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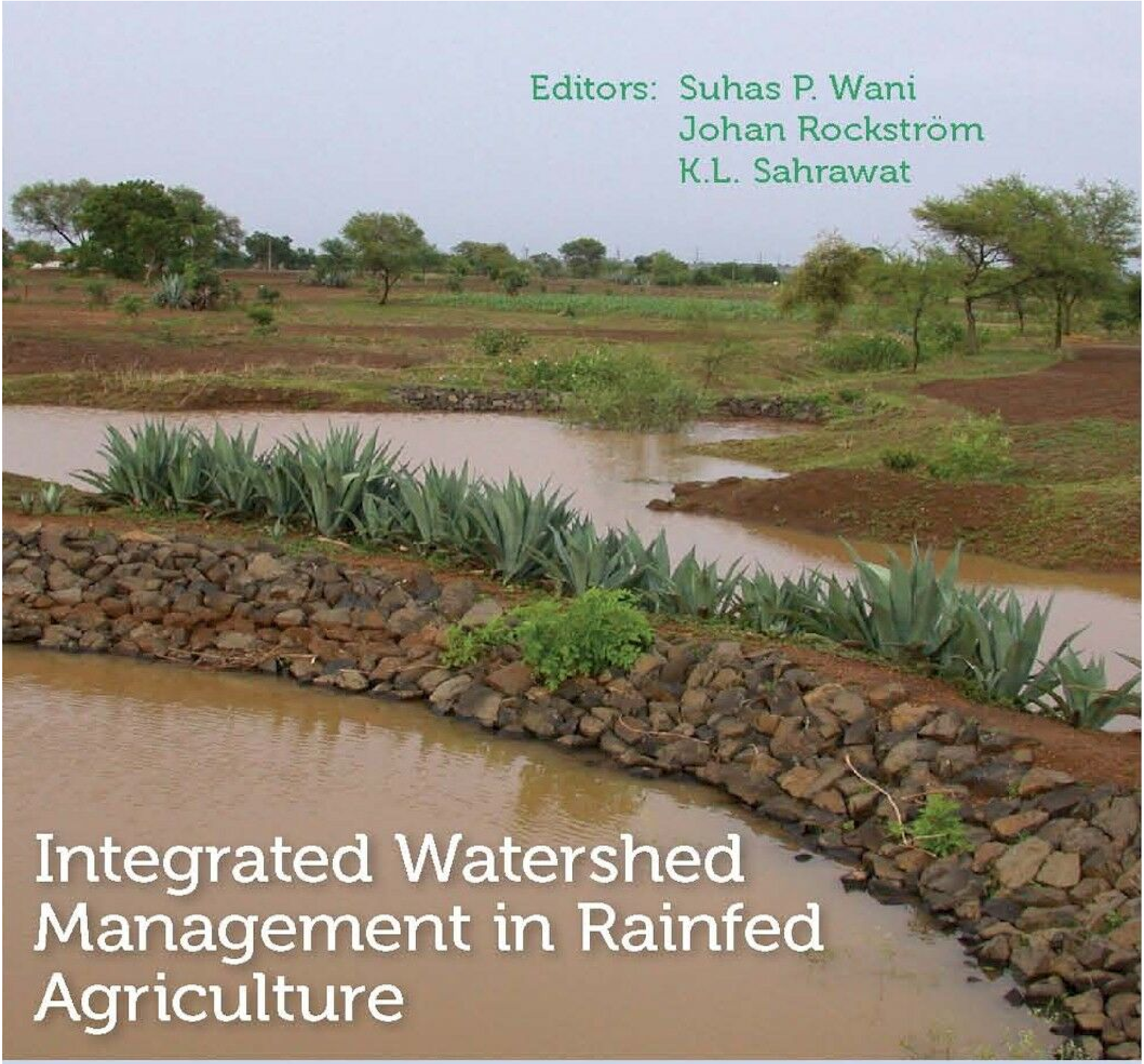
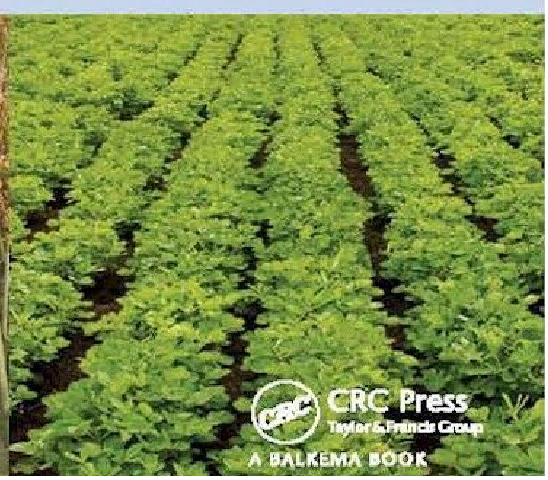


Integrated Watershed Management in Rainfed Agriculture



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Chapter 9

Management of emerging multinutrient deficiencies: A prerequisite for sustainable enhancement of rainfed agricultural productivity

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9.1 INTRODUCTION

Soil, water, vegetation, and production systems constitute the most important natural resources in an agroecosystem. In the rainfed production systems, the importance of water shortage and associated stress cannot be overemphasized especially in the semi-arid tropical (SAT) regions (Pathak *et al.*, 2009; Passioura and Angus 2010; Rockström *et al.*, 2010; Sahrawat *et al.*, 2010a; Sharma *et al.*, 2010). However, apart from water shortage, soil infertility is also the issue for crop production and productivity enhancement in much of the SAT regions of the world (El-Swaify *et al.*, 1985; Black 1993; Zougmore *et al.*, 2003; Sahrawat *et al.*, 2007, 2010a; Bationo *et al.*, 2008; Singh 2008; Twomlow *et al.*, 2008a; Bekunda *et al.*, 2010).

Apart from deficiencies of the major nutrients nitrogen (N) and phosphorus (P), the deficiencies of secondary nutrients especially of sulfur (S) and micronutrients have been reported with increasing frequencies from the intensified irrigated production systems (Kanwar 1972; Pasricha and Fox 1993; Takkar 1996; Scherer 2001, 2009; Fageria *et al.*, 2002; Singh 2008). While in the irrigated systems the deficiencies of various plant nutrients have been diagnosed through soil and plant testing and managed through the fertilization of crops, little attention has been paid to diagnosing the deficiencies of secondary nutrients such as S and micronutrients in dryland rainfed production systems (Sahrawat *et al.*, 2010a). In general, very little attention has been devoted to determine the fertility status of farmers' fields and hence to diagnose the nutrient problems in the rainfed production systems. Although, the information on the soil fertility status not only can help in enhancing crop productivity through balanced nutrient management, but also can promote judicious use of external inputs of nutrients (Wani 2008).

This apparent paradox of lack of application of adequate amounts of nutrients from external inputs (Katyal 2003; Bationo *et al.*, 2008) despite the common knowledge that the soil resource base in the rainfed systems of the SAT regions is relatively fragile and marginal compared to that under the irrigated production systems (El-Swaify *et al.*, 1985; Black 1993; Rego *et al.*, 2003; Sahrawat *et al.*, 2007, 2010a; Sharma *et al.*, 2009a, 2009b) is inexplicable. In the rainfed systems, water shortage has been the primary focus of research and developmental activities in these areas and soil infertility has largely been ignored (El-Swaify *et al.*, 1985; Wani *et al.*, 2003; Sahrawat *et al.*, 2010a, 2010b) or has not been addressed in an integrated manner (Wani *et al.*, 2002, 2009; Rockström *et al.*, 2007, 2010).

However, even in water-limiting environments there is potential to enhance agricultural productivity through efficient management of soil, water and nutrients in an integrated manner (Twomlow *et al.*, 2008a; Wani *et al.*, 2009; Sahrawat *et al.*, 2010a). To achieve the potential of productivity in water-limited environments, a concept of water-limited potential yield seems very appropriate as this forms the basis to reach the attainable yield in these environments by management of constraints other than just water shortage (Passioura 2006; Singh *et al.*, 2009). For example, in Australia, farmers have adopted the notion of water-limited potential yield as a benchmark for yield and if farmers find that their crops are performing below the benchmark, they look for the reasons and attempt to improve their management accordingly (Passioura and Angus 2010). We emphasize that in the concept of water-limited potential yield in the rainfed systems, natural resource management (NRM) in general and soil fertility management in particular need to be paid due attention alongside water stress management in view of the fragile nature of the soil resource base (Wani *et al.*, 2009; Sahrawat *et al.*, 2010a, 2010b).

Moreover, it is commonly believed that at relatively low yields of crops in the rainfed systems, the deficiencies of major nutrients, especially N and P are important for the SAT soils (El-Swaify *et al.*, 1985; Rego *et al.*, 2003; Sharma *et al.*, 2009a) and little attention has been devoted to diagnose the extent of deficiencies of the secondary nutrients such as S and micronutrients in various crop production systems (Sahrawat *et al.*, 2007, 2010a) on millions of small and marginal farmers' fields.

It is duly recognized and emphasized that the productivity of SAT soils is low due to water shortages. Although low fertility is also an issue, in practice the deficiencies of major nutrients (N and P) are considered important. Moreover, the input of major nutrients to dryland production systems is meager compared to that in the irrigated systems (Burford *et al.*, 1989; Rego *et al.*, 2005; Wani *et al.*, 2009). Also, due to low productivity of the rainfed crops, 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, soil and water conservation measures need to be integrated with plant nutrition, and choice of crops and their management (Burford *et al.*, 1989; Wani *et al.*, 2003; Passioura 2006; Passioura and Angus 2010; Sahrawat *et al.*, 2010b). The on-going farmer participatory integrated watershed management program at ICRISAT (International Crops Research Institute for the Semi-Arid Tropics) provided the opportunity to implement nutrient management strategy with soil and water conservation practices in farmers' fields in the Indian semi-arid tropics. For efficient and judicious use of nutrients through fertilizer inputs, assessing the soil's inherent nutrient status is a prerequisite (Sahrawat 2006).

Therefore, in this chapter the literature on the general fertility status of soils in the rainfed systems is reviewed and analyzed with emphasis on the diagnosis and management of the deficiencies of secondary and micronutrients in the rainfed systems of the SAT regions. Preference has been given to the results reported from the on-farm research in the SAT regions. First, the results on the fertility status of SAT soils are dealt, followed by the response of various food crops to balanced nutrient management considering the various nutrient deficiencies under the on-farm conditions. The role of soil testing in the diagnosis of nutrient deficiencies is demonstrated and the importance of integrated approach in which both water shortage and multi-nutrient deficiencies are simultaneously addressed is emphasized for sustainable enhancement of crop production and productivity in the rainfed systems.

9.2 SOIL DEGRADATION – ORGANIC MATTER AND NUTRIENT STATUS OF SAT SOILS

For the purpose of this chapter, we define soil degradation as the decline or loss of soil functions to produce goods of value to humans; and undoubtedly, soil degradation is at the heart of stagnant productivity, perpetuation of hunger, and malnutrition, and environmental security loss (Lal 1997, 2007; Sanchez 2002; Bationo *et al.*, 2008; Stringer 2009; Bekunda *et al.*, 2010). Soil degradation entails loss of soil (including organic matter and nutrients therein) as well as deterioration in its physical, chemical, and biological properties, and is a major threat to the sustainability of the agricultural systems (Bationo *et al.*, 2008; Sahrawat *et al.*, 2010b).

Soil organic matter is critical to soil fertility and water cycle management in the agroecosystems and its importance cannot be overemphasized in the SAT regions where soils are marginal and water shortage is the major stress to production systems (Bossio *et al.*, 2007). 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.*, 2010b). To maintain soil organic matter status, there is need to add organic materials including manures, organic and crop residues, on a regular basis (Bationo and Mokwunye 1991; Edmeades 2003; Harris 2002; Bationo *et al.*, 2008; Ghosh *et al.*, 2009; Materechera 2010).

Agricultural production related activities as a part of the NRM practice impact soil quality. The negative effects on soil quality that lead to soil degradation can be classified in two broad categories: (i) caused by soil loss due to water and wind erosion (Lal 1995; Pimentel *et al.*, 1995; den Biggelaar *et al.*, 2004a, 2004b; Montgomery 2007; Sahrawat *et al.*, 2010b), and (ii) 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.*, 2010b). The effects of soil loss on crop productivity vary widely depending on soil and NRM practices, and crop. Among the soil characteristics, soil organic matter status, clay, soil depth, etc. 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 and are major constraints to maintenance of soil quality, fertility, and agricultural productivity (van Asten 2003; Bellamy *et al.*, 2005; Pathak *et al.*, 2005; Singh 2008; Wani *et al.*, 2009; Bekunda *et al.*, 2010; Materechera 2010; Sahrawat *et al.*, 2010b; 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 included low soil fertility, fragile ecosystems, rainfall dependence, insufficient research, inadequate extension services, postharvest crop losses, insufficient market, and lack of consistent provisions for 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. For example, 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 loss of soil organic matter and major nutrients by erosion varies widely, but remains 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 it simply, for sustained productivity at a high level, the maintenance of soil fertility on a long-term basis 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 addition 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.*, 2010b). 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, 2010b). 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, 2004b; Pathak *et al.*, 2005; Sahrawat *et al.*, 2008a; Sharma *et al.*, 2009a, 2009b).

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 rainfed agricultural systems in the SAT regions of Asia and SSA. Negative nutrient balances (nutrient added minus nutrient harvested in crop) relative to mostly 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 is particularly acute in the rainfed 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 and 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 program (Wani *et al.*, 2009). Under this program, 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' landholding size (for details see Sahrawat *et al.*, 2008b). During these studies, soil samples were collected from farmers' fields in a farmer participatory manner, processed and analyzed

Table 9.1 Critical limits in the soil of plant nutrient elements to separate deficient samples from non-deficient samples[a]

Plant nutrient	*Critical limit* ($mg\,kg^{-1}$)
Sodium bicarbonate-extractable P	5
Ammonium acetate-extractable K	50
Calcium chloride-extractable S	8–10
Hot water-extractable B	0.58
DTPA-extractable Zn	0.75

[a]The data gleaned from various literature sources (for details see Rego *et al.*, 2007; Sahrawat *et al.*, 2007).

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 (BN) using the critical limits in the soil for various plant nutrients (Sahrawat 2006; Rego *et al.*, 2007; Sahrawat *et al.*, 2007) (Table 9.1) 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, soil type (especially clay and organic matter status), and agroclimatic conditions especially availability of irrigation water and status of other nutrients (other nutrients than the nutrient studied) 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).

The soil test results for pH, organic carbon (C), and extractable P, potassium (K), S, boron (B), and zinc (Zn) of a large number of soil samples collected from farmers' fields in the SAT regions of Indian states of Andhra Pradesh (3650), Karnataka (22867), 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 9.2). The soil analysis was carried out following methods described in Sahrawat *et al.* (2010a).

These first results on the fertility status of farmers' fields at a large scale showed that the samples were generally low in organic C (used as a proxy for N supplying capacity of a soil), low to medium in Olsen extractable P, medium to high in exchangeable K, and generally low in calcium chloride extractable S, hot water extractable B, and DTPA extractable Zn (Table 9.2). The results clearly demonstrate that soils are not only low in organic C and Olsen-P but also low in secondary nutrients such as S and micronutrients such as B and Zn. The number of farmers' fields sampled from 14 districts of Karnataka was fairly large and based on these some plausible conclusions can be drawn for the prevalence of plant nutrient problems in the state, which is the second largest state in the country with rainfed 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% 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 3650 farmers' 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 9.2). In Madhya Pradesh, B deficiency

Table 9.2 Chemical characteristics of soil samples collected from farmers' fields in the SAT regions of India[a]

District (No.of 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								
Adilabad	Range	6.4–8.9	0.27–1.33	0.2–48.8	46–549	2.0–142.2	0.10–0.74	0.22–2.90
(63)	Mean	8.2	0.62	6.9	204	12.2	0.34	0.62
	% Deficient			60	2	76	92	75
Anantapur	Range	5.4–9.6	0.11–1.45	0.6–42.4	14–352	0.2–117.3	0.02–1.40	0.14–5.00
(593)	Mean	7.5	0.30	7.7	73	4.5	0.21	0.59
	% Deficient			33	31	94	98	83
Kadapa	Range	5.3–8.8	0.11–0.79	0.2–25.4	17–387	1.7–41.9	0.04–3.02	0.24–5.20
(114)	Mean	7.4	0.27	3.9	80	6.6	0.39	0.76
	% Deficient			75	43	85	81	67
Khammam	Range	5.1–8.8	0.32–1.50	0.2–57.8	31–856	3.6–71.9	0.12–1.22	0.28–6.80
(102)	Mean	6.8	0.70	8.5	180	10.6	0.39	1.09
	% Deficient			60	2	67	87	45
Kurnool	Range	5.6–9.7	0.09–1.06	0.4–36.4	33–509	1.4–53.8	0.04–2.04	0.08–4.92
(331)	Mean	7.9	0.34	7.6	144	6.3	0.37	0.45
	% Deficient			42	5	85	79	91
Mahabubnagar	Range	5.3–10.2	0.08–2.18	0.2–247.7	16–1263	1.2–801.0	0.02–4.58	0.12–35.60
(1035)	Mean	7.4	0.42	12.6	119	16.2	0.30	1.11
	% Deficient			25	10	60	88	59
Medak	Range	5.0–9.1	0.09–3.00	0.5–75.1	11–978	1.7–431.0	0.08–1.84	0.24–3.26
(258)	Mean	7.7	0.49	8.0	161	12.4	0.57	0.78
	% Deficient			45	11	78	59	57
Nalgonda	Range	5.0–9.2	0.12–1.36	0.2–50.4	21–379	1.4–140.3	0.02–1.48	0.08–16.00
(441)	Mean	7.6	0.42	8.9	120	10.2	0.30	0.82
	% Deficient			31	7	78	90	66
Prakasam	Range	6.4–9.3	0.12–1.30	0.2–41.7	28–697	0.6–19.2	0.02–1.86	0.20–10.8
(492)	Mean	8.4	0.43	5.7	205	4.1	0.45	0.53
	% Deficient			56	1	94	71	88

Ranga Reddy (121)	Range	5.1–8.2	0.15–1.56	0.2–60.0	24–405	1.1–81.6	0.06–1.24	0.30–5.72
	Mean	6.7	0.50	8.9	92	3.7	0.26	1.16
	% Deficient			39	17	98	98	35
Warangal (100)	Range	6.1–9.4	0.08–0.84	0.2–53.4	21–280	1.8–48.9	0.10–1.42	0.26–3.88
	Mean	7.8	0.41	16.0	118	9.4	0.38	0.96
	% Deficient			14	5	77	84	50
State total (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
Karnataka								
Bengaluru Rural (2223)	Range	5.0–9.5	0.01–1.31	0.3–220.8	9–847	0.9–94.5	0.10–5.12	0.14–235
	Mean	6.4	0.41	18.9	93	5.4	0.39	1.47
	% Deficient			16	30	94	68	34
Bidar (1189)	Range	5.6–8.7	0.19–1.98	0.6–118.6	18–2297	1.0–181.3	0.12–2.96	0.16–18
	Mean	7.6	0.63	8.5	221	7.2	0.56	0.94
	% Deficient			49	1	84	65	55
Bijapur (1395)	Range	6.7–9.2	0.00–1.21	0.1–91.9	24–2613	0.9–4647.4	0.02–18.22	0.15–10.4
	Mean	8.2	0.44	3.9	225	38.5	0.93	0.58
	% Deficient			80	3	77	46	85
Chamaraja Nagara (818)	Range	5.1–9.7	0.05–1.85	0.2–77.5	25–738	0.4–119.4	0.08–3.80	0.14–6.4
	Mean	7.8	0.43	9.6	188	5.6	0.63	0.77
	% Deficient			40	3	90	57	62
Chikkaballapur (2257)	Range	5.0–9.9	0.07–1.42	0.2–430.8	4–1650	0.5–470.0	0.06–1.98	0.06–21.5
	Mean	6.9	0.39	18.0	95	9.1	0.38	1.15
	% Deficient			37	34	80	80	52

(*Continued*)

Table 9.2 Continued

District (No.of fields)	*Parameter*	*pH*	*Organic C (%)*	*Olsen-P* ($mg\,kg^{-1}$)	*Exch. K* ($mg\,kg^{-1}$)	*Extractable nutrient elements* ($mg\,kg^{-1}$) *S*	*B*	*Zn*
Chitradurga (1489)	Range	5.1–10.1	0.03–1.36	0.2–480.0	12–1953	0.8–291.8	0.04–6.94	0.08–40.5
	Mean	7.8	0.40	7.0	137	7.3	0.63	0.64
	% Deficient			54	15	86	64	80
Davangere (1500)	Range	5.0–9.0	0.04–1.38	0.0–138.8	11–510	0.9–945.0	0.06–6.30	0.04–11.2
	Mean	7.0	0.51	13.1	109	12.7	0.54	0.74
	% Deficient			34	13	77	66	74
Dharwad (1129)	Range	5.1–9.3	0.17–1.99	0.2–207.0	36–2344	1.4–715.0	0.10–12.48	0.24–24.3
	Mean	7.4	0.65	9.3	220	9.7	0.82	0.98
	% Deficient		31	53	1	79	39	44
Gadag (655)	Range	5.0–9.2	0.04–1.41	0.0–65.6	27–526	1.0–223.3	0.08–9.62	0.06–4.9
	Mean	8.1	0.44	5.3	178	7.4	0.88	0.44
	% Deficient			65	2	85	36	90
Gulbarga (2811)	Range	5.1–10.0	0.01–2.50	0.0–97.3	14–1722	0.4–12647	0.02–24.90	0.10–14.8
	Mean	8.0	0.46	7.1	244	27.6	0.64	0.52
	% Deficient		65	58	2	79	66	87
Haveri (1532)	Range	5.1–10.5	0.08–3.60	0.1–143.0	25–3750	0.3–120.3	0.08–8.44	0.20–34.1
	Mean	7.7	0.51	12.4	133	7.0	0.71	0.81
	% Deficient			42	5	85	46	60
Kolar (2161)	Range	5.0–10.2	0.04–1.50	0.0–182.0	9–1144	0.7–141.2	0.04–1.82	0.14–14.4
	Mean	7.0	0.38	20.3	87	7.0	0.34	1.31
	% Deficient		81	31	34	85	87	32
Raichur (1667)	Range	5.1–9.7	0.05–1.48	0.2–169.6	13–1797	0.8–2488	0.04–26.24	0.12–15.24
	Mean	8.3	0.43	11.8	209	46.8	1.17	0.66
	% Deficient			47	4	64	37	78
Tumkur (3041)	Range	5.0–10.0	0.04–2.08	0.1–204.0	11–1470	0.1–128.4	0.03–3.60	0.14–17.26
	Mean	6.6	0.39	5.9	92	5.5	0.33	0.89
	% Deficient			65	34	92	91	50

State total (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
Madhya Pradesh								
Badwani (20)	Range	7.6–8.4	0.28–0.76	0.5–18.4	73–299	4.0–40.4	0.18–0.70	0.30–1.14
	Mean	8.1	0.51	4.6	146	11.8	0.42	0.58
	% Deficient			70	0	55	80	75
Dewas (24)	Range	7.0–8.7	0.31–1.00	0.2–10.8	46–456	3.9–9.5	0.12–0.56	0.24–0.82
	Mean	8.0	0.60	2.1	137	6.3	0.24	0.45
	% Deficient			96	4	100	100	96
Guna (38)	Range	7.2–8.5	0.47–1.11	0.1–10.2	86–303	2.7–14.3	0.22–2.20	0.24–1.74
	Mean	8.0	0.65	3.2	158	6.3	0.67	0.51
	% Deficient			79	0	87	50	95
Indore (23)	Range	7.8–8.3	0.43–1.08	0.5–42.2	129–716	5.9–134.4	0.46–1.30	0.56–3.00
	Mean	8.1	0.66	10.4	263	29.7	0.82	1.11
	% Deficient			39	0	9	17	22
Jhabua (22)	Range	6.4–7.4	0.58–1.53	0.2–42.2	88–506	2.7–28.2	0.26–0.76	0.66–3.18
	Mean	7.0	0.88	9.7	216	6.3	0.40	1.54
	% Deficient			45	0	95	91	5
Mandla (21)	Range	5.9–7.2	0.45–1.25	1.0–7.2	82–287	2.0–13.2	0.06–0.80	0.48–1.14
	Mean	6.6	0.68	2.8	143	4.8	0.29	0.79
	% Deficient			90	0	90	86	52
Raisen (20)	Range	7.9–8.4	0.42–0.97	0.5–13.4	118–275	2.9–12.8	0.20–0.74	0.30–0.98
	Mean	8.1	0.58	3.1	199	6.2	0.35	0.49
	% Deficient			90	0	90	90	90

(*Continued*)

Table 9.2 Continued

District (No.of fields)	Parameter	pH	Organic C (%)	Olsen-P ($mg\,kg^{-1}$)	Exch. K ($mg\,kg^{-1}$)	Extractable nutrient elements ($mg\,kg^{-1}$)		
						S	B	Zn
Rajagarah (30)	Range	6.7–8.3	0.44–1.41	1.6–19.2	51–434	2.9–50.4	0.30–0.92	0.38–3.82
	Mean	7.9	0.78	5.7	203	12.3	0.49	1.14
	% Deficient			60	0	53	73	27
Sagar (32)	Range	6.7–8.0	0.42–2.19	0.5–68.0	149–333	4.2–23.8	0.18–1.22	0.50–3.10
	Mean	7.4	0.72	7.1	265	10.1	0.36	1.04
	% Deficient			78	0	63	91	34
Sehore (19)	Range	7.3–8.4	0.36–0.69	0.5–17.2	48–256	3.0–20.5	0.28–0.62	0.36–0.92
	Mean	8.1	0.50	4.0	167	8.3	0.39	0.53
	% Deficient			84	5	74	95	95
Shajapur (20)	Range	7.1–8.2	0.46–1.15	1.0–25.8	51–249	5.6–42.0	0.18–0.72	0.46–1.42
	Mean	7.7	0.82	8.7	120	17.2	0.43	0.85
	% Deficient			25	0	25	80	40
Vidisha (72)	Range	7.6–8.6	0.31–0.92	0.5–14.1	96–401	1.8–16.6	0.12–0.74	0.10–1.00
	Mean	8.2	0.56	2.8	203	5.5	0.35	0.34
	% Deficient			92	0	96	93	97
State total (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
Rajasthan								
Alwar (30)	Range	7.9–8.8	0.33–0.66	0.5–44.0	53–515	4.5–17.2	0.20–0.68	0.20–2.00
	Mean	8.5	0.46	14.3	128	9.2	0.45	0.56
	% Deficient			10	0	63	87	83
Banswara (30)	Range	6.3–8.1	0.28–1.05	1.0–35.0	31–418	2.4–22.0	0.10–0.54	0.26–2.60
	Mean	7.2	0.56	7.7	107	9.2	0.23	0.70
	% Deficient			50	17	70	100	80
Bhilwara (30)	Range	7.2–8.9	0.32–1.87	0.8–27.0	33–460	4.0–44.9	0.32–1.30	0.16–2.30
	Mean	8.3	0.74	9.2	111	12.8	0.64	0.92
	% Deficient			40	17	43	47	37

Bundi (36)	Range	6.2–8.7	0.18–1.17	0.9–20.1	23–563	3.3–51.0	0.10–0.98	0.20–1.78
	Mean	7.6	0.60	6.2	87	9.2	0.44	0.65
	% Deficient			53	50	72	72	67
Dungarpur (99)	Range	6.2–8.0	0.48–1.99	1.0–28.2	34–240	4.0–31.3	0.28–1.50	0.88–14.10
	Mean	6.9	1.26	6.6	100	9.0	0.70	2.11
	% Deficient			48	8	72	31	0
Jhalawar (30)	Range	8.0–8.6	0.46–1.15	0.9–22.6	51–1358	1.9–78.0	0.22–1.36	0.40–3.40
	Mean	8.4	0.76	10.2	214	8.3	0.49	0.75
	% Deficient			30	0	87	77	60
Sawai Madhopur (44)	Range	7.8–9.4	0.16–0.70	0.2–11.8	44–438	3.1–26.6	0.20–2.18	0.34–28.60
	Mean	8.5	0.38	4.0	137	6.8	0.64	2.54
	% Deficient			73	7	86	52	41
Tonk (78)	Range	6.8–10.2	0.09–1.11	0.2–28.2	14–243	2.3–29.8	0.08–2.46	0.18–14.00
	Mean	8.1	0.36	5.7	83	7.7	0.62	1.61
	% Deficient			55	32	79	64	58
Udaipur (44)	Range	7.3–9.0	0.25–2.37	2.6–41.0	52–288	3.2–274.0	0.22–1.50	0.70–3.92
	Mean	8.2	0.83	15.2	145	26.7	0.83	1.57
	% Deficient			18	0	48	25	5
State total (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
Grand total (India) (28270)	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	10.9	147	13.6	0.55	0.88
	% Deficient			46	16	82	68	62

[a]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 (see Table 1).

was most prevalent (79% of 341 fields sampled), followed by S (74% fields), Olsen-P (74% fields), and Zn (66% fields) while in Rajasthan, the deficiency of S was most widespread (in 71% of 421 fields sampled), followed by B (56% fields), Zn (40% fields), Olsen-P (45% fields), and K (15% fields) (Table 9.2).

Considering all the four states in the SAT region of India, it can be concluded that the deficiency of S (calcium chloride extractable) was most widespread (on an average 82% of the 28270 farmers' fields sampled were deficient), followed by hot water extractable B (68% of the farmers' fields sampled were deficient), and DTPA extractable Zn (62% of the farmers' fields were deficient), and was indeed most revealing. These results are in accord with those reported earlier with a limited number of soil samples (Rego *et al.*, 2005; Sahrawat *et al.*, 2007, 2010a). On the other hand, K deficiency was not prominent (on an average only 16% of 28270 farmers' fields sampled were deficient) in the rainfed SAT soils (Table 9.2).

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 rainfed production systems of the SAT regions of India. The deficiency levels 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.*, 2009, 2010a). In the past, no survey of the nutrient deficiencies in SAT regions has been undertaken and so there are no benchmark results to compare the deficiencies of S and micronutrients in a large number of farmers' fields. But these results demonstrate clearly that in addition to water stress, multiple-nutrient deficiencies have to be managed to unlock the potential of rainfed 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 rainfed systems (El-Swaify *et al.*, 1985; Burford *et al.*, 1989; Sahrawat *et al.*, 1991, 2001; Rego *et al.*, 2003; Bationo *et al.*, 2008).

9.3 BALANCED NUTRIENT MANAGEMENT: CROP PRODUCTIVITY AND QUALITY

As mentioned earlier, soil fertility management research in the rainfed areas has focused mainly on the management of major nutrients (N, P, and K) and even the amounts of these nutrients 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 rainfed systems. However, recent work by ICRISAT and its partners and other researchers has shown that for realizing the potential of rainfed 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).

For example, during 2002–04, 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 BN based on soil test results using mung bean (*Vigna radiata*), maize (*Zea mays*), groundnut (*Arachis hypogaea*), castor (*Ricinus communis*), and pigeonpea (*Cajanus cajan*). There were two treatments: (i) control or farmer's nutrient input (FI); and (ii) BN, which consisted of the application of SBZn + NP over FI or FI + SBZn + NP.

Table 9.3 Grain yield of crops in response to fertilization under farmer's nutrient input (FI) and balanced nutrient management (BN) treatments in the semi-arid zone of Andhra Pradesh, India during three (2002 to 2004) rainy seasons[a]

		Grain yield (kg ha^{-1})				
Year	*Treatment*[b]	*Maize*	*Castor*	*Mung bean*	*Groundnut (pod)*	*Pigeonpea*
2002	FI	2730 (20)[c]	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]Source: Rego *et al.* (2007); data on pigeonpea crop are from ICRISAT.
[b]BN = FI + SBZn + NP
[c]The number of farmers' fields on which on-farm trials were conducted is given in parenthesis.

Briefly, for applying nutrients as per BN treatment (FI + SBZn + NP), S, B, and Zn were applied as 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}) 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 ha^{-1} for maize and castor or 20 kg N ha^{-1} for groundnut and mung bean; and P was added at 30 kg P_20_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 topdressed in the case of maize and castor. In the case of NP treatment, 20 kg N ha^{-1} and 30 kg P_20_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, and 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 were significantly increased under BN treatment with the application of SBZn + NP over the FI treatment in the three seasons (Table 9.3).

A large number of on-farm trials were also conducted in the semi-arid zone of Karnataka during five rainy seasons (2005–09) with maize, finger millet (*Eleusine coracana*), groundnut, and soybean (*Glycine max*) 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 FI treatment (Table 9.4). In another set of trials, conducted during 2005–07 in the semi-arid zone of Karnataka, BN treatment significantly increased maize grain yield and dry matter over the FI treatment; BN also significantly improved the harvest index of the crop during all the three seasons (Rajashekhara Rao *et al.*, 2010) (Table 9.5).

The results of on-farm trials conducted in the SAT zone of Madhya Pradesh with soybean in the rainy season (2008 and 2009) and chickpea in the postrainy season (2008) confirmed the superiority of the BN treatment over the FI treatment and significantly increased soybean and chickpea grain yields (Table 9.6). Similar results were obtained in the on-farm trials conducted during the 2008 rainy season in the semi-arid

Table 9.4 Grain yield of crops in response to fertilization under farmer's nutrient input (FI) and balanced nutrient management (BN) treatments in the semi-arid zone of Karnataka, India during five rainy seasons, 2005–09[a]

		Grain yield (kg ha^{-1})			
Year	*Treatment*[b]	*Maize*	*Finger millet*	*Groundnut*	*Soybean*
2005	FI	4000 (6)[c]	2100 (16)	1830 (8)	2030 (6)
	BN	6090	3280	1910	3470
	LSD (0.05)	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
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)
	BN	7800	2570	1500	2610
	LSD (0.05)	178	91	49.9	184

[a]Source: Data are from ICRISAT.
[b]BN = FI + SBZn + NP
[c]The number of farmers' fields on which on-farm trials were conducted is given in parenthesis.

Table 9.5 Yield of maize in response to fertilization under farmer's nutrient input (FI) and balanced nutrient management (BN) treatments in on-farm trials in the Haveri district of Karnataka, India, 2005–07[a]

	Yield (t ha^{-1})		
Treatment	*Grain*	*Stover*	*Harvest index (%)*[b]
2005 (9)[c]			
FI	4.00	4.62	46.5
BN	6.09	5.92	50.7
LSD (0.05)	0.49	0.54	1.2
2006 (20)[c]			
FI	3.77	3.80	49.8
BN	5.37	5.12	51.2
LSD (0.05)	0.56	0.52	1.2
2007 (17)[c]			
FI	5.10	4.84	47.2
BN	6.32	5.82	51.3
LSD (0.05)	0.65	0.77	1.6

[a]Source: Adapted from Rajashekhara Rao *et al.* (2010).
BN = FI + SBZn + NP
The plots under BN treatment received 80 kg N, 30 kg P_2O_5, 30 kg S, 10 kg Zn, and 0.5 kg B ha^{-1}.
[b]Harvest index is Grain wt/(Grain wt + Stover wt) × 100.
[c] Number of participating farmers is given in parenthesis.

Table 9.6 Grain yield of soybean (rainy season) and chickpea (postrainy season) in response to fertilization under farmer's nutrient input (FI) and balanced nutrient management (BN) treatments in Madhya Pradesh, India during 2008 and 2008–09 seasons[a]

		Grain yield[b] (kg ha^{-1})	
Year	*Treatment*	*Soybean*	*Chickpea*
2008	FI	1490 (117)	1250 (169)
	BN	1840	1440
	LSD (0.05)	56	29
2009	FI	2120 (140)	
	BN	2680	
	LSD (0.05)	95	

[a]Source: Data are from ICRISAT.
BN = FI + SBZn + NP
[b]The number of farmers' fields on which on-farm trials were conducted is given in parenthesis.

Table 9.7 Grain yield of maize and pearl millet in response to fertilization under farmer's nutrient input (FI) and balanced nutrient management (BN) treatments in the semi-arid zone of Rajasthan, India during 2008 rainy season[a]

	Grain yield[b] (kg ha^{-1})	
Treatment	*Maize*	*Pearl millet*
FI	2730 (17)	2310 (16)
BN	2980	2510
LSD (0.05)	55	34.3

[a]Source: Data are from ICRISAT.
BN = FI + SBZn + NP
[b]The number of farmers' fields on which on-farm trials were conducted is given in parenthesis.

zone of Rajasthan with pearl millet (*Pennisetum glaucum*) and maize as the test crops; and the grain yields of these crops were significantly increased in the BN treatment as compared to FI (Table 9.7).

On-farm trials were conducted during the 2006–07 season with a number of vegetable crops in watersheds in Dharwad, Haveri, and Chitradurga districts of Karnataka to study their responses to BN as compared to FI treatment. The results showed an impressive yield response to BN as compared to FI treatment; and the growing of these vegetables under BN was economically viable and remunerative (Srinivasarao *et al.*, 2010) (Tables 9.8 and 9.9).

Balanced plant nutrition is not only important for increasing crop productivity but also critical for enhancing crop quality including grain and stover/straw quality, which 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

Table 9.8 Response of vegetables to farmer's nutrient input (FI) and balanced nutrient management (BN) treatments in watersheds in Dharwad and Haveri districts of Karnataka, India[a]

Crop[b]	*Fresh fruit yield (kg ha^{-1})*		*Farm-gate price (₹ kg^{-1})*	*Additional cost (₹ ha^{-1})*	*Additional net returns (₹ ha^{-1})*	*Benefit-cost ratio*
	FI	*BN*				
Ridge gourd (2)	5400	6300	6.0	3050	5700	1.87
Bitter gourd (2)	3000	3900	9.3	3050	8250	2.71
Chili (4)	6000	8500	5.5	3050	13000	4.26
Brinjal (eggplant) (4)	6000	8000	6.8	3050	12770	4.19
Tomato (4)	11200	17100	6.4	3050	34800	11.4

[a]Source: Adapted from Srinivasarao *et al.* (2010).
BN = FI + SBZn + NP
[b]Number of farmers, is given in parenthesis.

Table 9.9 Comparative response of onion to farmer's nutrient input (FI) and balanced nutrient management (BN) treatments in various watersheds in Chitradurga district of Karnataka, India[a]

Watershed	*No. of farmers*		*Onion fresh wt. (t ha^{-1})*		*Increase in wt. (%)*
			FI	*BN*[b]	
Maradihalli	10	Range	21–30	30–37.5	41
		Mean	24.8	34.5	
Toparamalige	10	Range	22.5–31.5	27.0-38.8	31
		Mean	26.7	34.7	
Belagatta	4	Range	22.5–31.5	27.0–38.8	45
		Mean	27.3	35.6	

[a]Source: Adapted from Srinivasarao *et al.* (2010).
[b]BN = FI + SBZn + NP

of crops along with improved cultivars of crops and crop management cannot be overemphasized for producing nutritious food (Welch *et al.*, 1997; Graham *et al.*, 1998, 2007; Welch and Graham 2002, 2004; Parthasarathy Rao *et al.*, 2006; Sahrawat *et al.*, 2008a) and fodder (Kelly *et al.*, 1996; Sahrawat *et al.*, 2008a; Rattan *et al.*, 2009).

For example, in the on-farm experiments conducted to determine the effects of S, B, and Zn fertilization on the grain and straw quality of sorghum (*Sorghum bicolor*) and maize grown under rainfed conditions in the SAT region of India showed that BN through combined application of S, B, Zn, N, and P as compared to FI increased N, S, and Zn concentrations in the grain and straw of these crops (Sahrawat *et al.*, 2008a) (Tables 9.10 and 9.11). These results stress the importance of balanced mineral nutrition of crops for increased produce quality. For example, the S fertilization of oilseed crops such as soybean (Saha *et al.*, 2001), canola (Brennan and Bolland 2008; Brennan *et al.*, 2010), and sunflower (*Helianthus annuus*) (Usha Rani *et al.*, 2009) is not only required for increasing dry matter and seed yield but also essential for enhancing oil concentration and quality.

Table 9.10 Chemical composition of the grain and straw of sorghum crop as affected by farmer's nutrient input (FI) and balanced nutrient management (BN) treatments in the semi-arid region of India, 2003 rainy season[a]

Treatment[b]	*N* ($g\,kg^{-1}$)	*P* ($g\,kg^{-1}$)	*S* ($mg\,kg^{-1}$)	*B* ($mg\,kg^{-1}$)	*Zn* ($mg\,kg^{-1}$)
Grain					
FI	10.7	2.5	535	0.18	21
BN	13.2	2.8	766	0.22	31
LSD (0.05)	0.9	0.5	46	0.08	5.8
Straw					
FI	2.2	0.7	491	0.7	22
BN	2.6	0.6	537	1.1	31
LSD (0.05)	1.0	0.2	92	0.63	5.7

[a]Source: Adapted from Sahrawat *et al.* (2008a).
[b]BN = FI + SBZn + NP

Table 9.11 Chemical composition of the grain and straw of maize crop as affected by farmer's nutrient input (FI) and balanced nutrient management (BN) treatments in the semi-arid region of India, 2004 rainy season[a]

Treatment[b]	*N* ($g\,kg^{-1}$)	*P* ($g\,kg^{-1}$)	*S* ($mg\,kg^{-1}$)	*B* ($mg\,kg^{-1}$)	*Zn* ($mg\,kg^{-1}$)
Grain					
FI	14.0	3.2	1095	1.4	23
BN	15.1	3.0	1153	1.8	22
LSD (0.05)	1.0	0.4	52	0.67	1.7
Straw					
FI	7.9	1.5	798	5.1	18
BN	6.6	1.3	921	5.9	20
LSD (0.05)	0.7	0.4	193	1.45	4.0

[a]Source: Adapted from Sahrawat *et al.* (2008a).
[b]BN = FI + SBZn + NP

From this discussion on the results obtained in a large number of on-farm trials, it is evident that in the SAT region multiple nutrient deficiencies especially of N, P, S, B, and Zn are holding back the potential of rainfed systems. Also, soil fertility depletion has been recognized as the major biophysical cause of declining food availability in smallholder farms in SSA. Any program 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 (Pieri 1989; Sanchez *et al.*, 1997; Izac 2000; Vanlauwe 2004; 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 also equally essential for maintaining crop quality in terms of food, fodder, and feed quality (Kelly *et al.*, 1996; Sahrawat *et al.*, 2008a), especially iron (Fe) and Zn in the grain (Welch and Graham 2004; Graham *et al.*, 2007; Sahrawat *et al.*, 2008a; Rattan *et al.*, 2009). The results from on-farm studies also show that the productivity of the rainfed 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 rainfed systems. Because the area under rainfed 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.

9.4 SOIL QUALITY AND WATER USE EFFICIENCY

Soil quality is defined for various purposes, but for the purpose of this chapter we use the definition given by Doran and Parkin (1994) and Karlen *et al.* (1997) which relates to the soil's capacity to function, and to perform its agricultural production and environmental functions on a sustainable basis. In the general scientific literature, the terms soil quality and soil health have been interchangeably used, but in the soil science literature the term soil quality is preferred. While soil health refers to the state of soil as a living and dynamic system, soil quality on the other hand emphasizes the soil's capacity to sustain biological productivity and maintain environmental quality. Both soil quality and soil health are functional in nature and soil quality can also be used to cover the soil health too. For detailed discussion on soil quality and soil health, the readers are referred to extensive studies by various researchers (Doran *et al.*, 1996; Freckman and Virginia 1997; Karlen *et al.*, 1997, 2003; Sojka *et al.*, 2003; Sahrawat *et al.*, 2010b).

The productivity in rainfed systems have remained low because of frequent drought due to high variability in both the amount and distribution of rainfall in the growing season, poor soil quality, low use of plant nutrients, small farm holding size, and other farmers' socioeconomic conditions (Pieri 1995; Bationo *et al.*, 2008; Sharma *et al.*, 2009b; Sahrawat *et al.*, 2010b). However, the potential productivity under rainfed condition in the SAT agriculture can be enhanced by improving soil quality by managing plant nutrient disorders (Padwick 1983; Ouédraogo *et al.*, 2001; Tiwari 2008; Scherer 2009; Sahrawat *et al.*, 2010a) and increasing rainfall use efficiency (RUE) (Singh *et al.*, 2009; Wani *et al.*, 2009).

Efficient use of rainwater involves harvesting of extra runoff water (after recharge of the soil profile) in the rainy season and its efficient use for supplemental irrigation wherever the opportunity exists. The use of harvested water for supplemental irrigation of rainfed crops in the SAT regions showed that the benefits of supplemental irrigation in terms of enhancing and stabilizing crop productivity have been excellent even in the areas with relatively assured rainfall areas (Pathak *et al.*, 2009). In the drier areas, supplemental irrigation can make a large difference in crop production and in some instances it can make a difference in having a crop or no crop (Oweis and Hachum 2009). Thus, rainwater management holds the key to successful crop production in the SAT and dry regions (Rockström *et al.*, 2002; Wani *et al.*, 2002, 2008, 2009; Bationo *et al.*, 2008; Pathak *et al.*, 2009). In the light of very impressive responses of crop to supplemental irrigation, it is imperative that most efficient use is made of the scarce

Table 9.12 Effects of micronutrient application on rainfall use efficiency in various field crops in Andhra Pradesh and Madhya Pradesh, India[a]

	Rainfall use efficiency (kg mm^{-1} ha^{-1})	
Crop	*Farmer's practice*	*Farmer's practice + micronutrients*
Andhra Pradesh		
Maize	5.2	9.2
Groundnut	1.6	2.8
Mung bean	1.7	2.9
Sorghum	1.7	3.7
Madhya Pradesh		
Soybean	1.4	2.7

[a]Source: Adapted from Singh *et al.* (2009).

resource using efficient method of water application at a critical stage of the crop when the response is highest (for review see Oweis and Hachum 2009; Pathak *et al.*, 2009).

For efficient use of water and to increase RUE, soil quality especially the management of various nutrient deficiencies in the production systems is a prerequisite. For example, Singh *et al.* (2009) reported that the application of S, B, and Zn over the FI treatment in on-farm trials in the SAT regions of India (states of Andhra Pradesh and Madhya Pradesh) increased the productivity of rainfed crops, resulting in increased RUE. The RUE of maize for grain production under FI was 5.2 kg mm^{-1} water compared to 9.2 kg mm^{-1} water with the combined application of S, B, and Zn over the FI treatment (Table 9.12). The best results in terms of RUE for maize and several other crops however, were obtained under the BN treatment when N and P were added along with S, B, and Zn (Singh *et al.*, 2009). These results are in accord with those reported by Rego *et al.* (2007) who found that farmers were applying sub-optimum quantity of major nutrients especially N and P and thus the applications of NP along with SBZn (NP + SBZn) gave the best results in terms of crop yield and biomass production, and nutrient uptake.

In an on-farm study conducted for three seasons (2005-07) in the SAT region of Karnataka, Rajashekhara Rao *et al.* (2010) reported that BN not only increased grain and stover yield of rainfed maize (see results in Table 9.5) but also increased partial factor productivity [Grain yield in fertilized plot = (Grain yield in absolute control + Yield increase due to treatment) × Amount of nutrient applied], agronomic efficiency (the incremental efficiency of applied nutrients over the control), benefit-cost ratio [(Grain yield of fertilized plot × Price of grain): (Amount of nutrient applied × Price of the applied nutrient inputs)], and RUE (Grain yield/rainfall received during the growing season) for maize production (Table 9.13).

Results from on-farm trials conducted in the SAT regions of Karnataka and Madhya Pradesh in India during rainy season in 2008 and 2009 with maize, finger millet, groundnut, and soybean showed that BN treatment increased the grain yields of these crops and the yield increase was economically attractive and remunerative (Table 9.14).

Table 9.13 Partial factor productivity, agronomic efficiency, benefit-cost ratio and rainfall use efficiency under farmer's nutrient input (FI) and balanced nutrient management (BN) treatments, 2005–07[a]

Production efficiency parameters[b]	*FI*	*BN*[c]
Partial factor productivity (kg grain kg^{-1} of nutrients)	40.8	48.4 (18.6)
Agronomic efficiency (kg grain kg^{-1} of nutrients)	12.5	16.0 (28.0)
Benefit-cost ratio	3.2	4.6 (43.8)
Rainfall use efficiency (kg grain mm^{-1} of rainfall)	9.8	14.6 (49.2)

[a]Source: Adapted from Rajashekhara Rao *et al.* (2010).
[b]Calculated using mean grain yield values in 2005, 2006, and 2007 seasons.
[c]Values in parentheses indicate percent increase or decrease in each parameter over FI treatment.

Table 9.14 Economics of fertilizer use for grain production of crops in on-farm trials conducted during rainy season 2008 and 2009 in the SAT regions of India[a]

State	*Crop*	*Grain yield (kg ha^{-1})* FI[b]	*FI + SBZn*	*Yield increase (kg ha^{-1})*	*Support price of grain (₹ kg^{-1})*	*Additional income (₹)*	*Additional income per rupee invested*
2008							
Karnataka	Maize	4400	6130	1730	8.40	14532	7.9
	Finger millet	1680	2650	970	9.15	8876	4.8
	Groundnut (pod)	940	1430	490	21.00	10290	5.6
	Soybean	1390	1640	250	13.90	3475	1.9
Madhya Pradesh	Soybean	1490	1840	350	13.90	4865	2.6
2009							
Karnataka	Maize	5460	7800	2340	8.40	19656	10.6
	Finger millet	1630	2570	940	9.15	8601	4.6
	Groundnut (pod)	1100	1500	400	21.00	8400	4.5
	Soybean	1770	2610	840	13.90	11676	6.3
Madhya Pradesh	Soybean	2120	2680	560	13.90	7784	4.2
Mean							4.4
Fertilizer	*Recommended rate (kg ha^{-1})*	*Cost (₹ kg^{-1})*	*Total cost (₹ ha^{-1})*				
Gypsum	200	1.5	300				
Borax	5	40	200				
Zinc sulfate	50	27	1350				
Total cost (ha^{-1})			1850				

[a]Source: Data are from ICRISAT.
[b]FI = Farmer's nutrient input
1US$ = ₹45

Thus, soil quality or health is a major driver of enhanced RUE and productivity in the rainfed systems and needs an implementing strategy in which BN is integrated with soil and water conservation and management (Wani *et al.*, 2009). For maintaining soil health, the changes in soil quality, as impacted by NRM practices, need to be monitored and assessed on a continuing basis as the outcome of such research can offer the valuable opportunity for the implementation of corrective management practices, as and when needed (Mandal *et al.*, 2001; Wander *et al.*, 2002; Sanchez *et al.*, 2003; Andrews *et al.*, 2004; Lilburne *et al.*, 2004; Turner *et al.*, 2007; Wilson *et al.*, 2008; Cotching and Kidd 2010; Sahrawat *et al.*, 2010a).

In the monitoring and assessment of soil health or quality, most of the indices used are chemical and little use is made of the biological fertility indicators in the monitoring program. In a recent study on soil quality evaluation and the interaction with land use and soil order in Tasmania, Australia, Cotching and Kidd (2010) reported that six soil properties [pH, organic C, Olsen-P, aggregate stability, bulk density, and exchangeable sodium percentage (ESP)] were generally responsive to soil order and land use change, although there were differences in their responsiveness to soil order and land use change.

9.5 STRATEGY FOR SCALING-UP THE SOIL TEST-BASED APPROACH FOR ENHANCING AGRICULTURAL PRODUCTIVITY

Low productivity in rainfed systems coupled with water shortage, degraded and marginal soil resource base, and lack of investment in soil fertility maintenance has been marginalizing agriculture and livelihoods in the rainfed areas in much of the SAT regions. To come out of this cycle, there is an urgent need to address the two major constraints to rainfed productivity enhancement, i.e., to simultaneously address the twin problems of water shortage and soil infertility. The watershed approach seems most rational and appropriate to simultaneously implement in an integrated manner both soil and water conservation and management practices with BN at the farm level. The strategy to maintain soil quality and fertility is to use inputs of organic matter and nutrients from both mineral and organic sources (Palm *et al.*, 2001; Bationo *et al.*, 2008). The sources of organic matter inputs should be considered on site-specific basis, but their use is essential for maintaining the physical, chemical, and biological properties of the soil, a prerequisite for the soil to carry out its agricultural production and environmental quality related functions in a sustainable manner (Palm *et al.*, 2001; Sahrawat *et al.*, 2010a, 2010b).

In this section we discuss soil testing as a mechanism for fertility and soil quality management at the farm level. Soil test-based recommendations form the basis for BN to enhance productivity and produce quality. A large body of results presented and discussed in this chapter clearly demonstrates the potential of soil testing for diagnosing and management of the nutrient related disorders in the rainfed agroecosystem (Wani 2008; Subba Rao *et al.*, 2009; Sahrawat *et al.*, 2010a). Since 2002, ICRISAT and its partners have been conducting on-farm trials to develop BN practices to increase agricultural productivity and household incomes in the SAT regions with very impressive results in terms of yields of crops at the farm level. There is an urgent need to scale-up the program so that more and more numbers of farmers are able to benefit from soil test-based nutrient management intervention. This approach will lead to rational and judicious use of purchased inputs of nutrients to enhance and stabilize agricultural productivity in the rainfed areas of the SAT regions.

For scaling-up the soil test-based nutrient management approach at the farm level, a systematic approach is outlined, which has been found useful in our on-farm research (Wani *et al.*, 2002, 2008; Rego *et al.*, 2005, 2007; Sahrawat *et al.*, 2007, 2010a). The first step in this approach is to collect the baseline data on types of soils, dominant crops/cropping systems and their current yield levels, farmer holding size and their socioeconomic status following participatory rural appraisal in the watershed or the cluster of villages to be sampled.

For effective sampling, a watershed or a cluster of villages was divided into three groups based on the position of the fields on a toposequence: top, middle, and bottom, depending on the elevation and drainage of the landscape. Different soil types were separated in each group. For soil sampling, 20% of farmers in each position on the toposequence were randomly selected in proportion to the farm size. Using stratified random sampling methodology (for details see Sahrawat *et al.*, 2008b), 8 to 10 cores of surface soil (0–15 cm deep) were collected to make one composite sample. A farmer participatory approach was used for the collection of soil samples and farmers were trained to collect soil samples from their fields. The soil samples were transported to the ICRISAT laboratory in Patancheru, India for processing and analysis for soil chemical fertility parameters. The samples were air dried and powdered with a wooden hammer to pass through a 2-mm sieve. For organic C analysis, the samples were ground to pass through a 0.25-mm sieve. Standard methods were used for the analyses of soil samples for pH, organic C, and extractable or available major, secondary, and micronutrients (Sahrawat *et al.*, 2007).

The soil test results were shared with farmers during village meetings. They were briefed about the relevance of analysis of results from the stratified soil sampling and how it applies to their fields and recommendations were formulated for the application of BN alongside FI treatment in the on-farm trials. The results of the soil analysis were also disseminated through wall writings in the village. Later, on-farm participatory research and development (PR&D) trials were conducted to determine and compare the crop yields under BN with those in the FI treatment. The results were explained to other farmers during the field days. Various crop, nutrient, and soil management practices are described by Rego *et al.* (2007) and Sahrawat *et al.* (2010a).

For example, in the first year of the study, the on-farm trials were conducted in nine nuclear microwatersheds or cluster of villages in a district. During the second year, the nutrient management trials were extended to 5×9 watersheds in the same district; and in a period of 3 to 4 years the entire district was covered by the trials. Following the same methodology, the trials cover several districts in a state and eventually the entire state could be covered by BN (Rego *et al.*, 2007). Data from several districts in a state are summarized and interpreted to learn lessons for the extension of such trials in a state or region. The crops covered in these trials include the most important or dominant crops in the district and the results of BN treatment are compared with those of FI treatment. The key to the success of such a program hinges on the participatory nature of the farmers who are involved in planning of the on-farm activities, soil sampling, discussion, and sharing of soil test results for the formulation of recommendations for BN (for details see Rego *et al.*, 2005, 2007; Wani 2008).

The data on yield and additional income earned by farmer households as a result of soil test-based BN, are discussed with farmers and this acts as a catalyst to create awareness and interest among other farmers who had seen good crops in the participating farmers' fields. This has a multiplier effect in the adoption of the technology with adequate support for soil testing, capacity building of all the stakeholders, and implementation of the various practices in the technology at the farm level (Wani 2008; Sahrawat *et al.*, 2010a).

For practical utilization of the soil test-based nutrient management, we have been mapping using the geographical information system (GIS) based extrapolation methodology, the deficiencies of nutrients especially those of S, B, and Zn in various districts in Karnataka. Finally, the soil test-based fertilizer application has been made web-based so that the recommendations can be downloaded and made available nutrient-wise to farmers using color codes depicting the deficiency or sufficiency of a nutrient. Such information can be easily used by smallholder farmers. Typical examples of nutrient mapping for extractable (available) S, B, and Zn, using data from selected districts of Karnataka are shown in Figure 9.1. 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.

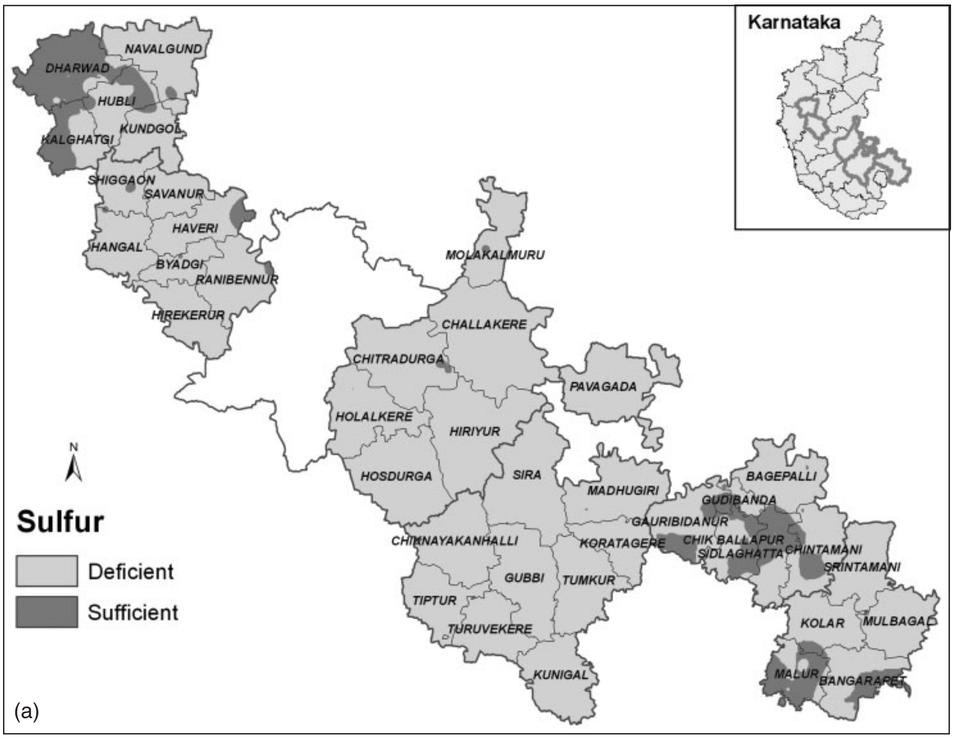

Figure 9.1 Distribution of extractable sulfur, boron, and zinc in soil samples from various districts of Karnataka, India

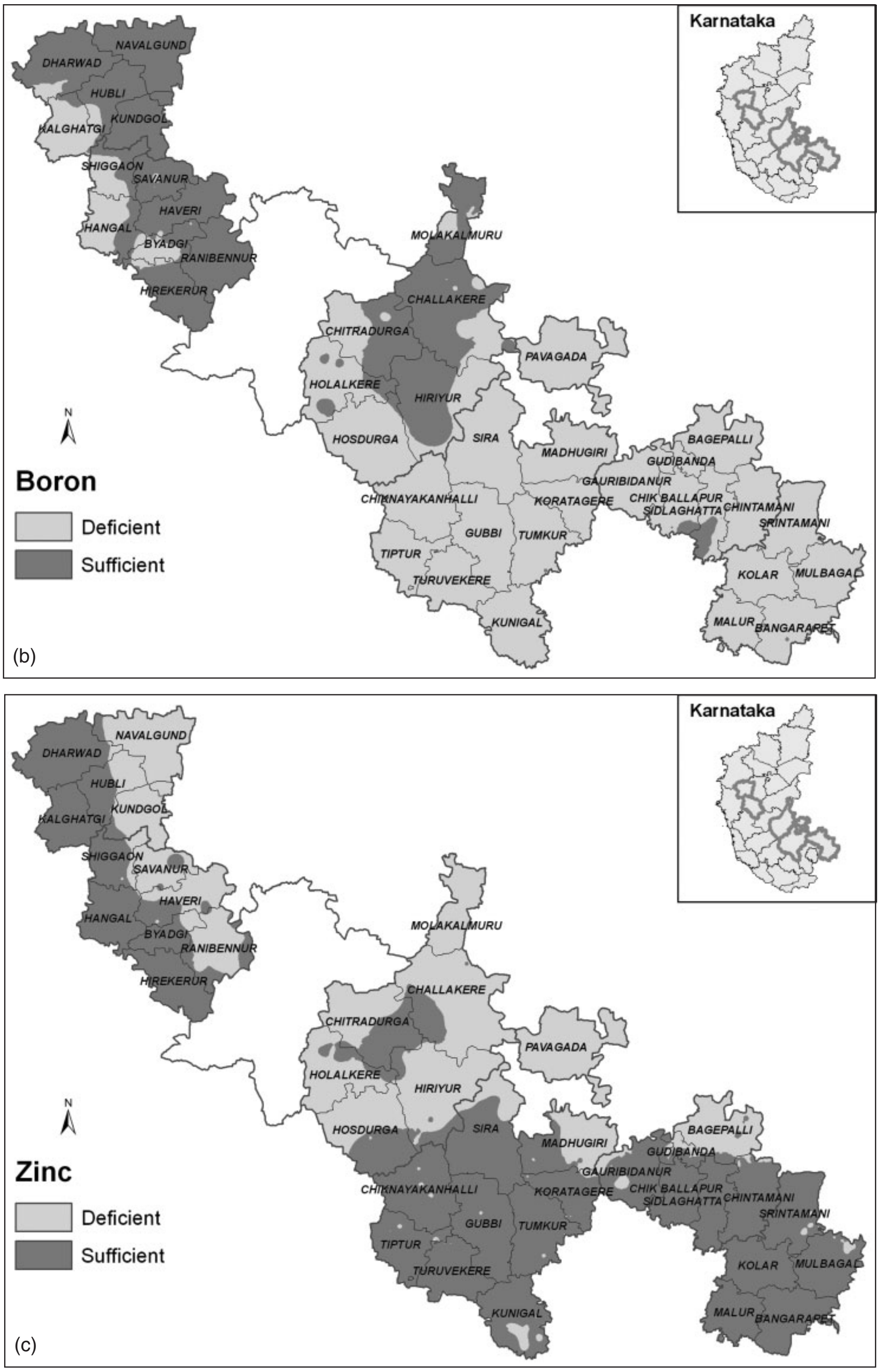

Figure 9.1 Continued

9.6 GENERAL DISCUSSION AND CONCLUSIONS

It is recognized that water shortage related plant stress is the primary constraint to crop production and productivity in the rainfed systems in the SAT regions and consequently the importance of water shortage has globally been rightly emphasized (Molden 2007; Pathak *et al.*, 2009). At the same time, it has been emphasized that the potential of the rainfed systems is much higher than indicated by the current productivity levels (Wani *et al.*, 2009; Rockström *et al.*, 2010). Equally importantly, the water constraint is not always related to absolute water shortage, but is generally caused by a large variability in the availability of water during the cropping season and its improper management. And hence, water management to cover water stress during dry spells can greatly reduce risks (Oweis and Hachum 2009; Pathak *et al.*, 2009; Rockström *et al.*, 2010).

However, apart from water shortage, severe soil infertility is also a problem in the rainfed systems (Black 1993; Rego *et al.*, 2007; Bekunda *et al.*, 2010; Sahrawat *et al.*, 2010a) and managing water stress alone cannot sustainably enhance the productivity of rainfed systems. Hence for achieving sustainable gains in rainfed productivity both water shortage and soil fertility problems need to be simultaneously addressed through effective NRM practices (Wani *et al.*, 2009; Sahrawat *et al.*, 2010b).

For the first time, a large number of farmers' fields in the SAT regions of India were sampled and analyzed for organic C and extractable or available nutrients in an effort to diagnose the prevalence of major and micronutrient deficiencies. Critical limits for various nutrients in the soil from published literature and ICRISAT data were used (Table 9.1) to separate deficient fields from the non-deficient ones (Black 1993; Mills and Jones 1996; Sahrawat 2006; Mahler and Shafii 2009) and for nutrient recommendation for the follow-up on-farm crop response trials. The results on the analyses of 28,270 soil samples (Table 9.2) demonstrate that the soils in rainfed areas are indeed infertile and they are not only deficient in major nutrients especially N (soil organic C status used as an index for available N) and P but are low in organic matter reserve. The most revealing results however, were the widespread acute deficiency of secondary nutrients such as S and micronutrients (especially B and Zn) (Rego *et al.*, 2007; Sahrawat *et al.*, 2007, 2009, 2010a).

A summary of the results on on-farm responses of several field crops to applications of deficient nutrients together with N and P demonstrated that BN has indeed the potential to significantly enhance the productivity of a range of crops (Tables 9.3 to 9.9), improve grain and straw quality (Tables 9.10 and 9.11), enhance RUE (Tables 9.12 and 9.13) and economic gains (Tables 9.13 and 9.14) in the SAT regions under rainfed conditions.

It would appear from these results that soil test-based nutrient management approach can be an important entry point activity and also a mechanism to diagnose and manage soil fertility in practical agriculture. Soil and plant tests have long been used as tools to diagnose and manage soil fertility problems in the intensified irrigated systems and commercial crops including fruit and vegetable crops to maximize productivity (Dahnke and Olson 1990; Black 1993; Mills and Jones 1996; Reuter and Robinson 1997; Subba Rao *et al.*, 2009), but rarely has soil testing been used to diagnose and manage nutrient problems in farmers' fields in the SAT regions at a scale reported in this chapter. The critical limits for P, K, S, B, and Zn in the soil (Table 9.1) seem to provide a fair basis for separating deficient soils from those that are not deficient. Soils below the critical limits of the nutrients evaluated responded to the applications of nutrients; although the overall crop response was regulated by the rainfall received during the cropping season (Rego *et al.*, 2007; Sahrawat *et al.*, 2007, 2010a; Srinivasarao *et al.*, 2008). Soil test-based nutrient application also allows judicious and efficient use of nutrient inputs at the local and regional levels (Black 1993; Subba Rao *et al.*, 2009).

Regarding the source of nutrients, it is recommended that an integrated approach in which both mineral and organic sources of nutrients should be used through the inclusion of legumes in the production systems to supply organic matter as well as nutrients as the organic matter inputs to the soil in any form helps to improve soil physical, chemical, and biological aspects of fertility (Rego and Rao 2000; Aulakh *et al.*, 2001; Bot and Benites 2005; Bationo *et al.*, 2008; Srinivasarao *et al.*, 2009). However, it should be kept in mind that the application of manure alone may not supply enough nutrients to achieve economic yield and the use of organic fertilizers as a complementary nutrient source enhances the contribution of inorganic or chemical fertilizers to yield and soil physical, chemical, and biological properties (Singh *et al.*, 2007; Yan and Gong 2010). Moreover, the nutrient contents of manures vary widely (Lupwayi *et al.*, 2000) and hence it is of critical importance that the rate of application of manure is adjusted based on its nutrient content (Williams *et al.*, 1995; Williams 1999).

For more widespread adoption and use of soil testing for the diagnosis and management of plant nutrient deficiencies in the rainfed systems of the SAT regions, there is a need to strengthen the soil testing facilities at the local and regional levels for science-based management and consider maintenance of soil fertility as a prerequisite for sustainable increase in productivity of the rainfed systems in the SAT (Sahrawat *et al.*, 2007, 2010a). We hope that the research reported in this chapter would stimulate research for widespread use of soil testing as a means for soil fertility management in farmers' fields.

For enhancing the overall agricultural productivity and crop quality of the rainfed systems, the choice of crops and adapted cultivars along with soil, water, and nutrient management practices need to be integrated at the farm level (Wani *et al.*, 2009; Sahrawat *et al.*, 2010a). To achieve this, research and extension support and backstopping along with capacity building of all the stakeholders need to converge (Wani 2008; Sahrawat *et al.*, 2010). Indeed, ICRISAT and its research partners most appropriately advocate the integration of genetics (crops and cultivars) and NRM for technology targeting and greater impact of agricultural research in the SAT regions (Twomlow *et al.*, 2008b). The strategy is based on the use of crop cultivars that are adapted to the harsh conditions of the SAT regions especially water stress and nutrient deficiencies. The soil, water, and nutrient management practices are developed around the adapted cultivars to realize the potential of the cultivars in diverse production systems (Ae *et al.*, 1990; Rego and Rao 2000; Condon *et al.*, 2004; Passioura 2006; Hiradate *et al.*, 2007; Bationo *et al.*, 2008; Sahrawat 2009; Passioura and Angus 2010).

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