Climate Change And Agriculture

About the Book

Rainfed agriculture is gaining importance throughout the globe in view of its inherent problem of low or sparse rainfall which is accentu ted further by climate change. To sustain agriculture and ther related activities, we need to know more about the soils and other natural resources including plants, insects and other biological elements which are experiencing climatic stress due to global warming.

On the basis of expertise by a team of leading scientists from national and international organizations, the 16 chapters of this book discuss the issues and priorities for agricultural and related managements. Covering areas such as north-eastern Himalayas, semi-arid tropics, eastern and north-eastern India and the Indo-Gangetic Plains with an overall global scenario of the rainfed agriculture, this book will be necessary for both the academics and policy makers in understanding natural resources and their management for sustainable agriculture.

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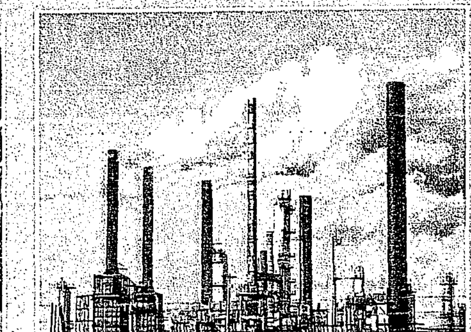

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Nutrient Deficiencies and their Management in Soils of the Semi-Arid Tropical Regions

KANWAR L. SAHRAWAT[1] AND SUHAS P. WANI

ABSTRACT

In the semi-arid tropical (SAT) regions, the loss of soil, organic matter, and nutrients are of great concern. Nutrient imbalance in the case of major plant nutrients has been reported for a long period of time as a result of decline in soil organic carbon status in the rainfed areas of Asia and Sub-Saharan Africa. In India, the results of analysis of a large number of soil samples collected from farmers' fields in Andhra Pradesh, Karnataka, Madhya Pradesh and Rajasthan, showed that the samples were low in organic carbon, low to medium in available phosphorus (P), medium to high in potassium (K), low in sulphur (S), boron (B) and zinc (Zn). The results indicated that multiple nutrient-deficiencies in the SAT have to be managed to unlock the potential of rainfed production systems. It is suggested that balanced plant nutrition is critical to increase crop productivity in the rainfed system. Since the area under rainfed cropping is quite large, even a modest increase in productivity will make a large contribution to the overall food and feed supply.

Keywords: Dry regions, Major and micro nutrients, Crop productivity.

1. INTRODUCTION

Water shortage as a constraint to crop production and productivity in the semi-arid tropical (SAT) regions is well recognized and in many cases, management of water rather than the availability *per se* limits the crop production (Wani *et al.*, 2009; Rockström *et al.*, 2010). In addition to water shortage, soil infertility is also an issue for enhancing crop production and

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productivity in much of the semi-arid tropical regions, especially in Africa and Asia (El–Swaify *et al.*, 1985; Black, 1993; Sanchez *et al.*, 1997; Sahrawat *et al.*, 2001, 2007; Bationo *et al.*, 2008; Singh, 2008; Bekunda *et al.*, 2010).

Apart from the major nutrients [nitrogen (N), phosphorus (P) and potassium (K)], the deficiencies of sulfur (S) and micronutrients have been reported with increasing frequency from intensive, irrigated production systems (Kanwar, 1972; Pasricha and Fox, 1993; Takkar, 1996; Scherer, 2001); and it is believed that micronutrient deficiency is one of the main causes for decline in the intensive irrigated production systems (Takkar, 1996; Tandon, 2009). While in the irrigated systems, the deficiencies of various plant nutrients have been diagnosed by soil and plant testing, and corrected through the fertilization of crops, little attention seems was paid for diagnosing and managing nutrient deficiencies, especially the secondary nutrients such as S and micronutrients in farmers' fields in dryland production systems of SAT India (Rego *et al.*, 2005, 2007; Sahrawat *et al.*, 2007, 2010a).

The soils in the Indian SAT are marginal compared to irrigated soils (El–Swaify *et al.*, 1985; Rego *et al.*, 2003). However, it is generally believed that at relatively low yields of crops in the rain-fed systems, the deficiencies of only major nutrients, especially N and P and to a lesser extent of K are important for the SAT Indian soils (El–Swaify *et al.*, 1985; Rego *et al.*, 2003). The productivity of SAT soils is low due to water shortage; in practice, however, low fertility is also an important issue in the SAT regions of India. Moreover, in practice the deficiencies of major nutrients (N and P) are considered important, although even the inputs of major nutrients to dryland production systems are meager (Sahrawat *et al.*, 2010a). Also, due to low productivity of the drylands, it is generally assumed that the mining of micronutrient reserves in soils is much less than in irrigated production systems (Rego *et al.*, 2003).

For sustained increase in dryland productivity, both water shortage and soil infertility need attention simultaneously along with the choice of crops and their management (Wani *et al.*, 2003). The objectives of this paper are twofold: (i) to show as to how soil testing can be used to diagnose nutrient deficiencies in farmers' fields in SAT, India, and (ii) to demonstrate from the results of recent on-farm trials as to how balanced nutrient management strategy, based on the soil test results, can be used to enhance dryland productivity in SAT, India.

2. ORGANIC CARBON AND AVAILABLE NUTRIENT STATUS OF SOILS

Soil degradation is common in the SAT regions, which results in not only the loss of soil, but also of organic matter and nutrients therein. Moreover, it causes deterioration in soil physical, chemical and biological properties, and is a major threat to the sustainability of the agricultural systems in SAT agriculture (Lal, 1995; Pathak *et al.*, 2005; Bationo *et al.*, 2008; Sahrawat *et al.*, 2010a, b).

Soil organic matter is critical to soil fertility and water cycle management in agro-ecosystems and its importance cannot be overemphasized in the SAT regions where soils are marginal and water shortage is the major stress to production systems (Bationo *et al.*, 2008; Sahrawat *et al.*, 2010a, b). The maintenance of soil organic matter at a threshold level depending on the soil type and climatic factors is critical for the physical, chemical and biological integrity of the soil and for the soil to perform its agricultural productivity and environmental functions on a sustainable basis (Pathak *et al.*, 2005; Bationo *et al.*, 2008; Sahrawat *et al.*, 2010a). To maintain soil organic matter status, there is need to add organic materials including manures, organic and crop residues on a regular basis to compensate the loss of organic matter by various processes (Edmeades, 2003; Harris, 2002; Bationo *et al.*, 2008; Ghosh *et al.*, 2009; Materechera, 2010).

The negative effects on soil quality that lead to soil degradation can be classified in two broad categories—one negative effects caused by soil loss by water and wind erosion (Lal, 1995; Pimentel *et al.*, 1995; den Biggelaar *et al.*, 2004a, b; Montgomery, 2007; Sahrawat *et al.*, 2010a), secondly, negative effect takes place as a result of deterioration in physical, chemical and biological properties of the soil (Pathak *et al.*, 2005; Poch and Martinez–Casanovas, 2006; Sahrawat *et al.*, 2010a). The effects of soil loss on crop productivity vary widely depending on soil and NRM practices, and the crop. Among the soil characteristics, soil organic matter status, clay and soil depth among others are important. The causes of physical, biological and chemical degradation of soil include loss of organic matter, salinization and alkalization, waterlogging, and the contamination of water resources. Both types of soil degradation result in the loss of organic matter and nutrients especially micronutrients, which mostly are present in the top soil layer, are major constraints to the maintenance of soil quality, fertility and agricultural productivity (Bellamy *et al.*, 2005; Singh, 2008; Pathak *et al.*, 2005; Wani *et al.*, 2009; Bekunda *et al.*, 2010; Materechera, 2010; Sahrawat *et al.*, 2010a, b; Verhulst *et al.*, 2010).

Bationo *et al.* (2008) and Bekunda *et al.* (2010) extensively reviewed the various causes that hamper agricultural production and productivity and overall agricultural development in Sub-Saharan Africa (SSA). The most important constraints among others included low soil fertility, fragile ecosystems, rainfall dependence, insufficient research, inadequate extension services, post harvest crop losses, insufficient market and lack of consistent enabling agricultural policies and land tenure. Overdependence on rainfall and associated water shortage related problems along with soil infertility constitute the major constraints to sustainable increase in agricultural productivity.

The fundamental biophysical cause for the declining per capita food production in smallholder farms in SSA during the past 3–5 decades was solely ascribed to soil fertility depletion including the loss of soil organic matter, and major plant nutrients (N, P and K). The application of major nutrients from external sources remains dismally low (Sanchez *et al.*, 1997; Rego *et al.*, 2005; Bationo *et al.*, 2008; Bekunda *et al.*, 2010). The main factors contributing to soil fertility depletion were identified as erosion by water and wind, especially in the semi-arid and arid regions. Sterk *et al.* (1996) reported a total loss of 45.9 t ha^{-1} soil by wind erosion in the arid region of Niger. The figures on the loss of soil organic matter and major nutrients by erosion vary widely, but remain a major threat to soil fertility and environmental quality (for review see Bationo *et al.*, 2008). Moreover, nutrients are removed by crops and unless their pool is replenished by addition there is depletion in nutrient reserves, eventually leading to nutrient deficiencies. To put simply, for sustained productivity at a high level, sustainable maintenance of soil fertility is a prerequisite. And for sustained fertility, it is essential that organic matter and nutrients removed in harvest or produce plus those lost through various physical, biological and chemical processes are replenished through external inputs on a regular basis such that soil organic matter status is maintained and nutrient balances are not negative in the longer term (Rego *et al.*, 2003; Wani *et al.*, 2007; Sahrawat *et al.*, 2010a).

It has been observed that the intensification of production systems without adequate investment to sustain the system, results in the loss of fertility (Katyal, 2003; Morris *et al.*, 2007; Sahrawat *et al.*, 2010a, b). The effects of loss of soil fertility (organic matter and nutrients) are in the longer-term manifested as reduced crop yields and quality due to reduced soil quality (Lal, 1997; Carpenter, 2002; den Biggelaar *et al.*, 2004a, b; Pathak *et al.*, 2005; Sahrawat *et al.*, 2008a; Sharma *et al.*, 2009a, b).

Soil organic matter and major plant nutrient (N, P and K) depletion remains a major constraint to long-term agricultural sustainability in much of the rain-fed agricultural systems in the SAT regions of Asia and SSA. Negative nutrient balances mostly for major plant nutrients have been reported as the nutrient removal exceeds input over a long period of time with concomitant decline in soil organic matter status. Organic matter depletion problem is particularly acute in the rain-fed systems where the external inputs of organic matter and nutrients is far lower than the loss or removal (Burford *et al.*, 1989; Sahrawat *et al.*, 1991; Black, 1993; Bationo *et al.*, 1998, 2008; Stoorvogel and Smaling, 1998; Rego *et al.*, 2003; Bijay-Singh *et al.*, 2004; Bekunda *et al.*, 2010).

Since 1999, ICRISAT and its partners have been conducting systematic, detailed studies on the diagnosis and management of nutrient deficiencies in

the semi-arid regions of Asia with emphasis on the semi-arid regions of India under the integrated watershed management programme (Wani *et al.*, 2009). Under this programme, first a soil sampling methodology was developed to take representative soil samples in a watershed. The methodology is based on stratified random sampling of the watershed considering the soil types including topography, major crops, and farmers' land holding size (for details see Sahrawat *et al.*, 2008b).

During these studies soil samples were collected from the farmers' fields in a farmer participatory manner, processed and analyzed for soil chemical fertility parameters in the ICRISAT central analytical laboratory. The soil test results were shared with farmers and recommendations were developed for balanced nutrient management using the critical limits in the soil for various plant nutrients (Sahrawat, 2006; Rego *et al.*, 2007; Sahrawat *et al.*, 2007) for the follow up on-farm crop response studies. However, it must be stated that the critical limits of major, secondary and micronutrient elements in the soil as well as in plant tissue vary with crop and variety of a crop, soil type (especially clay and organic matter status) and agroclimatic conditions, especially the availability of irrigation water and status of other nutrients in the soil (Mills and Jones, 1996; Takkar, 1996; Reuter and Robinson, 1997; Fageria *et al.*, 2002; Sahrawat, 2006; Rattan *et al.*, 2009; Scherer, 2009; Tandon, 2009).

A summary of soil test results (range and mean) for pH, organic C and extractable P, K, S, B and Zn of a large number of soil samples collected from farmers' fields in the SAT regions of Indian states of Andhra Pradesh (3,650 farmers' fields), Karnataka (22,867), Madhya Pradesh (341) and Rajasthan (421) showed that the results varied with district in a state and had a wide range in soil chemical fertility parameters (Table 1). Soil analysis was carried out following standard methods (see Sahrawat *et al.*, 2010a).

Table 1: Summary of results on chemical characteristics of soil samples collected from farmers' fields in the SAT regions of India.

No. of farmers' fields	*Parameter*	*pH*	*Organic C (%)*	*Olsen P (mg kg^{-1})*	*Exch.K (mg kg^{-1})*	*Extractable nutrient elements (mg kg^{-1})*		
						S	*B*	*Zn*
				Karnataka				
22867								
	Range	5.0–10.5	0.01–3.6	0.1–480	4–3750	0.1–12647	0.02–26.24	0.04–235
	Mean	7.4	0.45	11.4	150	14.4	0.59	0.89
	% Deficient			47	16	83	66	61

Table 1: (*Contd...*)

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No. of farmers' fields	*Parameter*	*pH*	*Organic C (%)*	*Olsen P (mg kg^{-1})*	*Exch.K (mg kg^{-1})*	*Extractable nutrient elements (mg kg^{-1})*		
						S	*B*	*Zn*
				Andhra Pradesh				
3650								
	Range	5.0–10.2	0.08–3.00	0.2–247.7	11–1263	0.2–801	0.02–4.58	0.08–35.6
	Mean	7.6	0.41	9.1	129	9.6	0.34	0.81
	% Deficient			38	12	79	85	69
				Rajasthan				
421								
	Range	6.2–10.2	0.09–2.37	0.2–44	14–1358	1.9–274	0.08–2.46	0.16–28.6
	Mean	7.8	0.72	8.1	116	10.6	0.6	1.49
	% Deficient			45	15	71	56	40
				Madhya Pradesh				
341								
	Range	5.9–8.7	0.28–2.19	0.1–68	46–716	1.8–134.4	0.06–2.2	0.10–3.82
	Mean	7.8	0.65	5.0	190	9.6	0.43	0.72
	% Deficient			74	1	74	79	66
Total	Range	5.0–10.5	0.01–3.6	0.1–480	4–3750	0.1–12647	0.02–26.24	0.04–235
28270	Mean	7.4	0.45	10.9	147	13.6	0.55	0.88
	% Deficient			46	16	82	68	62

Critical limits used in the soil were 5 mg kg^{-1} for Olsen P; 50 mg kg^{-1} ammonium acetate-extractable K; 8–10 mg kg^{-1} calcium chloride-extractable S; 0.58 mg kg^{-1} hot water-extractable B; and 0.75 mg kg^{-1} DTPA–extractable Zn.

Source: The results on soil analyses of samples from Andhra Pradesh, Rajasthan and Madhya Pradesh are from Sahrawat *et al.* (2007). The data from Karnataka are unpublished ICRISAT results.

These first results on the fertility status of farmers' fields at a relatively large scale showed that the samples were generally low in organic C, which is used as a proxy for N supplying capacity of a soil; low to medium in Olsen extractable P; medium to high in exchangeable K; generally low in calcium chloride extractable S; hot water extractable B and DTPA extractable Zn (Table 1). The results clearly demonstrate that soils are not only low in organic C and hence in N supplying capacity and Olsen-P, but also low in secondary nutrient such as S and micronutrients such as B and Zn.

The number of farmers' fields sampled from 14 districts of Karnataka state was fairly large and based on these results some plausible conclusions can be drawn on the prevalence of plant nutrient problems in the state, which is the second largest state with rain-fed agriculture after Rajasthan. The mean organic C content in the soil samples was 0.45%, Olsen-P was deficient in 47% of the 22867 farmers' fields sampled, exchangeable K was deficient only in 16% farmers' fields, extractable S in 83% fields, hot water extractable B in 66% fields and DTPA extractable Zn was deficient in 61% of the sampled farmers' fields.

In Andhra Pradesh, B deficiency was most prevalent (in 85% of the 3650 fields sampled), followed by S, which was deficient in 79% of the farmers' fields and Zn was deficient in 69% of the farmers' fields. Olsen-P was deficient in 38% of the fields and K only in 12% of the fields (Table 1). In Madhya Pradesh (341 farmers' fields sampled), B deficiency was most prevalent (79% fields), followed by S (74%), Olsen-P (74%) and Zn (66%). In Rajasthan (421 fields sampled), the deficiency of S was most widespread (in 71% of the fields), followed by B (56%), Zn (62%), Olsen-P (46%) and K (15%) (Table 1).

Considering all the four states in the SAT region of India, it was concluded that the deficiency of S (calcium chloride extractable) was most widespread (on an average 82% of the 28,270 farmers' fields sampled were deficient), followed by extractable B (68% of the farmers' fields sampled were deficient) and extractable Zn (62% of the farmers' fields were found deficient), and the results were most interesting. These results are in accord with those reported earlier with a limited number of soil samples (Rego *et al.*, 2005; Sahrawat *et al.*, 2007, 2010b). On the other hand, K deficiency was not prominent at all (on an average only 16% of the farmers' fields out of a total of 28,270 farmers' fields sampled) in the rain-fed SAT soils (Table 1).

These results are significant in showing the widespread nature of the occurrence of the deficiencies of major nutrients such as N and P, but more importantly those of S, B and Zn in the rain-fed production systems of the SAT India. The extent of deficiencies of nutrients appear as widespread as those reported from the intensified irrigated systems (Pasricha and Fox, 1993; Takkar, 1996; Scherer, 2001; Fageria *et al.*, 2002; Tandon, 2009; Sahrawat *et al.*, 2010a). To our knowledge, no comprehensive on-farm survey of nutrient status (deficiencies) especially of S and micronutrients in farmers' fields in the SAT regions has been undertaken, and so there are no benchmark results to compare these results on nutrient deficiencies. But these results demonstrate clearly that in addition to water stress, multiple-nutrient deficiencies have to be managed to unlock the potential of rain-fed production systems. The earlier research has mostly concentrated on the major nutrients and the deficiencies of N and P have been reported to be widespread in the rain-fed systems (El–Swaify *et al.*, 1985; Burford *et al.*, 1989; Sahrawat *et al.*, 1991, 2001; Rego *et al.*, 2003; Bationo *et al.*, 2008).

3. CROP RESPONSES TO BALANCED NUTRIENT MANAGEMENT

Soil fertility management research in the rain-fed areas has focused mainly on the management of major nutrients (N, P and K) and even amounts of these nutrients added is generally inadequate (Rego *et al.*, 2007; Bationo *et al.*, 2008; Sahrawat *et al.*, 2010a). Water stress by erratic and low rainfall is the major bottleneck for farmers to apply adequate amounts of nutrients in the rain-fed systems. However, recent work by the ICRISAT and its partners and other researchers has shown that for realizing the potential of rain-fed systems, both water stress and nutrient deficiencies need to be attended simultaneously (Wani *et al.*, 2003; Ncube *et al.*, 2007; Bationo *et al.*, 2008; Sahrawat *et al.*, 2010b).

Results from recent research conducted on farmers' fields in the SAT regions of India on the effects of balanced nutrient management based on soil test results are briefly reviewed here. During 2002–2004 seasons, Rego *et al.* (2007) conducted a number of on-farm trials during the rainy season (June–October) in three districts of Andhra Pradesh in the SAT region of India, to evaluate crop responses to balanced nutrient management using mung bean, maize, groundnut, castor and pigeonpea as the test crops. There were two treatments (i) control or farmer's nutrient input (FI) and (ii) balanced nutrient (BN) management, which consisted of the applications of SBZn +NP over FI.

In the balanced nutrient management (BN = FI + SBZn +NP) treatment, S, B and Zn were applied via a mixture, which consisted of 200 kg gypsum (30 kg S ha^{-1}), 5 kg borax (0.5 kg B ha^{-1}) and 50 kg zinc sulfate (10 kg Zn ha^{-1}); the mixture was surface broadcast on the plot before the final land preparation. The SBZn + NP treatment consisted of the same amount of S, B and Zn as in SBZn plus 60 kg N for maize and castor or 20 kg N ha^{-1} for groundnut and mung bean; and P was added at 30 kg P_2O_5 ha^{-1}. The treatment SBZn was applied along with P plus 20 kg N ha^{-1} as basal to all crops and 40 kg N ha^{-1} was top dressed in case of maize and castor. In case of NP treatment, 20 kg N and 30 kg P_2O_5 ha^{-1} were applied to all crops as basal and 40 kg N ha^{-1} as topdressing for maize and castor. Other nutrient treatments including FI + SBZn, FI + SBZn + NP or BN were applied as described above (Rego *et al.*, 2007). The grain yields of maize, castor, mung bean, groundnut (pod yield) and pigeonpea crops were significantly increased under BN with the application of SBZn + NP over the FI treatment in the three seasons (Table 2).

The ICRISAT along with its partners conducted a large number of on-farm trials in the semi-arid zone of Karnataka during five rainy seasons (2005–2009) with maize, finger millet, groundnut and soybean as the test crops. Again, as in the case of trials in Andhra Pradesh, BN treatment significantly increased the grain yields of these crops over the farmers' inputs treatment (Table 3). In another set of trials, conducted during 2005–2007 in

the semi-arid zone of Karnataka, the balanced nutrient management or BN significantly increased maize grain yield and dry matter over the farmers' inputs treatment; BN treatment also significantly improved the harvest index of the crop during all the three seasons (Rajashekhara Rao *et al.*, 2010).

Table 2: Grain yields of crops in response to fertilization according to farmers' inputs (FI) and balanced nutrient management (BN, BN = FI + SBZn + NP) treatments in the semi-arid zone of Andhra Pradesh, India during three (2002 to 2004) rainy seasons.

Year	*Treatment*	*Grain yield (kg ha⁻¹)*				
		Maize	*Castor*	*Mung bean*	*Ground-nut (pod)*	*Pigeonpea*
2002	FI	2730 (20)[a]	590 (8)	770 (9)	1180 (19)	536 (43)
	BN	4560	880	1110	1570	873
	LSD (0.05)	419	143	145	92	156
2003	FI	2790 (24)	690 (17)	900 (6)	830 (30)	720 (12)
	BN	4880	1190	1530	1490	1457
	LSD (0.05)	271	186	160	96.8	220
2004	FI	2430 (19)	990 (6)	740 (12)	1320 (40)	1011 (21)
	BN	4230	1370	1160	1830	1564
	LSD (0.05)	417	285	131	122.5	106

[a] The values in parentheses are the number of farmers' fields on which on-farm trials were conducted.

Source: The results on maize, castor, mung bean and groundnut crops are from Rego *et al.* (2007), and the data on pigeonpea crop are from ICRISAT unpublished results.

Table 3: Grain yields of crops in response to fertilization according to farmers' inputs (FI) and balanced nutrient management (BN, BN = FI + SBZn + NP) treatments in the semi-arid zone of Karnataka, India during five (2005 to 2009) rainy seasons.

Year	*Treatment*	*Grain yield (kg ha⁻¹)*			
		Maize	*Finger millet*	*Groundnut*	*Soybean*
2005	FI	4000 (6)[a]	2100 (16)	1830 (8)	2030 (6)
	BN (0.05)	6090	3280	1910	3470
	LSD	395	338	91.5	664
2006	FI	4050 (22)	1700 (17)	1080 (17)	1120 (7)
	BN	5400	2170	1450	2650
	LSD (0.05)	240	440	341.4	538
2007	FI	5670 (19)	2000 (27)	1310 (23)	2120 (11)
	BN	8710	2940	2160	3120
	LSD (0.05)	572	230	191.4	262

Table 3: (*Contd...*)

Table 3: *(Contd...)*

Year	*Treatment*	*Grain yield (kg ha^{-1})*			
		Maize	*Finger millet*	*Groundnut*	*Soybean*
2008	FI	4400 (27)	1680 (152)	940 (149)	1390 (16)
	BN	6130	2650	1430	1640
	LSD(0.05)	336	125	80.3	249
2009	FP	5460 (90)	1630 (165)	1100 (178)	1770 (36)
	IP	7800	2570	1500	2610
	LSD(0.05)	178	91	49.9	184

[a]The values in parentheses are the number of farmers' fields on which on-farm trials were conducted.
Source: Unpublished results from ICRISAT.

Results of the on-farm trials conducted in the SAT zone of Madhya Pradesh with soybean in the 2008–2009 rainy season and chickpea in the 2008–2009 post-rainy seasons confirmed the superiority of the BN treatment over the FI treatment and significantly increased soybean and chickpea grain yields. Similar results were obtained in the on-farm trials conducted during the 2008 rainy season in the semi-arid zone of Rajasthan, India, with pearl millet and maize as the test crops; and the grain yields of these crops were significantly increased in the BN treatment as compared to FI (ICRISAT, unpublished results).

On-farm trials conducted during the 2006–2007 season with a number of vegetable crops in watersheds in Dharwad, Haveri and Chitradurga districts of Karnataka to study their responses to balanced nutrient management as compared to farmers' input treatment, showed an impressive yield response to balanced nutrient management as compared to farmers' treatment; and the growing of these vegetables under balanced nutrient management crops was economically viable and remunerative (Srinivasarao *et al.*, 2010).

Balanced plant nutrition is not only important for increasing crop productivity, but is also critical for enhancing crop quality including grain and stover/straw quality and this has implications for human (grain as food) and animal (straw used as fodder or feed) nutrition. There is a relationship between soil health and food and feed quality which in turn impacts human and animal health. The importance of mineral nutrition of crops along with improved cultivars of crops and crop management cannot be overemphasized for producing nutritious food (Graham *et al.*, 2007; Parthasarathy Rao *et al.*, 2006) and fodder (Kelly *et al.*, 1996; Sahrawat *et al.*, 2008a; Rattan *et al.*, 2009). Balanced nutrient management approach is also essential for increasing productivity through efficient use of rainwater by enhancing rainwater use efficiency (Wani *et al.*, 2009).

In the on-farm experiments conducted to determine the effects of S, B and Zn fertilization on the grain and straw quality of sorghum and maize grown under rain-fed conditions in the SAT region of India showed that the balanced mineral nutrition (BN) through combined application of S, B, Zn, N and P as compared to the FI (farmer's inputs) increased N, S and Zn concentrations in the grain and straw of these crops (Sahrawat *et al.*, 2008a). These results stress the importance of balanced mineral nutrition of crops for increased produce quality. For example, S fertilization of oilseed crops such as soybean (Saha *et al.*, 2001), canola (Brennan and Bolland, 2008; Brennan *et al.*, 2010) and sunflower (Usha Rani *et al.*, 2009) is not only required for increasing dry matter and seed yield, but is also essential for enhancing oil concentration and quality.

4. CONCLUSIONS

The results obtained from a large number of on-farm trials demonstrate that in the SAT region, multiple nutrient deficiencies especially of N, P, S, B and Zn are holding back the potential of rain-fed systems. Also, soil fertility depletion has been recognized as the major biophysical cause of declining food availability in smallholder farms in Sub-Saharan Africa. It was suggested that any programme aimed at reversing the trend in declining agricultural productivity and food quality, and preserving the environmental quality must begin with soil fertility restoration and maintenance. The decline in productivity is related to decline in soil fertility, which in turn is directly related to decline in soil organic matter status and depletion of the plant nutrient reserves in various production systems with little or no investment in recuperating soil fertility in agroecosystems (Sanchez *et al.*, 1997; Bationo *et al.*, 2008; Lal, 2008; Stringer, 2009; Bekunda *et al.*, 2010).

Soil fertility maintenance is not only a prerequisite for sustainable increase in crop productivity, but is equally essential for maintaining crop quality in terms of food, fodder and feed quality (Kelly *et al.*, 1996; Sahrawat *et al.*, 2008a) especially Fe and Zn in the grain (Graham *et al.*, 2007; Sahrawat *et al.*, 2008b; Rattan *et al.*, 2009). The results from on-farm studies also show that the productivity of the rain-fed systems can be enhanced through management of various nutrient deficiencies. Unless the constraints to soil fertility management are alleviated, it would not be possible to achieve the potential productivity of the rain-fed systems. Since the area under rain-fed production is very large, even a modest increase in yield would contribute in a big way to global food pool, apart from providing source of income and livelihoods to the rural poor.

For utilization of the soil test-based nutrient management in practical agriculture, we have prepared soil nutrient maps relative to S, B and Zn using the GIS based extrapolation methodology in various districts of Karnataka (ICRISAT, unpublished results). Finally, the soil test-based

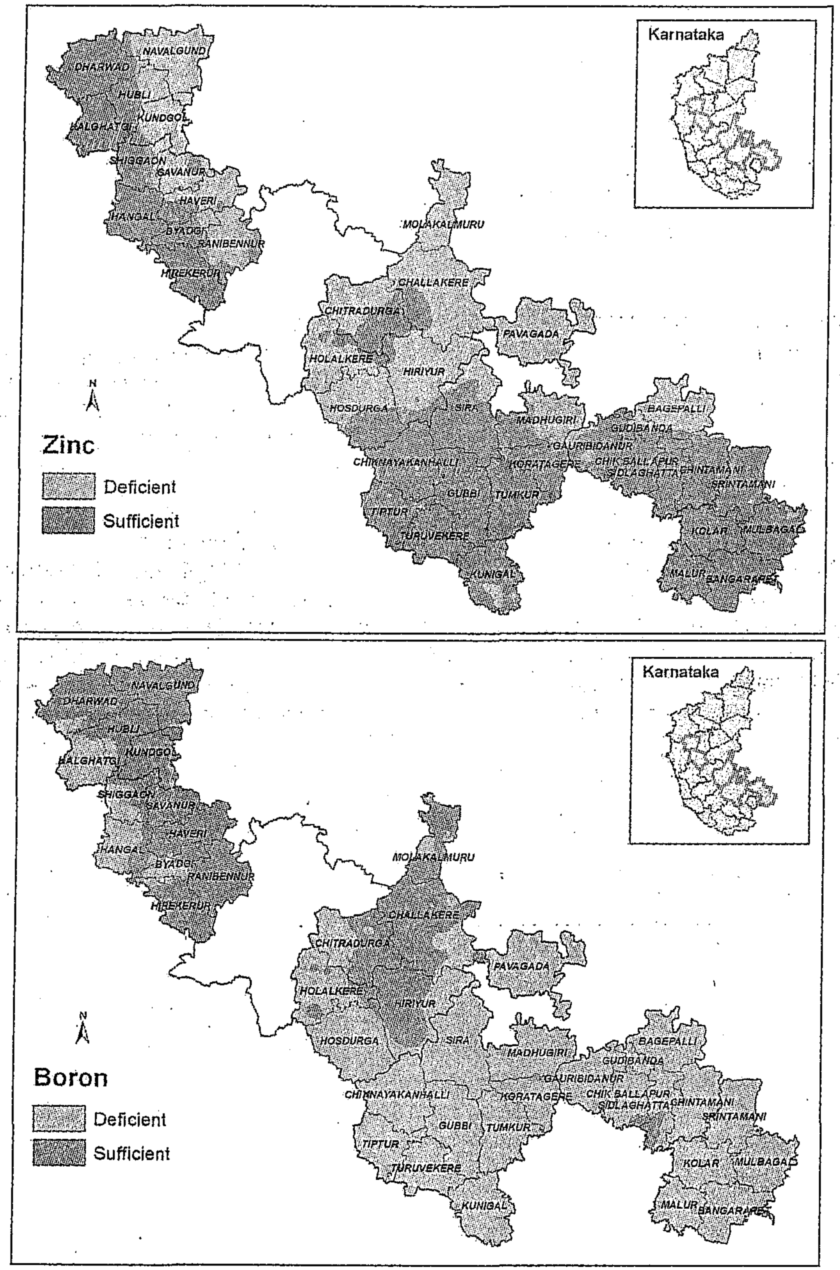

Fig. 1. Distribution of extractable boron and zinc in soil samples from various districts of Karnataka. The two color codes indicate the deficiency and sufficiency of a nutrient.

fertilizer application has been made web-based so that the recommendations can be downloaded and made available nutrient-wise to farmers using colour codes depicting the deficiency or sufficiency of a nutrient. Such information can be easily used by small farmers. A typical example of nutrient mapping for extractable (available) B, and Zn, using data from selected districts of Karnataka, are shown in Figure 1. Such maps can be extended and used by farmers in a cluster of villages to plan the application of deficient plant nutrients to production systems.

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