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# Soil Nutrient Mapping for On-farm Fertility Management

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## 3.1 Introduction

Feeding the projected population of 9.1 billion globally and 1.6 billion in India by 2050 is one of the greatest challenges of the century, and in this endeavour to ensure future food security, efficient soil nutrient management is crucial (Wani *et al.*, 2003; Sahrawat *et al.*, 2010; Chander *et al.*, 2013). Since the era of the Green Revolution in India in the late 1960s, the focus has been on only three macronutrients, namely nitrogen (N), phosphorus (P) and potassium (K), and this has brought nutrient imbalances and widespread deficiencies of micro and secondary nutrients such as sulfur (S), boron (B) and zinc (Zn) in addition to macronutrients (Wani *et al.*, 2009; Sahrawat and Wani, 2013; Chander *et al.*, 2014). Most farmers and stakeholders are not aware of soil fertility issues and management alongside water and crop management, which is the main reason for large yield gaps in the semi-arid tropics (SAT). In order to ensure future food security and the future of smallholder farmers, science-led interventions are needed to bridge the yield gaps in the SAT. Some pilot initiatives such as the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT)–Andhra Pradesh Rural Livelihood Programme (APRLP) initiative in Andhra Pradesh and the Bhoochetana initiative in Karnataka have shown that soil nutrient mapping is the best entry point

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activity to enhance productivity and livelihoods through soil-need-based fertility management (Wani *et al.*, 2011; Chander *et al.*, 2013; Sahrawat and Wani, 2013). This chapter therefore focuses on soil fertility management issues and the need of soil nutrient mapping for informed decisions.

## 3.2 Soil Infertility – A Major Constraint in Addition to Water Shortage

In rainfed production systems, the importance of water shortage and associated stress effects on crops can hardly be overemphasized, especially in the SAT regions (Bationo *et al.*, 2008; Pathak *et al.*, 2009; Passioura and Angus, 2010; Rockström *et al.*, 2010). However, apart from water shortage, soil infertility is the issue for crop production and productivity enhancement in much of the SAT regions of the world, and SAT regions of India are no exception (El-Swaify *et al.*, 1985; Twomlow *et al.*, 2008; Wani *et al.*, 2009; Sahrawat and Wani, 2013; Chander *et al.*, 2014).

Equally importantly, apart from the deficiencies of major nutrients, especially N and P, deficiencies of secondary nutrients especially of 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 production systems, the deficiencies of various plant nutrients have been diagnosed through soil and plant testing and managed through the fertilization of crops, but little attention has been paid to diagnosing the deficiencies of secondary nutrients such as S and micronutrients in dryland rainfed production systems especially in SAT regions of India (Sahrawat *et al.*, 2007, 2010; Sahrawat and Wani, 2013).

In the past, little attention has been devoted to survey and determine the fertility status of farmers' fields with an overall objective to diagnose the nutrient problems in the rainfed production systems, which is a prerequisite for developing effective nutrient management strategies for enhancing agricultural productivity in these areas.

Moreover, we have observed that lack of adequate analytical laboratory infrastructure to provide high-throughput analytical research support, coupled with lack of awareness of the mining of secondary and micronutrients in production systems, is constraining the cause of upgrading rainfed agriculture (Wani *et al.*, 2009; Sahrawat, 2013; Sahrawat and Wani, 2013). Information on the soil fertility status of farmers' fields is needed not only for enhancing crop productivity through balanced nutrient management, but also to promote judicious use of costly external inputs of nutrients and to enhance the efficiency of scarce water resources in developing countries like India (Sahrawat, 2006; Wani, 2008; Sahrawat and Wani, 2013; Chander *et al.*, 2014).

This apparent paradox of lack of application of adequate amount of nutrients from external inputs is rather inexplicable (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 with that under irrigated production systems (El-Swaify *et al.*, 1985; Rego *et al.*, 2003; Sahrawat *et al.*, 2007, 2010; Sahrawat and Wani, 2013).

In Indian rainfed systems, water management for reducing water shortage has been the primary focus of research and developmental activities in these areas, and soil infertility has been largely rather ignored (El-Swaify *et al.*, 1985; Wani *et al.*, 2003; Sahrawat *et al.*, 2010) or has not been addressed in a comprehensive and integrated manner along with soil and water conservation practices (Wani *et al.*, 2009; Rockström *et al.*, 2010). However, it has been observed that even in water-limiting environments there is indeed potential to enhance agricultural productivity through efficient management of soil, water and nutrients in an integrated manner (Twomlow *et al.*, 2008; Wani *et al.*, 2009; Sahrawat *et al.*, 2010; Chander *et al.*, 2013).

For achieving the potential of productivity in water-limited environments, a concept of water-limited potential yield seems quite appropriate as this forms the basis to reach the attainable yield in these environments through management of various constraints other than only 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 crop 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). It must be emphasized that in the concept of water-limited potential yield in the rainfed systems, natural resource management 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.*, 2010; Sahrawat and Wani, 2013).

In addition there is a commonly held belief among researchers and agriculturists that at relatively low yields of crops in the rainfed systems of India, only the deficiencies of major nutrients (especially those of N and P) are important for the SAT Indian soils (El-Swaify *et al.*, 1985; Rego *et al.*, 2003). As a result of this belief, very little attention has been devoted to diagnosing the extent of deficiencies of the secondary nutrients such as S and micronutrients in various crop production systems on millions of small and marginal farmers' fields (Rego *et al.*, 2005, 2007; Sahrawat *et al.*, 2007, 2010).

However, there is no denying the fact that the productivity of the 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 and the role of secondary and micronutrients in enhancing water use efficiency in various rainfed production systems is neglected. Also, even the input of major nutrients to dryland production systems is rather meagre compared with that in the irrigated systems (Rego *et al.*, 2005; Wani *et al.*, 2009). Because of low productivity of the rainfed crops, it is assumed that the uptake and mining of secondary and micronutrient reserves in soils is much less than in irrigated production systems (Rego *et al.*, 2003).

Nevertheless for sustained increase in dryland productivity, soil and water conservation measures need to be integrated with balanced plant nutrition, and the choice of crops and/or cultivars, and their management (Wani *et al.*, 2003; Passioura, 2006; Passioura and Angus, 2010; Sahrawat *et al.*, 2010). The ongoing farmer participatory integrated watershed management programme of the ICRISAT, Patancheru, India, provided an appropriate opportunity to implement a balanced nutrient management strategy alongside soil and water conservation practices in farmers' fields in the Indian SAT. For achieving efficient and judicious use of nutrients through fertilizer inputs, assessing the soil's inherent nutrient status is considered a prerequisite (Sahrawat, 2006; Sahrawat and Wani, 2013).

## 3.3 Identifying a Suitable Entry Point Activity (EPA)

The choice of an appropriate knowledge-based entry point activity (EPA) for building rapport with the community cannot be overemphasized as an EPA is capable of providing a head start to a community-based programme such as watershed management for overall rural development. During our watershed work over a decade, we learnt that it is useful to consider the following points while selecting an appropriate EPA for integrated community watershed management:

- The EPA should be knowledge-based and should not involve direct cash payment through the project in the village.
- The EPA should have a high success probability (> 80–90%), and be based on proven research results.
- The EPA should involve a participatory research and development approach, and community members should preferably be involved in undertaking the activity in watersheds.
- An EPA should result in the measurable tangible economic benefits to the farming community with a relatively high benefit–cost ratio.
- The EPA preferably should be simple and easy for the participating farmers to undertake its participatory evaluation.

- Most importantly, the EPA should benefit the majority of farmers in the watershed.
- The EPA should have a reliable and cost-effective approach to assess the constraints.

Based on our experience with watershed work and considering the above-stated requirement for an EPA, we felt that for building rapport with the community, good participatory rural appraisal (PRA) and knowledge about local natural resources can be used to identify a knowledge-based EPA. The knowledge-based EPAs were found to be superior to the subsidy- or cash-based EPA for enabling community participation of higher order (cooperative and collegiate) rather than in a contractual mode (Dixit *et al.*, 2007).

Indeed, there is much need to innovate new methods to share knowledge with primary stakeholders as the traditional methods of extension have not been successful (Olson, 1971; Sreedevi *et al.*, 2004; Wani, 2008; Wani *et al.*, 2009).

## 3.4 Use of Soil Testing as an EPA

With the purpose of soil fertility augmentation, and for judicious use of nutrient inputs from external sources, it was indeed considered most appropriate to introduce and evaluate the concept of soil-test-based use of plant nutrients in our ongoing on-farm research in watersheds. The objective was to diagnose the deficiencies of all nutrients, including major, secondary and micronutrients in a comprehensive manner through high-volume soil analysis in the ICRISAT Central Analytical Services Laboratory, and based on soil-test-based nutrient management develop a balanced nutrient management strategy to sustainably enhance systems' productivity by increasing rainwater use efficiency.

Soil testing indeed was thought as a most appropriate tool for on-farm soil fertility management; and further, the integration of soil-test-based balanced nutrient management with the implementation of soil and water conservation practices was considered a prerequisite for sustainably increasing the productivity in rainfed areas of the SAT (Sahrawat and Wani, 2013).

The use of soil testing was introduced in a joint ICRISAT–APRLP watershed project as a science-based activity to diagnose the nutrient deficiencies and associated soil fertility problems prior to conducting on-farm productivity enhancement trials. A farmer-participatory stratified random sampling methodology was employed for collecting soil samples from farmers' fields (Sahrawat *et al.*, 2008). During 2002–2004 seasons, soil testing was employed to diagnose the nutrient deficiencies in the farmers' fields in three districts (Mahabubnagar, Nalgonda and Kurnool) of Andhra Pradesh, India. The results of soil analysis were shared with the participating farmers; and based on the results, recommendations were formulated for balanced nutrient management and the nutrients found deficient were added. The results were presented in the local language along with the necessary interpretative details and shared with the farmers in group meetings at the block level in a district.

The results of soil analyses showed that 81–99% of soil samples were deficient in Zn, B and S (Rego *et al.*, 2007). Past research experience at ICRISAT also emphasized that carefully conducted PRA along with the knowledge of local practices followed by farmers could help diagnose the constraints for identifying knowledge- and constraint-based EPA (Sreedevi *et al.*, 2004; Wani, 2008).

Follow-up on-farm trials on the comparative evaluation of farmers' input treatment with that based on soil-test-based balanced nutrient management, conducted during three seasons (2002–2004) under the ICRISAT–APRLP joint project showed significant responses of crops over the farmers' input treatment (Rego *et al.*, 2007). The results further demonstrated that an appropriate EPA such as soil testing could indeed ensure tangible economic benefit to individual farmers. As indicated earlier, the identification of major constraints limiting crop production and their alleviation ensured tangible economic benefits to individual farmers, and thereby triggered farmers' interest to participate in the project activities. Other researchers have also reported on the importance of using natural resource management as an EPA in community-based projects such as watershed management (Olson, 1971; Sreedevi *et al.*, 2004; Wani, 2008; Wani *et al.*, 2009).

However, it must be stated that since 1997 the natural resources management group at the ICRISAT centre in India, along with its partners, has 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. It started with detailed analysis of farmers' fields in the Milli watershed at Lalatora in Madhya Pradesh where analysis of soil samples for micronutrients was deliberately included as a part of the baseline characterization of the site (Sahrawat *et al.*, 2010).

ICRISAT and its partners have been working with the Government of Karnataka to sustainably enhance the productivity of rainfed areas of the state covering all the 30 districts. The strategy used to enhance agricultural production and productivity is based on the principle of 'Bhoochetana' or rejuvenating the soil, by enhancing its fertility. In this mission mode programme, soil testing was used as an EPA to diagnose the nutrient disorders and manage them via a balanced nutrient management approach in farmer participatory manner.

## 3.5 Soil Sampling Methodology and Soil Analysis

First and foremost, a soil sampling methodology was developed and standardized to collect representative soil samples in a watershed. Following several seasons' work experience in watersheds in Andhra Pradesh, the methodology based on the principle of stratified random sampling was found most appropriate for collecting soil samples to represent an entire watershed. The standardized methodology takes into consideration several factors in the watershed, including soil types, topography of the land, major crops grown, and farmers' land-holding size (for details see Sahrawat *et al.*, 2008). For example, for an effective soil sampling of land in an undulating landscape, farmers' fields were divided into three groups based on the position on the toposequence: top, middle and bottom, depending on the elevation and drainage pattern. We separated different soil types in each category. For soil sampling of the entire watershed, we randomly selected 20% of farmers in each position on the toposequence, taking into consideration the farm size, types of soils and crops grown (Sahrawat *et al.*, 2008).

The soil sampling programme of watersheds in various states was initiated in 2002, and has been continuing since. The main feature of this programme is farmer participation in the soil sampling. The soil sampling methodology was demonstrated to farmers in groups; and following this, the participating farmers themselves collected the soil samples from their respective fields. Using stratified random sampling methodology (Sahrawat *et al.*, 2008) eight to ten cores of surface (0–15 cm depth) soils were collected to make one composite sample.

The soil samples were air dried and using a wooden hammer were turned into a powder that could pass through a 2-mm sieve. For organic carbon (C) analysis, the soil samples were ground to pass through a 0.25-mm sieve. Prepared samples were analysed for various fertility characteristics in the ICRISAT Central Analytical Services Laboratory (Sahrawat and Wani, 2013).

For soil analysis, pH was measured by a glass electrode using a soil-to-water ratio of 1:2. Organic C was determined using the Walkley–Black method (Nelson and Sommers, 1996). Exchangeable K was determined using the ammonium acetate method (Helmke and Sparks, 1996). Available S was measured using 0.15% calcium chloride ($CaCl_2$) as an extractant (Tabatabai, 1996; Sahrawat *et al.*, 2009), and available P (Olsen-P) was measured using sodium bicarbonate ($NaHCO_3$) as an extractant (Olsen and Sommers, 1982). Available Zn was extracted by DTPA reagent (Lindsay and Norvell, 1978) and available B was extracted by hot water (Keren, 1996). Details of the methods used for testing soil samples for various fertility parameters are given in Sahrawat *et al.* (2007, 2010).

## 3.6 Knowledge Sharing with Farmers

The soil test results of soil samples collected from farmers' fields were shared with farmers in their own language via various modes of communication, including wall writing and soil health cards (Wani, 2008). The need to apply nutrients found deficient, as part of a balanced nutrient management strategy for enhancing productivity, was also discussed with the participating farmers.

Based on the results of soil samples collected from farmers' fields, recommendations were developed at block level for balanced nutrient management of crops in farmers' fields. For this, critical limits in the soil for various plant nutrients were used (Table 3.1) to separate deficient soil samples from the non-deficient ones (Sahrawat, 2006; Rego *et al.*, 2007; Sahrawat *et al.*, 2007) for follow-up on-farm crop response studies.

**Table 3.1.** Critical limits in the soil of plant nutrient elements to separate deficient samples from non-deficient samples. (Data gleaned from various literature sources, for details see Rego *et al.*, 2007; Sahrawat *et al.*, 2007.)

| Plant nutrient | Critical limit (mg/kg) |
|---|---|
| Sodium bicarbonate-extractable P | 5 |
| Ammonium acetate-extractable K | 50 |
| Calcium chloride-extractable S | 10 |
| Hot water-extractable B | 0.58 |
| DTPA-extractable Zn | 0.75 |

For practical utilization of the soil-test-based nutrient management, we have already mapped, using the geographical information system (GIS)-based extrapolation methodology, the deficiencies of all nutrients including especially those of S, B and Zn along with soil fertility parameters pH, electrical conductivity (EC) (indicator of soluble salts) and organic C in all the 30 districts of Karnataka state, India (Wani *et al.*, 2011). 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 colour codes depicting the deficiency or sufficiency of a nutrient. Such information can be easily used by smallholders, and the farmers can be kept updated regularly with the latest results on the website.

For soil parameter mapping covering the entire state of Karnataka, a total of 92,904 soil samples were collected from farmers' fields in watersheds in all the 30 districts of Karnataka. Soil test results of the soil samples analysed for pH, EC, organic C and extractable (available) major, secondary and micronutrients, from all the 30 districts of Karnataka at the block (or *mandal*) level, were used for mapping individual soil fertility parameters. Detailed mapping of soil fertility parameters, and discussion and interpretation of the results for use by researchers, agriculturists and farmers is provided in a separate treatise (Wani *et al.*, 2011). 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. However, a summary of the results on various soil fertility parameters is provided in Table 3.2. The values of fertility parameters pH, EC, organic C, extractable or available P, K, S, B and Zn in terms of range, mean and the percentage of samples deficient (for organic C and available P, K, S, B and Zn) are summarized district-wise for all the 30 districts of Karnataka (Table 3.2). As mentioned earlier, the maps for soil fertility parameter for the 30 districts at the block or *mandal* level are available in Wani *et al.* (2011).

## 3.7 Correlations Among Soil Parameters

Soil characteristics, especially those related to soil fertility, are interrelated among themselves. We studied the relationships among various soil fertility parameters (pH, EC, organic C and available (extractable) P, K, S, Zn and B) using 92,904 soil samples collected from the 30 districts of Karnataka.

Soil pH is an important property to influence different soil parameters through adsorption and precipitation reactions of nutrients, modifying uptake by influencing activities of microorganisms and influencing the abilities of plants to absorb ions. Correlation studies showed a positive relationship of pH with EC, K and B, while the pH was negatively correlated with organic C, P, S and Zn (Table 3.3). Soil organic C and EC were found to have a positive relationship between them and with rest of the soil fertility parameters. Therefore, there is a need to manage optimum amounts of soil organic C to regulate adequate supplies of essential plant nutrients. There were positive significant correlations between available P and K, P and S, P and Zn, K and Zn, K and B, S and Zn, S and B, and Zn and B, while there were negative significant correlations between P and B, and K and S (Table 3.3).

The positive correlations among various extractable or available nutrients are due to the fact that all these nutrients are in the deficient range, and hence there is hardly any scope for antagonistic relationships, which have usually been reported in the literature, for example between Zn and P (Sahrawat, 2006). Clearly, the positive role of soil organic C status on available nutrient elements is obvious in these soils, which are low in organic matter without very low inputs of plant nutrients from external sources as mineral or organic fertilizers (Bationo *et al.*, 2008; Sahrawat and Wani, 2013).

**Table 3.2.** Summary of results on chemical characteristics[a] of soil samples collected from farmers' fields covering all the 30 districts of Karnataka.

| District[b] | pH | EC (dS/m) | Organic C (%) | Available P (ppm) | Available K (ppm) | Available S (ppm) | Available Zn (ppm) | Available B (ppm) |
|---|---|---|---|---|---|---|---|---|
| Bagalkot (2,440) – range | 6.3–8.9 | 0.11–1.99 | 0.18–1.23 | 0.6–6.2 | 17–74 | 4.1–39.9 | 0.50–10.69 | 0.12–12.78 |
| – Mean | 7.8 | 0.35 | 0.62 | 2.3 | 60 | 11.7 | 0.92 | 0.70 |
| – Percentage of samples deficient | – | – | 36 | 97 | 28 | 59 | 55 | 69 |
| Belgaum (4,560) – range | 4.7–8.9 | 0.04–5.11 | 0.02–2.62 | 0.0–15.3 | 0–169 | 0.2–460.0 | 0.02–3.48 | 0.01–3.29 |
| – Mean | 7.3 | 0.44 | 0.64 | 2.1 | 52 | 152.2 | 0.66 | 0.59 |
| – Percentage of samples deficient | – | – | 29 | 95 | 52 | 2 | 68 | 74 |
| Bellary (2,100) – range | 6.2–9.0 | 0.10–2.25 | 0.20–1.24 | 0.6–6.2 | 16–74 | 4.1–41.4 | 0.52–13.81 | 0.12–18.02 |
| – Mean | 7.4 | 0.40 | 0.63 | 2.9 | 55 | 11.1 | 1.27 | 1.20 |
| – Percentage of samples deficient | – | – | 32 | 90 | 33 | 67 | 19 | 36 |
| Bengaluru Rural (4,448) – range | 4.2–9.5 | 0.01–9.96 | 0.01–1.50 | 0.0–543.8 | 9–1,414 | 0.5–2,299.1 | 0.05–235.00 | 0.02–5.12 |
| – Mean | 6.3 | 0.28 | 0.41 | 18.0 | 100 | 6.8 | 1.50 | 0.37 |
| – Percentage of samples deficient | – | – | 73 | 21 | 23 | 90 | 29 | 79 |
| Bengaluru Urban (2,680) – range | 4.4–8.7 | 0.02–2.20 | 0.03–3.00 | 0.7–351.5 | 2–580 | 0.8–335.0 | 0.03–5.79 | 0.02–6.86 |
| – Mean | 6.7 | 0.19 | 0.49 | 43.0 | 125 | 29.3 | 1.30 | 0.60 |
| – Percentage of samples deficient | – | – | 58 | 10 | 14 | 6 | 37 | 60 |
| Bidar (2,375) – range | 5.5–9.5 | 0.03–4.04 | 0.12–1.98 | 0.6–118.6 | 18–2,297 | 1.0–181.3 | 0.16–18.00 | 0.10–6.18 |
| – Mean | 7.6 | 0.24 | 0.59 | 8.4 | 208 | 7.3 | 0.85 | 0.55 |
| – Percentage of samples deficient | – | – | 40 | 48 | 1 | 83 | 62 | 66 |
| Bijapur (2,791) – range | 6.1–9.4 | 0.05–78.00 | 0.02–1.50 | 0.1–91.9 | 24–2,613 | 0.9–4,647.4 | 0.12–10.40 | 0.02–18.22 |
| – Mean | 8.3 | 0.40 | 0.42 | 3.8 | 209 | 24.4 | 0.50 | 0.93 |
| – Percentage of samples deficient | – | – | 70 | 81 | 3 | 77 | 89 | 43 |
| Chamarajanagar (1,640) – range | 5.1–9.7 | 0.02–8.00 | 0.04–1.85 | 0.2–121.6 | 20–766 | 0.4–119.4 | 0.14–6.40 | 0.02–3.80 |
| – Mean | 7.7 | 0.29 | 0.41 | 10.0 | 188 | 6.3 | 0.73 | 0.58 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| – Percentage of samples deficient | – | – | 76 | 37 | 4 | 87 | 67 | 62 |
| Chikkaballapur (2,257) – range | 4.5–9.9 | 0.01–16.62 | 0.07–1.42 | 0.2–430.8 | 4–1,650 | 0.5–470.0 | 0.06–21.50 | 0.06–1.98 |
| – Mean | 6.9 | 0.19 | 0.39 | 18.0 | 95 | 9.1 | 1.15 | 0.38 |
| – Percentage of samples deficient | – | – | 78 | 37 | 34 | 80 | 52 | 80 |
| Chikmagalur (4,140) – range | 2.9–9.8 | 0.01–1.89 | 0.01–2.45 | 0.5–129.2 | 1–304 | 1.0–2,425.0 | 0.01–6.75 | 0.02–55.44 |
| – Mean | 6.5 | 0.13 | 0.62 | 17.6 | 82 | 31.7 | 0.59 | 1.46 |
| – Percentage of samples deficient | – | – | 48 | 15 | 44 | 34 | 77 | 43 |
| Chitradurga (1,489) – range | 4.7–10.1 | 0.01–4.11 | 0.03–1.36 | 0.2–480.0 | 12–1,953 | 0.8–291.8 | 0.08–40.50 | 0.04–6.94 |
| – Mean | 7.8 | 0.23 | 0.40 | 7.0 | 137 | 7.3 | 0.64 | 0.63 |
| – Percentage of samples deficient | – | – | 76 | 54 | 15 | 86 | 80 | 64 |
| Dakshina Kannada (1,418) – range | 4.8–8.3 | 0.01–1.38 | 0.04–3.63 | 0.1–364.2 | 1–336 | 0.2–613.6 | 0.01–8.94 | 0.01–22.08 |
| – Mean | 5.5 | 0.09 | 1.26 | 12.6 | 46 | 38.5 | 0.84 | 1.66 |
| – Percentage of samples deficient | – | – | 2 | 29 | 71 | 21 | 65 | 44 |
| Davangere (2,968) – range | 4.2–9.9 | 0.01–6.74 | 0.04–2.70 | 0.2–95.4 | 11–480 | 0.9–99.7 | 0.04–4.80 | 0.02–3.00 |
| – Mean | 7.0 | 0.22 | 0.49 | 14.0 | 108 | 10.4 | 0.69 | 0.54 |
| – Percentage of samples deficient | – | – | 59 | 30 | 12 | 76 | 74 | 64 |
| Dharwad (1,129) – range | 5.1–9.3 | 0.03–1.91 | 0.17–1.99 | 0.2–207.0 | 36–2,344 | 1.4–715.0 | 0.24–24.30 | 0.10–12.48 |
| – Mean | 7.4 | 0.24 | 0.65 | 9.3 | 220 | 9.7 | 0.98 | 0.82 |
| – Percentage of samples deficient | – | – | 31 | 53 | 1 | 79 | 44 | 39 |
| Gadag (1,270) – range | 5.1–9.6 | 0.04–5.53 | 0.04–1.41 | 0.0–82.8 | 27–1,145 | 0.4–223.3 | 0.06–7.98 | 0.10–9.62 |
| – Mean | 8.2 | 0.27 | 0.41 | 5.3 | 185 | 7.1 | 0.42 | 0.88 |
| – Percentage of samples deficient | – | – | 75 | 65 | 2 | 85 | 92 | 34 |
| Gulbarga (now Kalaburagi) (3,640) – range | 4.9–9.8 | 0.05–34.50 | 0.04–2.50 | 0.2–88.7 | 19–1,722 | 0.4–12,647.9 | 0.10–5.18 | 0.02–24.90 |
| – Mean | 8.0 | 0.34 | 0.49 | 5.7 | 266 | 28.1 | 0.53 | 0.63 |
| – Percentage of samples deficient | – | – | 60 | 64 | 1 | 83 | 86 | 71 |

*Continued*

**Table 3.2.** Continued.

| | | | | Available | | | | |
|---|---|---|---|---|---|---|---|---|
| District[b] | pH | EC (dS/m) | Organic C (%) | P (ppm) | K (ppm) | S (ppm) | Zn (ppm) | B (ppm) |
| Hassan (10,274) – range | 3.9–9.7 | 0.03–3.60 | 0.04–5.71 | 0.2–363.0 | 9–1,394 | 0.2–515.1 | 0.06–41.90 | 0.02–4.08 |
| – Mean | 6.3 | 0.24 | 0.58 | 19.4 | 116 | 8.4 | 1.12 | 0.32 |
| – Percentage of samples deficient | – | – | 48 | 23 | 18 | 82 | 50 | 91 |
| Haveri District (1,532) – range | 5.1–10.5 | 0.03–2.34 | 0.08–3.60 | 0.1–143.0 | 25–3,750 | 0.3–120.3 | 0.20–34.10 | 0.08–8.44 |
| – Mean | 7.7 | 0.18 | 0.51 | 12.4 | 133 | 7.0 | 0.81 | 0.71 |
| – Percentage of samples deficient | – | – | 55 | 42 | 5 | 85 | 60 | 46 |
| Kodugu (1,160) – range | 4.0–7.8 | 0.01–2.06 | 0.28–1.26 | 1.2–15.5 | 0–223 | 1.1–206.5 | 0.03–37.30 | 0.03–11.75 |
| – Mean | 5.6 | 0.07 | 1.15 | 7.0 | 53 | 12.7 | 4.13 | 1.21 |
| – Percentage of samples deficient | – | – | 0 | 59 | 68 | 74 | 24 | 28 |
| Kolar (2,161) – range | 4.6–10.2 | 0.02–13.00 | 0.04–1.50 | 0.0–182.0 | 9–1,144 | 0.7–141.2 | 0.14–14.40 | 0.04–1.82 |
| – Mean | 7.0 | 0.16 | 0.38 | 20.3 | 87 | 7.0 | 1.31 | 0.34 |
| – Percentage of samples deficient | – | – | 81 | 31 | 34 | 85 | 32 | 87 |
| Koppal (2,499) – range | 5.2–9.8 | 0.01–5.70 | 0.03–2.90 | 0.0–214.6 | 24–708 | 0.3–1,482.5 | 0.01–20.09 | 0.01–2.98 |
| – Mean | 7.7 | 0.26 | 0.45 | 19.6 | 147 | 82.5 | 0.84 | 0.30 |
| – Percentage of samples deficient | – | – | 65 | 7 | 2 | 22 | 59 | 87 |
| Mandya (5,479) – range | 4.5–8.9 | 0.01–3.10 | 0.01–1.26 | 1.5–27.2 | 7–164 | 1.0–278.3 | 0.01–4.86 | 0.01–3.98 |
| – Mean | 6.8 | 0.39 | 0.59 | 15.1 | 103 | 43.3 | 0.62 | 0.60 |
| – Percentage of samples deficient | – | – | 43 | 14 | 6 | 27 | 71 | 65 |
| Mysore (4,860) – range | 3.2–9.3 | 0.01–3.20 | 0.03–1.26 | 0.4–15.7 | 3–168 | 0.9–1,459.8 | 0.01–19.80 | 0.03–14.73 |
| – Mean | 6.8 | 0.18 | 0.43 | 10.1 | 129 | 59.7 | 2.13 | 0.68 |
| – Percentage of samples deficient | – | – | 69 | 25 | 3 | 13 | 26 | 60 |
| Raichur (3,343) – range | 4.8–9.8 | 0.02–56.90 | 0.03–1.60 | 0.0–169.6 | 13–1,797 | 0.8–49,083.7 | 0.12–15.24 | 0.01–34.34 |
| – Mean | 8.2 | 0.60 | 0.42 | 11.1 | 202 | 177.2 | 0.66 | 1.17 |
| – Percentage of samples deficient | – | – | 71 | 48 | 4 | 64 | 79 | 39 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Ramanagara (3,068) – range | 3.2–8.4 | 0.03–1.71 | 0.03–3.00 | 0.5–378.2 | 3–631 | 0.3–2,675.0 | 0.01–9.52 | 0.01–20.68 |
| – Mean | 6.4 | 0.16 | 0.41 | 25.4 | 104 | 175.0 | 1.05 | 0.32 |
| – Percentage of samples deficient | – | – | 70 | 5 | 15 | 13 | 48 | 88 |
| Shimoga (6,140) – range | 3.8–8.2 | 0.01–2.32 | 0.07–3.15 | 0.7–90.5 | 2–175 | 0.5–99.5 | 0.07–20.00 | 0.01–31.76 |
| – Mean | 5.6 | 0.13 | 0.71 | 8.8 | 80 | 15.8 | 1.03 | 0.80 |
| – Percentage of samples deficient | – | – | 23 | 41 | 46 | 34 | 36 | 36 |
| Tumkur (3,041) – range | 2.8–10.0 | 0.01–14.00 | 0.04–2.08 | 0.1–204.0 | 11–1,470 | 0.1–128.4 | 0.14–17.26 | 0.03–3.60 |
| – Mean | 6.6 | 0.13 | 0.39 | 5.9 | 92 | 5.5 | 0.89 | 0.33 |
| – Percentage of samples deficient | – | – | 77 | 65 | 34 | 92 | 50 | 91 |
| Udupi (1,000) – range | 5.4–7.0 | 0.10–0.59 | 0.36–0.99 | 1.5–14.2 | 20–169 | 3.1–25.5 | 0.12–4.18 | 0.11–3.55 |
| – Mean | 6.0 | 0.26 | 0.81 | 3.6 | 71 | 10.3 | 0.94 | 0.52 |
| – Percentage of samples deficient | – | – | 4 | 85 | 34 | 54 | 51 | 69 |
| Uttara Kannada (4,980) – range | 3.5–8.4 | 0.01–5.00 | 0.08–9.58 | 0.1–47.1 | 0–199 | 0.1–470.0 | 0.02–26.40 | 0.02–290.00 |
| – Mean | 5.5 | 0.12 | 0.56 | 6.4 | 64 | 81.6 | 0.95 | 4.05 |
| – Percentage of samples deficient | – | – | 46 | 41 | 45 | 28 | 53 | 48 |
| Yadgir (1,982) – range | 5.0–10.0 | 0.03–8.78 | 0.01–1.19 | 0.0–97.3 | 14–1,558 | 0.9–237.4 | 0.12–14.80 | 0.02–4.60 |
| – Mean | 7.9 | 0.35 | 0.40 | 9.6 | 204 | 26.8 | 0.49 | 0.66 |
| – Percentage of samples deficient | – | – | 74 | 48 | 5 | 72 | 90 | 58 |
| Karnataka State (92,904) – range | 3.5–10.0 | 0.03–8.78 | 0.01–9.58 | 0.0–543.8 | 0–3,750 | 0.9–237.4 | 0.00–235.00 | 0.02–4.60 |
| – Mean | 6.8 | 0.25 | 0.54 | 12.5 | 115 | 44.4 | 1.01 | 0.87 |
| – Percentage of samples deficient | – | – | 52 | 41 | 23 | 52 | 55 | 62 |

[a] EC, Electrical conductivity; C, carbon; P, phosphorus; K, potassium; S, sulfur; Zn, zinc; B, boron.

[b] The values in parentheses are the number of farmers' fields sampled.

**Table 3.3.** Correlations among different soil fertility parameters in soil samples collected from farmers' fields in Karnataka ($n$ = 92,904).[a]

| Parameter | EC | Organic C | Available P | Available K | Available S | Available Zn | Available B |
|---|---|---|---|---|---|---|---|
| pH | 0.19** | –0.20** | –0.06** | 0.40** | –0.03** | –0.10** | 0.06** |
| EC | | 0.03** | 0.05** | 0.17** | 0.15** | 0.02** | 0.20** |
| Organic C | | | 0.05** | 0.01 | 0.00 | 0.17** | 0.15** |
| Available P | | | | 0.15 ** | 0.05** | 0.19** | –0.01** |
| Available K | | | | | –0.05** | 0.03** | 0.10** |
| Available S | | | | | | 0.04** | 0.04** |
| Available Zn | | | | | | | 0.05** |

[a]**, Significant at 1% level.

## 3.8 General Discussion and Conclusions

It is well recognized that water-shortage-related plant stress is the primary constraint to crop production and productivity in the rainfed systems in the SATs, and consequently the importance of water shortage has globally been rightly emphasized (Wani *et al.*, 2002, 2003; Pathak *et al.*, 2009). However, apart from water shortage, severe soil infertility is another problem in the rainfed systems (Sanchez *et al.*, 1997; Zougmore *et al.*, 2003; Rego *et al.*, 2007; Lal, 2008; Bekunda *et al.*, 2010; Sahrawat *et al.*, 2010) 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 natural resource management practices (Wani *et al.*, 2009; Sahrawat *et al.*, 2010; Chander *et al.*, 2014).

Most probably for the first time, a large number of farmers' fields in the SAT regions of India were sampled and analysed for organic C and extractable or available nutrients in an effort to diagnose the prevalence of major and micronutrient deficiencies. The results of the analyses of soil samples from the farmers' fields demonstrated 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 nature of the deficiencies of S, B and Zn (Rego *et al.*, 2007; Sahrawat *et al.*, 2007, 2010; Sahrawat and Wani, 2013).

A summary of results of on-farm responses of several field crops to applications of deficient nutrients together with N and P demonstrated that balanced nutrient management has indeed the potential to significantly enhance the productivity of a range of crops, and improve grain and straw quality in the SAT regions under rainfed conditions (Sahrawat and Wani, 2013).

Our results from on-farm trials during the past decade suggest that a soil-test-based nutrient management approach can be an important EPA and also a mechanism to diagnose and manage soil fertility in practical agriculture (Wani, 2008). 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). However, soil testing has not been used to diagnose and manage nutrient problems in farmers' fields in the SAT regions at a large scale (Sahrawat and Wani, 2013).

The critical limits for P, K, S, B and Zn in the soil (see Table 3.1) 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, 2010). Soil-test-based nutrient application also allows judicious and efficient use of nutrient inputs at the local and regional levels (Black, 1993; Sahrawat *et al.*, 2010; Sahrawat and Wani, 2013).

For 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 maintenance of soil fertility, a prerequisite for sustainable increase in productivity of the rainfed systems (Sahrawat *et al.*, 2007, 2010; Sahrawat, 2013; Sahrawat and Wani, 2013).

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.*, 2010). 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). It is in this context that ICRISAT and its research partners most appropriately advocate the integration of genetics and natural resource management for technology targeting and greater impact of agricultural research in the SATs (Twomlow *et al.*, 2008; Chander *et al.*, 2013).

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