Economic gains from grain production by different crops with the applications of B, Zn, S, N and P in farmers' fields in three districts of Andhra Pradesh under dryland conditions in 2003. The results presented are averages of three districts.

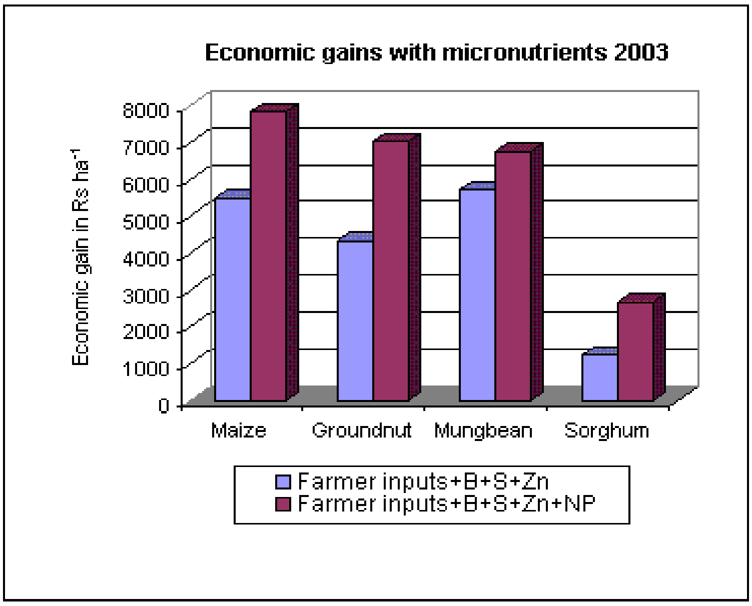

Figure 3. Economic gains from grain production by different crops under farmer's practice with the application of B, Zn and S with and without the applications of N and P in farmers' fields in three districts of Andhra Pradesh under dryland conditions in 2003. The results presented are averages of three districts.

Better availability of water through water harvesting and utilization has the potential for increasing crop yields through the applications of micronutrients such as Zn and B, which are acutely deficient, along with the major nutrients (N and P) and S.

In the Lalatora watershed of Madhya Pradesh too application of B, S, and B+S increased soybean yields by 34-40% over the best-bet option treatment based on recommended fertilizer doses, which served as control without amendments (Table 4). The economic analyses of these on-farm trials showed that combined application of B and S gave the maximum benefit of Rs 26450 ($ 581) followed by only B (Rs 26610 or $ 584) and S application (Rs 25955 or $ 572). The benefit cost ratio was up to 1.8 for amendment addition, while it was 1.3 for control. Some farmers in the Guna watershed evaluated the residual benefits of B and S application on chickpea and wheat following soybean, which had received the B and S amendments for the rainy season crop. Chickpea responded to residual S as well as to B. The highest response was observed for residual S, which was approximately 68% higher grain yield as compared to control (Table 5). In the case of wheat also residual benefits of B and S were observed (Table 6). Significant net returns were obtained due to the residual amendments.

Table 4. On-farm performance of efficient water use strategies, Lalatora, M.P, India, rainy season 2001.

Treatment	Grain yield (t ha^{-1}) Soybean	Wheat	Soybean + wheat system	Net profit (Rs. ha^{-1})
Boron (1 kg ha^{-1})	1.73	3.74	5.04	26610
Sulphur (30 kg ha^{-1})	1.74	3.50	5.24	25960
Boron + sulphur	1.77	3.60	5.37	26450
Control (best-bet treatment)	1.40	2.7	4.10	17760

Table 5. Residual effect of B, S, and B+S applied to soybean on grain and straw yield of chickpea in Guna, rabi 2002.

Treatment	Average yield (t ha^{-1})		Percent increase over control	
	Grain	Straw	Grain	Straw
Boron (1 kg ha$^{-1)}$	1.61	1.66	54	10
Sulphur (30 kg ha$^{-1)}$	1.76	1.92	68	27
Boron + sulphur	1.55	1.79	48	18
Control	1.05	1.51	--	--

Table 6. Residual effect of B, S, and B+S applied to soybean on grain and straw yield of wheat and economic benefits in Guna during rabi 2002.

Treatment	Yield (t ha^{-1})		Cost of cultivation (Rs. ha^{-1})	Gross returns (Rs. ha^{-1})	Net returns (Rs. ha^{-1})	Benefit: cost ratio
	Grain	Straw				
Boron (B)	2.58	2.92	13170	29590	16425	2.24
Sulphur (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
SE (m) ±	0.069	0.077	--	108.1	73.0	0.068

On farm trials on chickpea and wheat during the rabi season of 2002 in the Guna watershed clearly showed the response of grain and straw yield to direct application of Zn, S and Zn + S as shown in Tables 7 and 8. These amendments not only increased yields up to 60% and 40% over the control for chickpea and wheat, but also improved net returns resulting in higher benefit:cost ratio. These results demonstrated that widespread deficiencies of micro- and secondary nutrients exist in rainfed areas. Further, amendments with deficient nutrients increased economic yields as well as economic benefits from the rainfed systems.

Table 7. Effect of micronutrient amendments and best-bet option treatments on grain and straw yield and economics of chickpea, rabi 2002, Guna, MP, India.

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

Table 8. Effect of micronutrient amendments and best-bet option treatments on grain and straw yield and economics of wheat, rabi 2002, Guna, MP, India.

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

INCREASED RAINWATER USE EFFICIENCY

Rainfall use efficiency (RUE) indicates how best the precious rainfall has been used for crop production. The RUE has been calculated as a kilogram of grain produced per mm of rainfall during the season, or net returns (in rupees) per mm of rainfall received during the season. In Lalatora (Vidisha, Madhya Pradesh) during 2001 the RUE of soybean yield was 1.6 kg mm^{-1} of rainwater under farmers input condition, while it was 2.0 kg mm^{-1} of rainwater, which is 25% more productivity for the rainfed systems in Madhya Pradesh where micronutrients were applied. In the case of the soybean+wheat system the water use efficiency was substantially increased as evident from the increased grain yields with nutrient amendments over the non-amendment control plots with the same amount of water. In three districts of Andhra Pradesh (Kurnool, Mahaboobnagar and Nalgonda) during 2003 the RUE for yield and net returns were substantially higher where micronutrients were applied in all crops under the study. The RUE for grain yield in maize was 5.2 kg vs 9.2 kg with micronutrient amended plots, and in groundnut (1.6 vs 2.8 kg mm^{-1}), mungbean (1.7 vs 2.9 kg mm^{-1}) and sorghum (1.7 vs 3.7 kg mm^{-1}) in farmers' fields. 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 micronutrient amended plots as compared to the non-amended control plots.

CONCLUSION

There is need for monitoring the micronutrient status through analysis of soil and plant tissue in farmers' fields. Farmers are unaware of the hidden hunger and there is an urgent need to ensure that each farmer knows the health of his soil in order to ensure sustainable development of agriculture. It is clear that micronutrients are indeed playing a macro role in augmenting crop yields not only under irrigated agriculture but also in drylands. We can substantially increase the fertilizer (N and P) as well as rainwater use efficiency by supplying the micro- and secondary nutrients that are becoming severely limiting even under subsistence agriculture. It is of utmost importance to improve productivity, profitability, quality and sustainability of the rainfed systems which are generally neglected. For sustainable systems, a synergy between genetic tolerance and plant nutrition under improved soil and water conservation practices is much needed. The integrated genetic and natural resource management (IGNRM) approach, where watersheds are used as the entry point activity for improving livelihoods on a sustainable basis, has a great potential to make the Grey to Green revolution a reality. Micronutrients and secondary nutrients are as important as macronutrients, water and improved varieties.

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