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Balanced and integrated nutrient management for enhanced and economic food production: case study from rainfed semi-arid tropics in India

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Soil degradation in the semi-arid tropics (SAT) is mainly responsible for low crop and water productivity. In Madhya Pradesh and Rajasthan states in India, the soil analyses of farmers' fields revealed widespread deficiencies of S (9–96%), B (17–100%) and Zn (22–97%) along with that of P (25–92%). Soil organic C was deficient in 7–84% fields indicating specifically N deficiencies and poor soil health in general. During on-farm evaluations in rainy seasons 2010 and 2011, the soil test based addition of deficient nutrient fertilizers as balanced nutrition (BN) increased crop yields by 6–40% (benefit to cost ratios of 0.81–4.28) through enhanced rainwater use efficiency. The integrated nutrient management (INM), however, decreased the use of chemical fertilizers in BN by up to 50% through on-farm produced vermicompost and recorded yields at par or more than BN with far better benefit to cost ratios (2.26–10.2). Soybean grain S and Zn contents improved with INM. Applied S, B, Zn and vermicompost showed residual benefits as increased crop yields for succeeding three seasons. Hence, results showed INM/BN was economically beneficial for producing more food, while leading to resilience building of SAT production systems.

Keywords: soil degradation; micronutrients; vermicompost; productivity; resilience

Introduction

The sustainable production of more food from the limited and scarce land and water resources to feed the projected world population of 9.1 billion people in 2050 is one of the greatest challenges of the twenty-first century (Selvaraju et al. 2011). In India too, per capita arable land availability has decreased from 0.39 ha in 1951 to 0.12 ha in 2011 mainly due to increased population from 359 million in 1951 to 1.21 billion in 2011 (Ministry of Agriculture, Government of India 2012), which is further expected to rise to 1.39 billion by 2025 and 1.58 billion by 2050 (Amarasinghe et al. 2007) with associated decrease in per capita land availability (0.1 ha in 2025 and 0.09 ha by 2050). Within existing land constraints, India must increase the current food production to around 290 million tonnes in 2025 and 380 million tonnes in 2050 (Amarasinghe et al. 2007) to meet the growing food demand. Green revolution in India increased the food production through intensified use of irrigated areas and fertilizer and dwarf genotypes of wheat and rice. Forty per cent of irrigated area in India has reached a plateau in terms of productivity, and thus, the required increase in food production to meet the increasing demand should come largely from 89 million ha rainfed-cropped areas (Wani et al. 2008).

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In rainfed semi-arid and dry sub-humid regions, the yields of important crops like pearl millet [*Pennisetum glaucum* (L.) R. Br.], maize (*Zea mays*), wheat (*Triticum aestivum*), sorghum (*Sorghum bicolor*), paddy (*Oryza sativa*), cotton (*Gossypium* spp.), mustard (*Brassica* spp.), soybean (*Glycine max*), chickpea (*Cicer arietinum*), groundnut (*Arachis hypogaea*) and pigeonpea (*Cajanus cajan*) range from as low as 0.5 to 2 t ha^{-1}, with an average of 1 t ha^{-1} in sub-Saharan Africa, and 1–1.5 t ha^{-1} in Asia and North Africa (Rockström and Falkenmark 2000; Wani et al. 2003, 2011). Long-term studies at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) centre based at Patancheru, India, have shown that due to integrated soil-crop-water management practices, average crop yield can be increased sustainably fivefold in a sorghum-pigeonpea system as compared with traditional farmers' practice (FP) of cultivating sole sorghum in post-rainy season (Wani et al. 2003, 2011, Wani, Dixin, et al. 2012). The large gap between actual FP yield and attainable yield due to improved management suggests an untapped potential for yield increase to feed the burgeoning population. In the semi-arid tropics (SAT), soil degradation along with water scarcity are the main causes for low crop yields and inefficient utilization of existing water resources resulting into low water use efficiency. Rainfed soils are multinutrient deficient and need proper nutrient management strategies to bridge the existing gap between farmers' current yields and achievable potential yields (Sahrawat et al. 2010). In view of the observed deficiencies, the applications of major nutrients nitrogen (N), phosphorus (P) and potassium (K) as currently practised is important for the SAT soils (El-Swaify et al. 1985; Rego et al. 2003; Sharma et al. 2009), but very little attention has been paid to diagnose and take corrective measures for deficiencies of secondary and micro nutrients in various crop production systems (Rego et al. 2005; Sahrawat et al. 2007, 2011) followed in millions of small and marginal farmers' fields in the SAT. Role of soil organic carbon (C) in maintaining soil health is also well documented (Wani, Chander, et al. 2012). However, low soil organic C in SAT soils is another factor contributing to poor crop productivity (Lee and Wani 1989; Edmeades 2003; Ghosh et al. 2009; Materechera 2010). Although tropical soils are often deficient in C and essential plant nutrients, large quantities of carbon and nutrients contained in domestic wastes and agricultural byproducts are wasted. Presently in India, about 960 million tonnes of solid waste is being generated annually as by-products during municipal, agricultural, industrial, mining and other processes, and solely 350 million tonnes are organic wastes from agricultural sources (Pappu et al. 2007). Such large quantities of organic wastes can be converted through simple vermicomposting technique into valuable manure called vermicompost (VC) (Wani 2002; Nagavallemma et al. 2004).

Vermicomposting is faster than other composting processes due to biomass breakdown while passing through the earthworm gut and enhanced microbial activity in earthworm castings. Some earlier studies showed that VC is an enriched source of nutrients with additional plant growth promoting properties, and VC application can improve nutrient availability, crop growth, yield and nutrient uptake (Nagavallemma et al. 2004). So, the on-farm produced VC can enhance soil health and save costs of chemical fertilizers leading to economic productivity improvement.

In this scenario, we hypothesized that rainfed areas in Madhya Pradesh and Rajasthan could be used more sustainably to increase farmers' crop yields through soil test based balanced and integrated nutrient management (INM) practices. The specific objectives of this study were (1) to assess nutrient deficiencies in representative fields in the target districts of Madhya Pradesh and Rajasthan, (2) to conduct farmer participatory action research trials (FPART) using soil test based balanced and INM recommendations and (3) to assess effect of balanced and INM practices on crop productivity and economic viability.

Materials and methods

Study sites

The target ecoregions for this study were the dryland areas of Madhya Pradesh and eastern Rajasthan in India with assured rainfall (Figure 1). The predominant soils of target regions are Vertisols, Vertic Inceptisols and Alfisol varying in soil depth. The length of growing period varies from 90 to 180 days and in some cases extends up to 210 days. Agriculture is the predominant occupation and source of livelihood for rural people in these regions, and therefore, natural resource base is the lifeline of millions of rural poor. The rainfall received in the target regions was recorded at the nearest location where rain gauge was

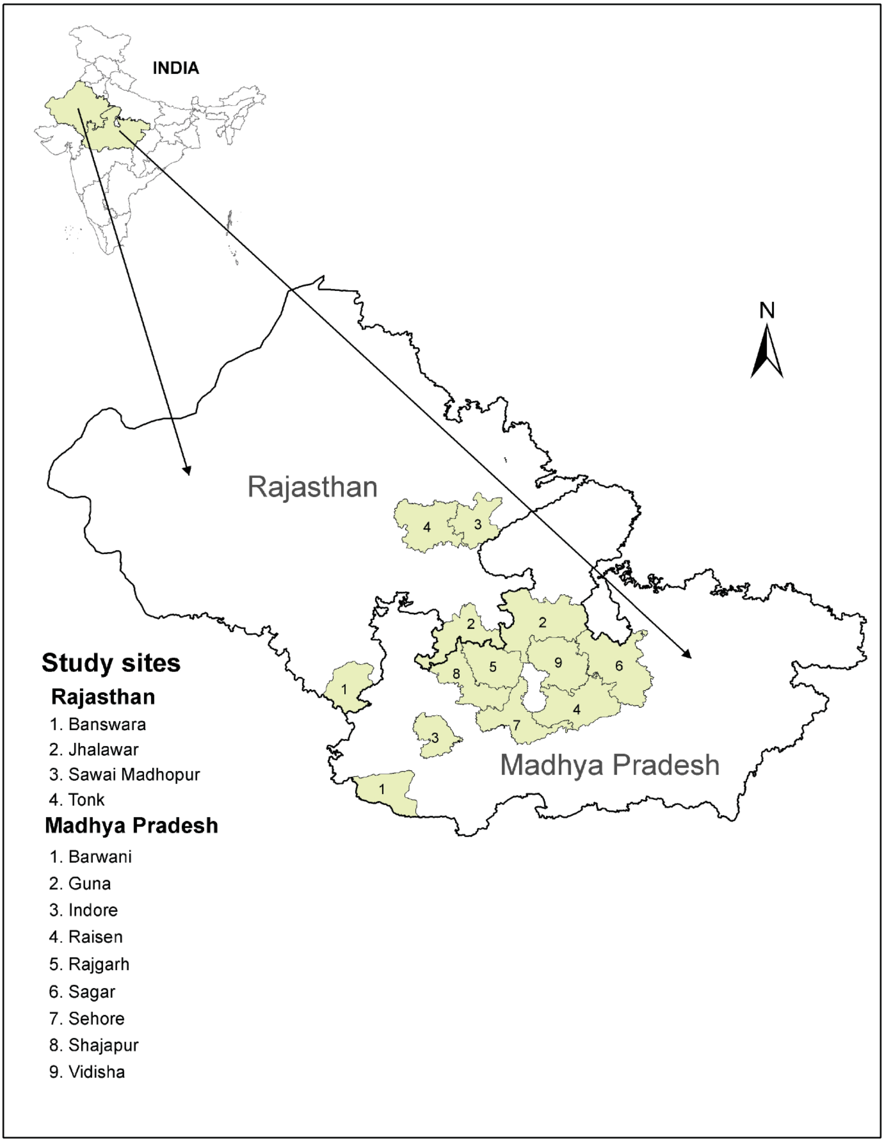

Figure 1. Study sites in Rajasthan and Madhya Pradesh, India.

available (Table 1). The sources of rainfall data were ICRISAT rain gauge in Guna and Raisen districts, krishi vigyan kendra rain gauge in Shajapur, revenue office rain gauge in Vidisha, while government of Rajasthan rain gauges at all locations in Rajasthan.

Diagnosis of soil fertility constraints and development of fertilizer recommendations

To diagnose soil fertility related constraints, soil samples (274 in 9 districts of Madhya Pradesh and 182 in 4 districts of Rajasthan) were collected from farmers' fields in target ecoregions by adopting participatory stratified soil sampling method (Sahrawat et al. 2008, 2011). Under this method, we divided target ecoregions in the districts into three topo-sequences. At each toposequence location, samples were taken proportionately from small, medium and large farm-holding sizes to address variations that may arise due to different management because of different economic status in each farm size class. Within each farm size class in a toposequence, the samples were chosen carefully to represent all possible soil fertility variations as judged by soil colour, texture, cropping system and agronomic management. At ultimate sampling unit in a field, we collected 8–10 cores of surface (0–0.15 m) soil samples and mixed them together to make a composite sample. The samples were processed and analysed for pH, organic C, available sulphur (S), boron (B), zinc (Zn), P and K in Charles Renard Analytical Laboratory, ICRISAT (see details in 'soil and plant chemical analysis' section).

Based on soil analysis results and variable soil fertility across the region, fertilizer recommendations were developed at the level of cluster of villages called block, a lower administrative unit in a district. In India, the blanket fertilizer recommendations involve, in general, N, P and K at the state (comprising of some districts) level which rarely match soil fertility need, while totally ignoring secondary and micronutrients. In this study, soil test based fertilizer recommendations were designed at block level by considering practical aspects like available infrastructure, human power and economics in research for impact on smallholders in the Indian SAT. The critical values for delineating deficiency are 5.0 g kg^{-1} for organic C, 5 mg kg^{-1} for P, 50 mg kg^{-1} for K, 10 mg kg^{-1} for S, 0.58 mg kg^{-1} for B and 0.75 mg kg^{-1} for Zn (Sahrawat et al. 2010). We recommended to apply full dose of a particular nutrient if its deficiency was in >50% farms in a block and

Table 1. Observed rainfall (mm) at (or near) study sites in Madhya Pradesh and Rajasthan, India during 2010 and 2011.

District	Location	Rainy, 2010 (June–September)	Post-rainy, 2010–2011 (October–November to January–February)	Rainy, 2011 (June–September)
Madhya Pradesh				
Guna	Barkhedakhurd	723	72	1650
Raisen	Siyalwada	773	35	1015
Shajapur	Shajapur	550	69	1092
Vidisha	Vidisha	765	56	1349
Rajasthan				
Banswara	Kushalgarh	588	17	987
Jhalawar	Jhalarpatan	560	39	1047
Sawai Madhopur	Khandar	675	111	747
Tonk	Deoli	675	93	786

half dose of a nutrient if its deficiency was in <50% farms. This way of nutrient recommendation was adopted to manage existing risks in rainfed agriculture in the SAT while targeting optimum yields to improve livelihoods of poor SAT farmers. The state fertilizer recommendations for N, P and K (Table 2) were modified based on this principle to meet varying soil fertility needs at block level. Similarly, for newly emerged deficiencies of S, B and Zn, the per ha general recommendations of 30 kg S (through gypsum), 5 kg Zn and 0.5 kg B to be added once in 2 years, evaluated and standardized earlier (Rego et al. 2005), were also adjusted based on the aforementioned principle of deficiency to meet soil fertility needs.

Participatory on-farm trials

Participatory trials were conducted on farmers' fields in the rainfed target districts of Rajasthan and Madhya Pradesh states of India during 2010 and 2011 rainy (June to September) seasons (Table 3; Figure 1). Fields were selected based on the willingness of farmers to engage in participatory research to evaluate the scientific based strategy and those who had on-farm produced VC were promoted as part of this study. Selection also ensured trials with all prominent crops in both the states. Selected farmers participated in each and every research intervention like soil sampling, input application yield estimation and residual benefits in succeeding seasons. Farmer participatory approach was adopted as a part of capacity strengthening strategy through enabling farmers learn and evaluate benefits from scientific based strategy and bring them in the centre stage to own the initiative, a pre-requisite for sustainability of any on-farm impact centred initiative. On-farm trials were conducted to evaluate the soil test based balanced nutrition (BN) and the use of VC as a source of organic matter and plant nutrients by partially replacing chemical fertilizers. There were three treatments added and evaluated on new farms both during rainy season 2010 and 2011:

(1) FP of application of N, P and K only,
(2) BN comprising of FP inputs plus S + B + Zn and
(3) INM i.e. 50% BN inputs + VC.

Table 2. Official recommendations for nutrient application in different crops (respective state agricultural universities and ICRISAT).

	Recommended nutrients (kg ha^{-1})					
Crop	N	P_2O_5	K_2O	S	Zn	B
Madhya Pradesh Chickpea (*Cicer arietinum*)	20	60	20	30	10	0.5
Soybean (*Glycine max*)	20	60	20	30	10	0.5
Wheat (*Triticum aestivum*)	80	40	20	30	10	0.5
Rajasthan Chickpea (*Cicer arietinum*)	10	25	–	30	10	0.5
Groundnut (*Arachis hypogaea*)	15	60	–	30	10	0.5
Maize (*Zea mays*)	50	30	–	30	10	0.5
Pearlmillet [*Pennisetum glaucum* (L.) R. Br.]	60	30	–	30	10	0.5
Soybean (*Glycine max*)	20	40	–	30	10	0.5
Wheat (*Triticum aestivum*)	80	30	–	30	10	0.5

Table 3. Details of farmer participatory research trials on evaluation of BN and INM in two states of India.

District	Crop	Number of BN and INM evaluation trials		Number of trials on residual effects of 2010 added S, B, Zn and VC		
		Rainy, 2010	Rainy, 2011	Post-rainy, 2010–2011	Rainy, 2011	Post-rainy, 2011–2012
Madhya Pradesh						
Guna	Soybean (*Glycine max*)	12	6	–	13	
Raisen	Soybean (*Glycine max*)	30	–		–	–
	Wheat (*Triticum aestivum*)	–	–	7	–	3
	Chickpea (*Cicer arietinum*)	–	–	4	–	7
Shajapur	Soybean (*Glycine max*)	15	5	–	15	–
	Wheat (*Triticum aestivum*)	–	–	6	–	8
	Chickpea (*Cicer arietinum*)	–	–	7	–	2
Vidisha	Soybean (*Glycine max*)	2	6	–	4	–
	Wheat (*Triticum aestivum*)	–	–	2	–	–
Rajasthan						
Banswara	Maize (*Zea mays*)	15	15	–	–	–
	Wheat (*Triticum aestivum*)	–	–	11	–	–
	Chickpea (*Cicer arietinum*)	–	–	4	–	–
Jhalawar	Soybean (*Glycine max*)	15	15	–	–	–
Sawai Madhopur	Maize (*Zea mays*)	2	2	–	–	–
	Pearl millet [*Pennisetum glaucum* (L.) R. Br.]	9	2	–	–	–
Tonk	Maize (*Zea mays*)	5	2	–	–	–
	Groundnut (*Arachis hypogaea*)	7	6	–	–	–
	Pearl millet [*Pennisetum glaucum* (L.) R. Br.]	3	3	–	–	–

Full dose of inputs under farmers' practice varied from 50–80 kg N ha^{-1} and 30–40 kg P_2O_5 ha^{-1} and 20 kg K_2O ha^{-1} in non-legumes and 10–20 kg N ha^{-1}, 25–60 kg P_2O_5 ha^{-1} and 20 kg K_2O ha^{-1} in legume crops (Table 2). The BN treatment contained in addition to N, P and K, S, B and Zn, and the full dose consisted of 30 kg S ha^{-1}, 10 kg Zn ha^{-1} and 0.5 kg B ha^{-1}. The nutrient/fertilizer recommendations were adjusted at block level in the districts as explained in the previous section. The INM treatment consisted of applying 50% of recommended fertilizers as per BN concept plus VC. VC (1.0% N and 0.8% P) was added to replace 50% of N requirement in non-legumes and 50% of P requirement in legumes. The fertilizer sources for nutrients were urea for N, DAP (Diammonium phosphate) for P and N, gypsum for S, zinc sulphate for Zn and agribor (20% B) for B. The treatments were imposed on 2000 m^2 plots without replicates on a farm, side by side and uniform crop management practices were ensured in all three treatments viz. FP, BN and INM. Application of all nutrients and VC were made basal except N in non-legumes of which 50% was added as basal and the remaining in two equal splits at one month interval.

The residual benefits of S, B, Zn and VC applied as BN and INM during 2010 rainy season were also evaluated in the next three succeeding seasons by monitoring yields in FP, BN and INM treatments.

Use of VC

VC was prepared from on-farm organic wastes and cow dung. Rock phosphate being a cheap source of P was added at 3% of composting biomass to improve P content in VC due to solubilization action of humic acids and phosphate solubilizing bacteria (Hameeeda et al. 2006) during vermicomposting process. *Eudrilus Eugenie* and *Eisenia foetida* species of earthworms were used for vermicomposting. The mature VC contained on an average 1.0% N, 0.8% P, 0.7% K, 0.26% S, 110 mg B kg^{-1}, 60 mg Zn kg^{-1} and 14% organic C (total nutrient contents on dry weight basis).

Soil and plant chemical analysis

The soil samples collected were air dried, ground and passed through a 2-mm sieve. For organic carbon, the soil samples were ground to pass through 0.25-mm sieve. Soil pH was measured by a glass electrode using soil to water ratio of 1:2, organic C was analysed following the Walkley–Black method (Nelson and Sommers 1996). Available P, K, S, B and Zn were extracted using the sodium bicarbonate for P (Olsen and Sommers 1982), ammonium acetate for K (Helmke and Sparks 1996), 0.15% calcium chloride for S (Tabatabai 1996), hot water for B (Keren 1996) and diethylene triamine pentaacetic acid (DTPA) reagent for Zn (Lindsay and Norvell 1978). Available P was determined using colorimetric method, while K was determined by Atomic Absorption Spectrophotometer (AAS). Analyses of S, B and Zn were made using Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES).

Composite plant samples (~2 kg) were collected from three representative sub-plots measuring 3 m × 3 m = 9 m^2 (used in yield estimation) in each of the three treatments in trials from Raisen district during the rainy season 2010. The plants were separated into grain and straw, ground and analysed for N, P, K, S, B and Zn contents. Total N, P and K-contents in plant materials were determined after digesting with sulphuric acid-selenium mixture, while N and P in the digests were analysed using an autoanalyser and K was analysed using AAS (Sahrawat et al. 2002a). Zinc (Zn) in the plant materials was determined after digesting with triacid and Zn in the digests was also determined using AAS (Sahrawat et al. 2002b). Total S and B in plant samples were determined by ICP-AES in the digests with nitric acid (Mills and Jones 1996).

Crop yield, benefit to cost ratio and rainwater use efficiency

At maturity, the crop yields were recorded from three sub-plots measuring 3 m × 3 m = 9 m^2, the average of which was converted into final yield. The additional cost on fertilizer application was worked out on prevailing average market prices of fertilizers used viz. 30 Rs kg^{-1} zinc sulphate, 120 Rs kg^{-1} agribor and 2 Rs kg^{-1} gypsum. Additional returns were calculated for crops based on-farm gate price of 17 Rs kg^{-1} soybean, 10 Rs kg^{-1}

maize, 28 Rs kg^{-1} groundnut, 9 Rs kg^{-1} pearl millet, 22 Rs kg^{-1} chickpea and 12 Rs kg^{-1} wheat. The benefit to cost ratios were worked out by dividing additional returns through higher yields with additional costs of S, B, Zn and VC in BN and INM over and above the FP. The total amount of water received through rainfall (mm) during crop growth at respective trial locations was used to calculate rainwater use efficiency (RWUE) of crop production as kg of food grain produced per ha per mm of rainwater received (kg mm^{-1} ha^{-1}).

Statistics

The data collected were subjected to statistical analysis with ANOVA to test the least significant difference of treatment means at 5% level using the Genstat 13th edition (Ireland 2010). The experimental design was a completely randomized design, and each farmers' field in a district was treated as a replication for statistical analysis of the data.

Results and discussion

Soil analysis

Diagnostic analyses done on soils collected from fields in Madhya Pradesh revealed widespread deficiencies of secondary and micronutrients mainly S, B and Zn along with macronutrient P (Table 4). Most (>50%) fields in the districts in Madhya Pradesh in general with some exceptions in Indore, Shajapur, Rajgarh and Sagar were detected with low levels or high deficiency of S (53–96%), B (50–95%), Zn (75–97%) and P (60–92%). Most of the fields in Rajgarh and Sagar districts were rather sufficient in Zn; while in Shajapur the fields were sufficient in S, Zn and P. Similarly, the soils in Indore district were relatively better in most fields with sufficient contents of all essential nutrients. All soils across the districts showed low soil organic C at varying levels (9–53% deficiency), but those in Sehore district were critical with respect to most (53%) fields which were found to be deficient in soil organic C. K was sufficient in all fields in Madhya Pradesh except in Sehore district where it was found to be deficient in 5% fields.

The soils sampled from fields in Rajasthan also showed similar soil degradation (Table 4). In contrast to Madhya Pradesh, the Rajasthan soils were relatively poorer in soil organic C, particularly in Sawai Madhopur and Tonk districts, where in most fields low levels of soil organic C were detected (72–84% deficiency). Deficiencies of K (0–32%) were also noted in the districts of Rajasthan. In all the districts barring Sawai Madhopur for Zn and Jhalawar for P; there were critical deficiencies of S (70–87%), B (52–100%), Zn (60–94%) and P (50–73%) in most fields.

Similar micro and secondary nutrients deficiencies have been reported in other rainfed SAT regions of India (Sahrawat et al. 2010; Chander et al. 2012). The current fertilization practices of farmers in the target regions consider only crop macronutrient (NPK) needs and lack application of deficient S, B and Zn nutrients, which apparently is the reason for low crop yields and declining response to macronutrients observed in the Indian SAT.

Response to BN and INM

In Madhya Pradesh, the soil test based BN management significantly increased soybean productivity over the FP both during the year 2010 (12–25%) and 2011 (14–16%) (Table 5).

Table 4. pH, organic C and available nutrient status of farmers' fields in two states of India.

District	Number of farmers	pH	% deficiency (range of available contents[a])					
			Organic C	P	K	S	B	Zn
Madhya Pradesh								
Barwani	20	7.6–8.4	45 (2.8–7.6)	**70** (0.5–18.4)	0 (73–299)	**55** (4.0–40.5)	**80** (0.18–0.70)	**75** (0.30–1.14)
Guna	38	7.2–8.5	21 (4.7–11.1)	**79** (0.1–10.2)	0 (86–303)	**87** (2.7–14.3)	**50** (0.22–2.20)	**95** (0.24–1.74)
Indore	23	7.8–8.3	9 (4.3–10.8)	39 (0.5–42.2)	0 (129–716)	9 (5.9–134.4)	17 (0.46–1.30)	22 (0.56–3.00)
Raisen	20	7.9–8.4	30 (4.2–9.7)	**90** (0.5–13.4)	0 (118–275)	**90** (2.9–12.8)	**90** (0.20–0.74)	**90** (0.30–0.98)
Rajgarh	30	6.7–8.3	13 (4.4–14.1)	**60** (1.6–19.2)	0 (51–434)	**53** (2.9–50.4)	**73** (0.30–0.92)	27 (0.38–3.82)
Sagar	32	6.7–8.0	9 (4.2–21.9)	**78** (0.5–68.0)	0 (149–333)	**63** (4.2–23.8)	**91** (0.18–1.22)	34 (0.50–3.10)
Sehore	19	7.3–8.4	**53** (3.6–6.9)	**84** (0.5–17.5)	5 (48–256)	**74** (3.0–20.5)	**95** (0.28–0.62)	**95** (0.36–0.92)
Shajapur	20	7.1–8.2	10 (4.6–11.5)	25 (1.0–25.8)	0 (51–249)	25 (5.6–42.0)	**80** (0.18—.72)	40 (0.46–1.42)
Vidisha	72	7.6–8.6	32 (3.1–9.2)	**92** (0.5–14.1)	0 (96–401)	**96** (1.8–16.6)	**93** (0.12–0.74)	**97** (0.10–1.00)
Rajasthan								
Banswara	30	6.3–8.1	43 (2.8–10.5)	**50** (1.0–35.0)	17 (31–418)	**70** (2.4–22.0)	**100** (0.10–0.54)	**80** (0.26–2.60)
Jhalawar	30	8.0–8.6	7 (4.6–11.5)	30 (0.9–22.6)	0 (51–1358)	**87** (1.9–78.0)	**77** (0.22–1.36)	**60** (0.40–3.40)
Sawai Madhopur	44	7.8–9.4	**84** (1.6–7.0)	**73** (0.2–11.8)	7 (44–438)	**86** (3.1–26.6)	**52** (0.20–2.18)	41 (0.34–28.60)
Tonk	78	6.8–10.2	**72** (0.9–11.1)	**55** (0.2–28.2)	32 (14–243)	**79** (2.3–29.8)	**64** (0.08–2.46)	**94** (0.06–11.92)

Notes: Bold values in Table 4 indicate % fields deficient in particular nutrient i.e. baseline status of farmers' fields and does not involve statistics or significance.
[a]Values in parentheses indicate the range of available contents in mg kg^{-1} for all parameters except organic C in g kg^{-1} (Sahrawat et al. 2011).

Table 5. Effects of nutrient managements on soybean (Glycine max) grain yield, benefit to cost ratio and rainwater use efficiency under rainfed conditions in Madhya Pradesh, India.

	Grain yield (kg ha^{-1})				Benefit to cost ratio		Rainwater use efficiency (kg mm^{-1} ha^{-1})		
District	FP	BN	INM	LSD (5%)	BN	INM	FP	BN	INM
2010									
Guna	1270	1440	1580	34	1.31	4.58	1.76	1.99	2.19
Raisen	1360	1600	1600	115	1.85	3.55	1.76	2.07	2.07
Shajapur	1900	2120	2410	69	2.99	10.2	3.45	3.85	4.38
Vidisha	1130	1410	1700	640	2.16	8.43	1.48	1.84	2.22
2011									
Guna	1370	1560	1600	169	1.47	3.4	0.83	0.95	0.97
Shajapur	1220	1400	1510	44	2.45	5.8	1.12	1.28	1.38
Vidisha	1190	1380	1460	91	1.47	3.99	0.88	1.02	1.08

Note: FP, farmers' practice (application of N, P, K only); BN, balanced nutrition (FP inputs plus S + B + Zn); INM, integrated nutrient management (50% BN inputs + VC).

A benefit to cost (1.31–2.99) analysis for both the years showed BN as an economically remunerative option. Rainfed crops in other parts of India have also shown positive response to BN (Rao et al. 2009; Sahrawat et al. 2010; Chander et al. 2012). However, the substitution of 50% of chemical fertilizers with VC in INM option, in general increased yields further over BN with nutrients applied solely through chemical fertilizers. In the INM, soybean productivity increased by 18–50% during the year 2010 and by 17–24% during the year 2011 as compared with FP. In contrast, the additional cost of INM (850–1150 Rs ha^{-1}) over and above FP is very less as compared with BN (1250–2200 Rs ha^{-1}), but the net returns under INM (2760–8540 Rs ha^{-1}) are far better than that under BN (690–2560 Rs ha^{-1}). RWUE was also enhanced under the improved management, the INM practice recorded 0.97–4.38 kg mm^{-1} ha^{-1} followed by BN at 0.95–3.85 kg mm^{-1} ha^{-1} as compared with FP with lowest RWUE of 0.83–3.45 kg mm^{-1} ha^{-1}. The nutrient management similar to grain yield biomass apparently recorded profused root biomass that could effectively utilize scarce water from far-off places and convert otherwise unproductive evaporation loss into productive transpiration under the INM treatment followed by BN. INM thus resulted in greater benefits in terms of economic productivity improvement and efficient resource utilization including on-farm wastes.

Similarly in Rajasthan, BN brought a significant yield advantage over the FP by 15–40% in maize, 10–20% in pearl millet, 14–17% in groundnut and 6–22% in soybean during the years 2010 and 2011 (Table 6). The INM recorded yields either at par with BN or more over it. An economic analysis showed the benefit to cost ratio of BN in the range of 1.59–4.28 for maize, 0.81–1.43 for pearl millet, 1.78–2.42 for groundnut and 0.85–3.32 for soybean. While the benefit to cost ratio of INM was far better than BN viz. 4.59–8.24 for maize, 2.26–3.66 for pearl millet, 5.84–7.79 for groundnut and 3.96–8.42 for soybean. The INM brought an additional net return over the FP by 5083–10,193 Rs ha^{-1} in maize, 1353–3858 Rs ha^{-1} in pearl millet, 5570–7810 Rs ha^{-1} in groundnut and 4068–10,188 Rs ha^{-1} in soybean. The INM practice resulted in the most efficient use of scarce water resources by crops like maize, pearl millet, groundnut, soybean, and recorded RWUE of 1.57–6.16 kg mm^{-1} ha^{-1}. BN was the next best treatment from RWUE point of view at 1.42–5.77 kg mm^{-1} ha^{-1}, while the FP treatment recorded the lowest RWUE of 1.21–4.85 kg mm^{-1} ha^{-1}. The results from the

Table 6. Effects of nutrient managements on crop yield, benefit to cost ratio and rainwater use efficiency under rainfed conditions in Rajasthan, India.

	Grain yield (kg ha^{-1})				Benefit to cost ratio		Rainwater use efficiency (kg mm^{-1} ha^{-1})			Grain yield (kg ha^{-1})				Benefit to cost ratio		Rainwater use efficiency (kg mm^{-1} ha^{-1})		
District	FP	BN	INM	LSD (5%)	BN	INM	FP	BN	INM	FP	BN	INM	LSD (5%)	BN	INM	FP	BN	INM
2010									2011									
Maize (*Zea mays*)																		
Banswara	2850	3390	3620	780	2.45	5.8	4.85	5.77	6.16	2410	3290	3140	1456	4	5.5	2.44	3.33	3.18
Sawai Madhopur	1560	2180	2530	268	4.28	8.24	2.31	3.23	3.75	2330	2700	3000	324	2.55	5.69	3.12	3.61	4.02
Tonk	2840	3350	3560	280	2.32	5.08	4.21	4.96	5.27	2410	2760	3060	378	1.59	4.59	3.07	3.51	3.89
Pearl millet [*Pennisetum glaucum* (L.) R. Br.]																		
Sawai Madhopur	1410	1590	1700	234	1.12	2.42	2.09	2.36	2.52	1340	1470	1610	73	0.81	2.26	1.79	1.97	2.16
Tonk	2210	2560	2800	325	1.43	3.66	3.27	3.79	4.15	1720	2060	2280	365	1.39	3.47	2.19	2.62	2.90
Groundnut (*Arachis hypogaea*)																		
Tonk	820	960	1060	107	1.78	5.84	1.21	1.42	1.57	1340	1530	1660	142	2.42	7.79	1.70	1.95	2.11
Soybean (*Glycine max*)																		
Jhalawar	1700	1810	2020	82	0.85	3.96	3.04	3.23	3.61	1940	2370	2620	307	3.32	8.42	1.85	2.26	2.50

Note: FP, farmers' practice (application of N, P, K only); BN, balanced nutrition (FP inputs plus S + B + Zn); INM,integrated nutrient management (50% BN inputs + VC).

Table 7. Effects of nutrient managements on soybean (*Glycine max*) grain nutrient contents and total nutrient uptake in Raisen district, Madhya Pradesh, India during rainy season in 2010.

	Grain nutrient contents					
	N	P	K	S	B	Zn
Treatment	g kg^{-1}			mg kg^{-1}		
FP	59.8	5.20	18.8	3254	33.7	55.6
BN	60.2	5.20	18.3	3279	33.9	56.4
INM	61.0	5.70	18.9	3807	34.6	67.3
LSD (5%)	7.2	0.80	1.7	415	5.09	11.2
	Total nutrient uptake					
	N	P	K	S	B	Zn
	kg ha^{-1}				g ha^{-1}	
FP	98	9.71	53.5	5.78	88	101
BN	134	12.5	61.8	8.20	103	156
INM	138	13.8	65.1	9.29	108	179
LSD (5%)	26	2.96	8.53	1.71	20	30

Note: FP, farmers' practice (application of N, P, K only); BN, balanced nutrition (FP inputs plus S + B + Zn); INM, integrated nutrient management (50% BN inputs + VC).

present on-farm study thus proved very clearly that the soil fertility management through INM or BN enabled crop plants to produce more food per drop of available water, and so is one of the most important rainwater management strategies to improve water productivity (Rockström et al. 2010) in the water scarce SAT regions.

Nutrient content and uptake

The BN and INM treatments, in general, tended to increase soybean grain nutrient contents over the FP, the differences, however, were insignificant except for S and Zn contents under INM (Table 7). Conjoint application of S and Zn along with VC under the INM apparently reduced fixation and leaching losses of nutrients and thereby enhanced their availability in soil and uptake by plants. INM also included application of B which is necessary to maintain membrane integrity (Cakmak et al. 1995) and hence can enhance ability of membranes to transport available nutrients.

Nutrient uptake also increased under the improved management practices as compared with the farmers' practice, while INM recorded the highest uptake. The results are on expected lines due to the increased crop yield and plant nutrient contents.

Residual benefits of S, B, Zn and VC

In Madhya Pradesh, the plots with applied S, B, Zn and VC in BN and INM during the rainy season 2010 also showed significant residual benefits during the succeeding post-rainy season 2010–2011, rainy season 2011 and post-rainy season 2011–2012; the benefits were, however, more under INM. During post-rainy season 2010–2011, wheat yields were higher by 12–26% and chickpea yields were higher by 14–39% in the plots having received INM as compared to FP (Table 8). Similarly, in the rainy season 2011, the soybean yields were higher by 9–33% under the INM-managed plots as compared to FP

Table 8. Residual effects of nutrient managements during rainy season 2010 on crop grain yield in succeeding three seasons in Madhya Pradesh, India.

	Grain yield (kg ha^{-1})			
District	FP	BN	INM	LSD (5%)
Post-rainy season 2010–2011				
Wheat (*Triticum aestivum*)				
Raisen	2270	2500	2540	266
Shajapur	3520	3760	3980	135
Vidisha	4500	5170	5670	541
Chickpea (*Cicer arietinum*)				
Raisen	1150	1290	1310	101
Shajapur	1200	1430	1670	72
Rainy season 2011				
Soybean (*Glycine max*)				
Guna	1290	1330	1400	100
Shajapur	1410	1550	1690	46
Vidisha	1090	1270	1450	74
Post-rainy season 2011–2012				
Wheat (*Triticum aestivum*)				
Raisen	3870	4110	4250	29
Shajapur	4570	4990	4800	103
Chickpea (*Cicer arietinum*)				
Raisen	1780	1950	2120	52
Shajapur	1280	1480	1370	115

Note: FP, farmers' practice (application of N, P, K only); BN, balanced nutrition (FP inputs plus S + B + Zn); INM, integrated nutrient management (50% BN inputs + VC).

plots. In the third consecutive season during post-rainy season 2011–2012 also, the INM-treated plots as compared to FP plots recorded higher yields by 5–10% in wheat and 7–19% in chickpea. In economic terms, INM strategy produced more food worth 2760–14,040 Rs ha^{-1} in wheat, 1980–10,340 Rs ha^{-1} in chickpea and 1870–6120 Rs ha^{-1} in soybean during each of the three succeeding seasons.

Similarly in Rajasthan, the residual benefits of applied S, B, Zn and VC as BN and INM in rainy season 2010 were studied in succeeding post-rainy season wheat and chickpea crops. Wheat yield increased to 3990 kg ha^{-1} under BN and 3850 kg ha^{-1} under INM as compared with the 3600 kg ha^{-1} under the FP. Similarly, chickpea yield increased to 1720 kg ha^{-1} under BN and 1610 kg ha^{-1} under INM as compared with the 1500 kg ha^{-1} under the FP. The yield advantage under BN or INM was at par with each other. As such, the yield increases of 11–15% were recorded under the BN applied plots and 7% under the INM applied plots. The residual benefits were worth 4680–4840 Rs ha^{-1} under BN and 2420–3000 Rs ha^{-1} under the INM management strategy. The results clearly showed that the adoption of improved management through INM and BN is not only economically remunerative in the season 1 of application but also leads to resilience building of production systems apparently through improved soil health which is manifested as yield benefits in succeeding seasons as noted in this study.

Conclusions

Widespread deficiencies of S, B and Zn were diagnosed in the semi-arid regions in Madhya Pradesh and Rajasthan states in India, which farmers should consider and include these deficient secondary and micro nutrients in their fertilizer management strategies every alternate year. The apparent yield losses in absence of the soil test based BN or INM practices are between 6% and 62% of current crop yield levels in season 1 and between 3% and 39% in each of the next three succeeding seasons. The INM practice proved to be superior over the BN solely through chemical fertilizers in realizing either at par or higher yield levels while cutting use and cost of 50% of chemical fertilizers through effective recycling of on-farm wastes. The on-farm evaluation results of this study suggest the need to promote the use of VC in food production for higher productivity and net returns. VC use for food production may be economical and practical only if it is produced on-farm from available wastes. The smallholders in the rainfed SAT in India are unaware of soil health issues and available technologies and are not in a position to implement the science led strategy of their own. So, there is a strong need for desired policy orientation by the respective governments to promote capacity strengthening and soil test based INM and BN strategies through appropriate incentives for poor smallholders in the SAT in India.

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