Enhancing Nutrient Use Efficiencies in Rainfed Systems

Suhas P. Wani, Girish Chander, and Rajneet K. Uppal

Abstract

Successful and sustained crop production to feed burgeoning population in rainfed areas, facing soil fertility-related degradation through low and imbalanced amounts of nutrients, requires regular nutrient inputs through biological, organic or inorganic sources of fertilizers. Intensification of fertilizer (all forms) use has given rise to concerns about efficiency of nutrient use, primarily driven by economic and environmental considerations. Inefficient nutrient use is a key factor pushing up the cost of cultivation and pulling down the profitability in farming while putting at stake the sustainability of rainfed farming systems. Nutrient use efficiency implies more produce per unit of nutrient applied; therefore, any soil-water-crop management practices that promote crop productivity at same level of fertilizer use are expected to enhance nutrient use efficiency. Pervasive nutrient depletion and imbalances in rainfed soils are primarily responsible for decreasing yields and declining response to applied macronutrient fertilizers. Studies have indicated soil test-based balanced fertilization an important driver for enhancing yields and improving nutrient use efficiency in terms of uptake, utilization and use efficiency for grain yield and harvest index indicating improved grain nutritional quality. Recycling of on-farm wastes is a big opportunity to cut use and cost of chemical fertilizers while getting higher yield levels at same macronutrient levels. Best management practices like adoption of high-yielding and nutrient-efficient cultivars, landform management for soil structure and health, checking pathways of nutrient losses or reversing nutrient losses through management at watershed scale and other holistic crop management practices have great scope to result in enhancing nutrient and resource use efficiency through higher yields. The best practices have been found to promote soil organic

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carbon storage that is critical for optimum soil processes and improve soil health and enhance nutrient use efficiency for sustainable intensification in the rainfed systems.

Keywords
N use efficiency • Nutrient efficient genotypes • P use efficiency • Rainfed agriculture • Soil health • Sustainable intensification

1 Introduction

Awareness of and interest in enhancing nutrient use efficiency have never been greater than as of today mainly due to the need to produce more food from limited land and to protect the environment through sustainable intensification. Regular nutrient inputs through chemical fertilizers have become an integral component of the production systems as the systems have become open to exporting of nutrients through food production areas (rural farming areas) to urban areas as well as to outside countries as against the traditional closed systems wherein nutrients were recycled. It is essential to recognize that in rainfed production systems, even with relatively low productivity level, the quantity of nutrient removal is quite substantial over the years, as these soils did not receive balanced nutrient applications. Furthermore, the quantum of nutrients available for recycling via crop residues and animal manures is grossly inadequate to compensate for the amounts removed in crop production. Thus, mineral fertilizers have come to play a key role where increased agricultural production is required to meet growing food demand and particularly in soils having low fertility. Though the consumption of chemical fertilizers has increased steadily over the years, the use efficiency of nutrients applied as fertilizers continues to remain awfully low. A review of best available information suggests that the average N recovery efficiency for fields managed by farmers ranges from about 20 to 30 % under rainfed conditions and 30 to 40 % under irrigated conditions (Roberts 2008).

Improving nutrient efficiency is a worthy goal and fundamental challenge. The opportunities are there, and tools are available to accomplish the task of improving the efficiency of applied nutrients. However, we must be cautious that improvements in efficiency do not come at the expense of the farmers' economic viability or the environment. Judicious application of nutrients targeting both high yields and nutrient efficiency will benefit farmers, society and the environment alike.

2 Importance of Rainfed Agricultural Systems

Addressing rainfed agricultural systems is very important as 80 % of the cultivated area worldwide is rainfed and contributes to about 60 % of the world's food (Wani et al. 2012a). Rainfed regions are the homes to the world's poor and malnourished people, and maximum population growth (95 %) is taking place here (Wani et al. 2012a). In India also, the rainfed-cropped areas comprise about 60 % (89 million ha) of the net-cultivated area (Wani et al. 2008). Irrigated regions in India have reached a productivity plateau, and today there is a big issue of concern to feed the burgeoning population. In spite of best efforts to increase irrigation, around 45 % of cultivated will still continue to remain rainfed by the year 2050 (Bhatia et al. 2006; Amarasinghe et al. 2007). There is no option of increasing arable land, and with burgeoning population, per capita arable land availability in India has decreased from 0.39 ha in 1951 to 0.12 ha in 2011 and is expected to be 0.09 ha by the year 2050 (Ministry of Agriculture, Government of India 2013; FAOSTAT 2013). Within existing land and water constraints, India must sustainably increase the productivity levels of the major rainfed crops to meet the ever-increasing demand of food to around 380 million tonnes in 2050 (Amarasinghe et al. 2007). Moreover, due to the role of agriculture in economic development and poverty reduction (Irz and Roe 2000; Thirtle et al. 2002; World Bank 2005), the upgradation of rainfed agriculture is priority of the government. So, in current context of suboptimal input use in rainfed systems, a regular use of nutrient inputs through chemical fertilizers is going to be increased with needs and opportunities for enhancing nutrient use efficiencies.

3 Large Yield Gaps and Untapped Potential

Yield gap analyses for major rainfed crops in semi-arid tropics (SAT) in Asia (Fig. 1) and Africa reveal large yield gaps, with farmers' yields being a factor of two- to fourfold lower than achievable yields for major rainfed crops grown in Asia and Africa (Rockström et al. 2007). At the same time, the dry subhumid and semi-arid regions experience the lowest yields and the lowest productivity improvements. Here, yields oscillate between 0.5 and 2 t ha^{-1}, with an average of 1 t ha^{-1}, in sub-Saharan Africa and 1–1.5 t ha^{-1} in SAT Asia (Rockström and Falkenmark 2000; Wani et al. 2003a, b; Rockström et al. 2007). Farmers' yields continue to be very low compared with the experimental yields (attainable yields) as well as simulated crop yields (potential yields), resulting in a very significant yield gap between actual and attainable rainfed yields. The difference is largely explained by inappropriate soil, water and crop management options used at the farm level, combined with persistent land degradation and inappropriate institutional and policy mechanisms. The vast potential of rainfed agriculture needs to be unlocked through knowledge-based management of soil, water and crop resources for increasing productivity and nutrient use efficiency through sustainable intensification.

4 Intensification to Bridge Yield Gaps and Environmental Implications

The intensive use of chemical fertilizers during the past four to five decades undoubtedly quadrupled global food grain production but has created implications for the environmental safety (Tilman et al. 2001, 2002; Hungate et al. 2003; Sutton et al. 2011). Worldwide, chemical fertilizer consumption has increased fourfold during the last 50 years (FAO 2011). As regards to N fertilizers, the increase in agricultural food production worldwide over the past four decades has been associated with a sevenfold increase in the use of N fertilizers (Rahimizadeh et al. 2010), with 33 % nitrogen use efficiency (Raun and Johnson 1999). Similarly, an overview of agriculture in India indicates that since the late 1960s (1966–1971), the period that coincides with the launch of green revolution, the food grain production is more than doubled during 2006–2009 with almost no change in area but accompanied by more than 12 times increase in nitrogenous fertilizer consumption (Ministry of Agriculture, Government of India 2013). High nitrifying nature of intensive production systems results in loss of nearly 70 % of the overall N-fertilizer inputs (Peterjohn and Schlesinger 1990; Raun and Johnson 1999). Rapid and unregulated nitrification from agricultural systems results in increased N leakage to the environment (Schlesinger 2009). Nitrogen-fertilizer-based pollution is also becoming a serious issue for many agricultural regions (Garnett et al. 2009). Inefficient use of N fertilizer is causing serious environmental problems associated with the emission of NH_3, N_2 and N_2O (the last being an important greenhouse gas implicated both in the global warming and ozone layer depletion in the stratosphere) to the atmosphere. N_2O is a powerful greenhouse gas having a global warming potential (GWP) 300 times greater than that of CO_2 (Kroeze 1994; IPCC 2007), while the earth's protective ozone layer is damaged by NOs that reach the stratosphere (Crutzen and Ehhalt 1977). The loss of NO_3 from the root

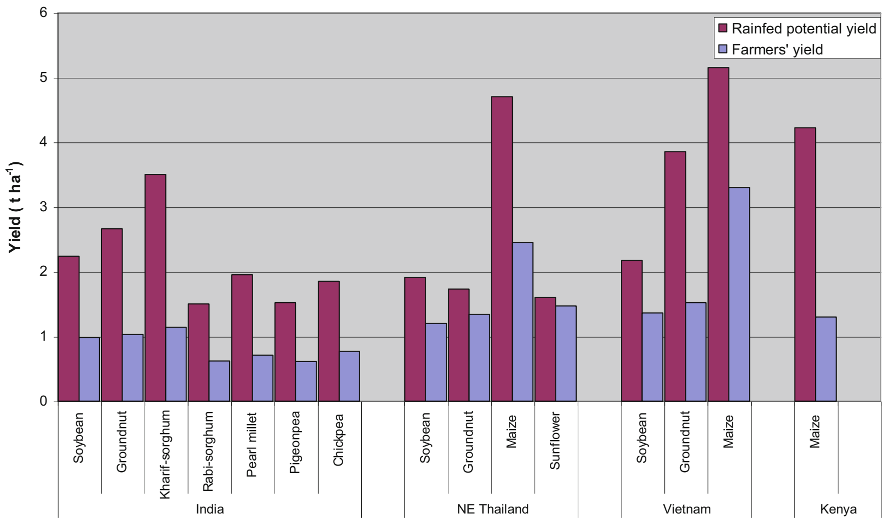

Fig. 1 Yield gap of important rainfed crops in different countries (Source: Rockström et al. 2007)

zone and NO_3 contamination of ground and surface water via nitrate leaching or run-off are major environmental concerns (Singh and Verma 2007; Tilman et al. 2001; Galloway et al. 2008; Schlesinger 2009). Current estimates indicate that N lost by NO_3 leaching from agricultural systems could reach 61.5 Tg N year^{-1} by 2050 (Schlesinger 2009). Excessive fertilizer run-off in water bodies results in growth of algal blooms leading to eutrophication, shifting the state of lake systems from clear to turbid water (Carpenter 2003). It was recently documented by Rockstorm et al. (2009) that planetary boundaries for nitrogen cycle have already crossed the biophysical thresholds. Similarly excessive phosphate fertilizer can be a significant contributor of potentially hazardous trace elements such as arsenic, cadmium and lead in croplands. These trace elements have the potential to accumulate in soils and be transferred through the food chain (Jiao et al. 2012). In response to continually increasing economic and environmental pressures, there is an urgent need to enhance efficient use of nitrogenous fertilizers and increase profitability by developing sustainable farming systems (Mahler et al. 1994).

5 Potential for Sustainable Intensification

Evidence from a long-term experiment at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, India, since 1976 demonstrated the virtuous cycle of persistent yield increase through improved land, water and nutrient management in rainfed agriculture. Improved systems of sorghum + pigeon pea intercrops produced higher mean grain yields (5.1 t ha^{-1}) through increased rainwater use efficiency compared with 1.1 t ha^{-1}, the average yield of sole sorghum in the traditional (farmers') post-rainy system, where crops are grown on stored soil moisture (Figs. 2 and 3). The annual gain in grain yield in the improved system was 70 kg ha^{-1} year^{-1} compared with 20 kg ha^{-1} year^{-1} in the traditional system. The large yield gap between attainable yield and farmers' practice as well as between the attainable yield of 5.1 t ha^{-1} and potential yield of 7 t ha^{-1} shows that a large potential of rainfed agriculture remains to be tapped. Moreover, the improved management system is still continuing to provide an increase

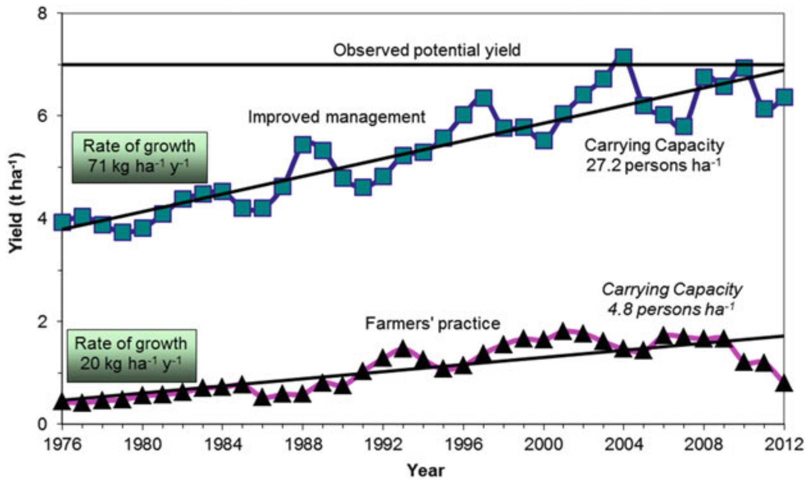

Fig. 2 Effects of improved management and farmers' management systems on crop yields during 1976–2012 at ICRISAT, Patancheru, India (Source: Wani et al. 2012a)

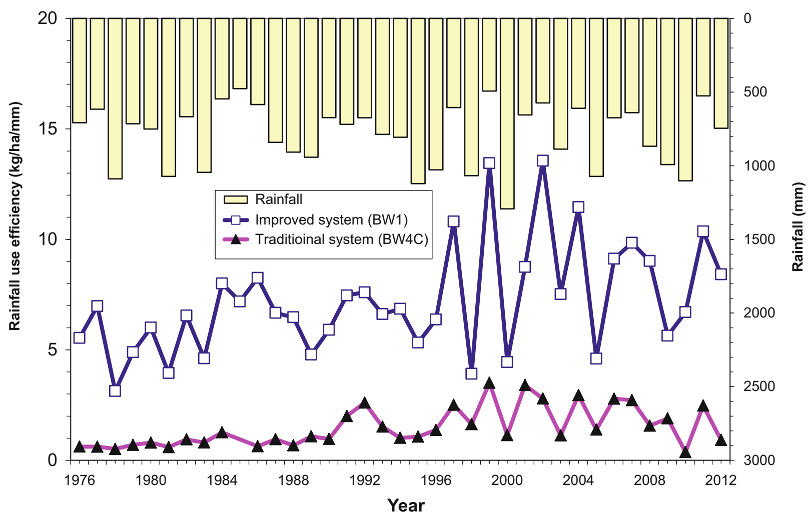

Fig. 3 Effects of improved management and farmers' management systems on rainfall use efficiency during 1976–2012 at ICRISAT, Patancheru, India

in productivity as well as improving soil quality (physical, chemical and biological parameters) along with increased carbon sequestration which is very much required to promote soil organic carbon storage critical for optimum soil processes to enhance nutrient use efficiency.

Long-term studies at ICRISAT showed that an improved system having balanced fertilization not only increased crop productivity but also increased soil organic C and nutrients like total and available N and Olsen P (Wani et al 2003a) in the system. This study showed that an additional quantity of 7.3 t C ha^{-1} (335 kg C ha^{-1} $year^{-1}$) was sequestered in soil under the improved system compared with the traditional system over the 24-year period. With an increase in biomass C (89 %), there was 83 % increase in mineral N, 105 % increase in microbial biomass N and about 18 % increase in total N in the improved system compared with the traditional system. Microbial biomass is one of the most labile pools of organic matter and serves as an important reservoir of plant nutrients such as N and P (Jenkinson and Ladd 1981). Biomass C, as a proportion of total soil C, serves as a surrogate for soil quality (Jenkinson and Ladd 1981). ICRISAT long-term study showed that under improved management practices, biomass C constituted a higher proportion of soil organic C up to 10.3 % as compared with 6.4 % under farmers' practice. Biomass N is comprised of about 2.6 % of total soil N in the improved system, whereas in the traditional system, it constituted only 1.6 %.

6 What Does Increased Nutrient Use Efficiency Imply?

Nutrient use efficiency can be defined in many ways and is easily misunderstood and misrepresented. Definitions differ, depending on the perspective. Increased nutrient use efficiency implies the following:

- Lesser nutrient need for obtaining a given level of production or more produce per unit of nutrient applied
- Lower cost of production per unit of produce
- Higher returns per $ invested on nutrient use
- Reduced risk of environmental pollution

Over- or under-application of needed nutrients will result in reduced nutrient use efficiency or losses in yield and crop quality. Improving nutrient efficiency is an appropriate goal for all involved in agriculture. However, maximizing efficiency may not always be advisable or effective, and effectiveness cannot be sacrificed for the sake of efficiency. Much higher nutrient efficiencies could be achieved simply by sacrificing yield, but that would not be economically effective or viable for the farmer or the environment. For a typical yield response curve, nutrient use efficiency is high at a low yield level, because any small amount of nutrient applied could give a large yield response. If nutrient use efficiency were the only goal, it would be achieved here in the lower part of the yield curve. As we move up the response curve, yields continue to increase, albeit at a slower rate, and nutrient use efficiency typically declines. However, the extent of the decline is dictated by the best management practices (BMPs) employed (i.e. right rate, right time, right place, improved balance in nutrient inputs, etc.) as well as soil and climatic conditions and is the target area of researchers to enhance the nutrient use efficiency through optimization of BMPs.

6.1 Measures of Nutrient Use Efficiency

The nutrient use efficiency is measured in different ways depending upon the perspective in which it is computed and considered. The agronomists, soil scientists, plant physiologists and agricultural economists use different expressions/measures for nutrient use efficiency. Taking nitrogen (N) as an example of plant nutrients, different measures of nutrient use efficiency can be defined as follows (Delogu et al. 1998; Lopez-Bellido and Lopez-Bellido 2001):

Nitrogen uptake efficiency (NUpE) is worked out by dividing total plant N uptake with N supply (Eq. 1).

$$\mathrm{NUpE}\left(\mathrm{kg\ kg^{-1}}\right) = \mathrm{Nt/N\ supply} \quad (1)$$

where Nt is the total plant N uptake and is determined by multiplying dry weight of plant parts by N concentration and summing over parts for total plant uptake. N supply is the sum of soil N content at sowing, mineralized N and N fertilizer. N supply is defined (Limon-Ortega et al. 2000) as the sum of (i) N applied as fertilizer and (ii) total N uptake in control (0 N applied).

Nitrogen utilization efficiency (NUtE) is worked out by dividing grain yield with total plant N uptake (Eq. 2).

$$\mathrm{NUtE}\left(\mathrm{kg\ kg^{-1}}\right) = \mathrm{Y/Nt} \quad (2)$$

where Y is grain yield.

Nitrogen use efficiency (NUE) is estimated by dividing grain yield with N supply (Eq. 3).

$$\mathrm{NUE}\left(\mathrm{kg\ kg^{-1}}\right) = \mathrm{Y/N\ supply} \quad (3)$$

The nitrogen harvest index (NHI) is determined by dividing total grain N uptake with total plant N uptake and multiplying by 100 (Eq. 4).

$$\mathrm{NHI}(\%) = (\mathrm{Ng/Nt}) \times 100 \quad (4)$$

where Ng is the total grain N uptake. Ng is determined by multiplying dry weight of grain by N concentration.

There are some incremental efficiency measures under Reddy (2013).

Agronomic efficiency of N (AEN) is the increase in crop yield per unit of N applied, i.e. ratio of the increase in yield to the amount of N applied (Eq. 5).

$$\text{AEN}\left(\text{kg kg}^{-1}\right) = (\text{Y}_\text{N} - \text{Y}_0)/\text{N applied} \quad (5)$$

where Y_N (kg ha^{-1}) is the economic yield with N application, Y_0 (kg ha^{-1}) is the economic yield without N application and N applied (kg ha^{-1}) is the amount of N applied.

Recovery efficiency of N (REN) refers to the increase in N uptake by plant (aboveground parts) per unit of N applied (Eq. 6).

$$\text{REN}(\%) = (\text{NnNo})/\text{N applied} \times 100 \quad (6)$$

where Nn (kg ha^{-1}) is the N uptake by crop with N application and No (kg ha^{-1}) is the N uptake by crop without N application.

Physiological efficiency of N (PEN) indicates the efficiency with which the plant utilizes the absorbed N to produce economic yield (Eq. 7).

$$\text{PEP}\left(\text{kg kg}^{-1}\right) = (\text{Y}_\text{N} - \text{Y}_0)/(\text{NnNo}) \quad (7)$$

Economic efficiency of N (EEN) refers to agronomic efficiency (AEP) expressed in monetary terms (Eq. 8). It can be equated with most popularly used benefit to cost ratio.

$$\begin{aligned}\text{EEP} = {} & (\text{Y}_\text{N} - \text{Y}_0)/\text{N applied} \\ & \times \text{Value of the produce(Rs)} \\ & /\text{Cost of the nutrient(Rs)} \end{aligned} \quad (8)$$

Partial factor productivity for N (PFPN) from applied N is the ratio of grain yield to amount of N applied (Eq. 9).

$$\text{PFPN}\left(\text{kg kg}^{-1}\right) = \text{Y}/\text{N applied} \quad (9)$$

7 Enhancing Nutrient Use Efficiency Through Bridging Yield Gaps

Crop yield directly or indirectly is the numerator in different terms of nutrient use efficiency, and the practices that increase crop yield may therefore increase nutrient use efficiency. The soil-water-crop management practices that promote crop productivity at the same level of fertilizer use are expected to enhance nutrient use efficiency. Similarly, all the management practices that minimize nutrient requirement while achieving desired productivity targets would also lead to increased nutrient use efficiency.

7.1 Integrated Watershed Management

In rainfed areas, watershed management is the approach used for conservation of water and other natural resources as well as for sustainable management of natural resources while enhancing ecosystem services such as provisioning production (food, fodder and fuel), erosion control, groundwater recharge, transportation of nutrients, recreation, etc. Watershed management is the process of organizing land use and use of other resources in a watershed to provide desired goods and services to people while enhancing the resource base without adversely affecting natural resources and the environment (Wani et al. 2001). The soil and water management measures in the treated watershed include field bunding, gully plugging and check dams across the main watercourse, along with improved soil, water, nutrient and crop management technologies.

In Adarsha watershed in Kothapally, Andhra Pradesh, India, there was a significant reduction in run-off from the treated watershed compared to the untreated area in 2000 and 2001 (Table 1). In high rainfall year (2000), run-off from the treated watershed was 45 % less than the untreated area. During a subnormal rainfall year (2001), run-off from the treated watershed was 29 % less than the untreated area. Of the 3 years during 1999–2001, 2 years (1999 and 2001) were low rainfall years. Besides low rainfall, most of the rainfall events were of low intensity. This resulted in very low seasonal run-off during 1999 and 2001. Generally, during the low run-off years, the differences between the treated and untreated watersheds are very small. During good rainfall, i.e. 2000, a significant difference in

Table 1 Seasonal rainfall, run-off and soil loss from the Adarsha watershed in Kothapally, Andhra Pradesh, India, 1999–2001

	Run-off (mm)			Soil loss (t ha^{-1})	
Year	Rainfall	Untreated	Treated	Untreated	Treated
1999	584	16	NR	–	–
2000	1,161	118	65	1.04	–
2001	612	31	22	1.48	0.51

Source: Sreedevi et al. (2004)
Untreated = control with no development work; treated = with improved soil, water and crop management technologies; NR = not recorded

the run-off was seen between treated and untreated watersheds (Table 1). The soil loss was measured both from treated and untreated watersheds during 2001. There was a significant reduction in soil loss from treated watershed (only 1/3 soil loss) compared to untreated watershed in 2001. Thus, integrated watershed management is an important vehicle of technologies to check nutrient losses or reversing nutrient losses through run-off water or along with soil lost. Thus, management at watershed scale is another important aspect that needs urgent attention to enhance efficiency of inherent nutrients in soil and added through fertilizers and manures.

More infiltrations through reduced run-off under watersheds (Wani et al. 2012b) also strengthen the green-water sources to create synergy with nutrients to get higher yields and nutrient use efficiency. For food production worldwide, the consumption of green water is almost threefold more than blue water (5,000 vs. 1,800 km^3 $year^{-1}$) (Karlberg et al. 2009) and thereby changes in it can result large impact on yields and also nutrient use efficiencies. Evidences from different watersheds (Table 2) have shown substantial productivity improvement as compared to non-watershed regions leading to efficient nutrient and resource use efficiency. As a result of watershed interventions, the rainwater use efficiency by different crops increased by 15–29 % at Xiaoxincun (China), 13–160 % at Lucheba (China) and 32–37 % at Tad Fa (Thailand), which brought in substantial productivity improvement (Table 2). The watershed interventions which improve substantially the green-water resources apparently led to better utilization of available water resources in productive transpiration and resulted in more food per drop of water. The run-off water harvested in tanks facilitated supplementary irrigation at critical stages and brought a change in production scenario. The results proved that integrated soil, crop and water management with the objective of increasing the proportion of the water balance as productive transpiration, which constitutes one of the most important rainwater management strategies to improve yields and water productivity, is effectively addressed through participatory watershed interventions. In addition to long-term sustainable benefits, crop production with watershed intervention is also a profitable option in terms of benefit: cost ratio.

7.2 Soil Health Management and Nutrient Use Efficiency

7.2.1 Widespread Soil Fertility Degradation Resulting Low Crop Yields and Nutrient Use Efficiency

Land degradation represents a diminished ability of ecosystems or landscapes to support the functions or services required for sustainable intensification. Agricultural production over a period of time particularly in marginal and fragile lands has resulted in degradation of the natural resource base, with increasing impact on productivity and nutrient use efficiency. Pervasive nutrient depletion and nutrient imbalances in agricultural soils are primary causes of decreasing yields and declining response to applied fertilizers. This depletion of selected soil nutrients often leads to fertility levels that limit production and severely affect nutrient use efficiency. Shorter fallow periods do not compensate for losses in soil organic matter and nutrients, leading to the mining of soil nutrients. In many African, Asian and Latin American countries, the nutrient depletion of agricultural soils is so high that current agricultural land use is not sustainable.

Table 2 Crop yield and rainwater use efficiency during pre- and post-watershed interventions in watersheds in China and Thailand

Crop	Pre-project period			Post-project period		
	Crop yield (kg ha^{-1})	RWUE (kg mm^{-1} ha^{-1})	B:C ratio	Crop yield (kg ha^{-1})	RWUE (kg mm^{-1} ha^{-1})	B:C ratio
Xiaoxincun, China						
Rice	5,800	9.5	1.9	6,300	11.2	2
Maize	4,500	7	1.9	5,200	8.1	2.2
Groundnut	1,400	2.2	1.8	1,800	2.8	2.2
Watermelon	10,500	16.4	3.4	12,500	19.5	3.9
Sweet potato	19,500	30.4	2.5	22,500	35.1	3
Lucheba, China						
Vegetables	36,900	28.8	1.4	41,900	32.6	1.8
Watermelon	11,300	8.8	1.5	29,300	22.8	1.6
Tad Fa, Thailand						
Maize	3,218	2.7	2.3	4,500	3.7	2.7
Cabbage	36,343	29.8	3.9	49,063	40.2	4.3
Chillies	2,406	2	4	3,188	2.6	4.6

Source: Wani et al. (2012a)

Table 3 Soil fertility status of farmers' fields in rainfed semi-arid tropics of India

State	No. of farmers	% deficiency (range of available nutrients)					
		Org-C	Av P	Av K	Av S	Av B	Av Zn
[a]Andhra Pradesh	3,650	76 (0.08–3.00)	38 (0.0–248)	12 (0–1,263)	79 (0.0–801)	85 (0.02–4.58)	69 (0.08–35.6)
[b]Gujarat	82	12 (0.21–1.90)	60 (0.4–42.0)	10 (30–635)	46 (1.1–150)	100 (0.06–0.49)	85 (0.18–2.45)
[c]Karnataka	92,904	52 (0.01–9.58)	41 (traces-544)	23 (traces-3,750)	52 (0.9–237)	62 (0.02–4.60)	55 (traces-235)
[a]Madhya Pradesh	341	22 (0.28–2.19)	74 (0.1–68)	1 (46–716)	74 (1.8–134)	79 (0.06–2.20)	66 (0.10–3.82)
[a]Rajasthan	421	38 (0.09–2.37)	45 (0.2–44)	15 (14–1,358)	71 (1.9–274)	56 (0.08–2.46)	46 (0.06–28.6)
[b]Tamil Nadu	119	57 (0.14–1.37)	51 (0.2–67.2)	24 (13–690)	71 (1.0–93.6)	89 (0.06–2.18)	61 (0.18–5.12)

Source: [a]Wani et al. (2012b), [b]Sahrawat et al. (2007), [c]Wani et al. (2011)
The figures in the parentheses indicate the range of nutrients % for Org-C and mg kg^{-1} for P, K, S, B and Zn

Nutrient depletion is now considered the chief biophysical factor limiting small-scale production in Africa (Drechsel et al. 2004). Recent characterization of farmers' fields in different states across India revealed a widespread deficiency of zinc (Zn), boron (B) and sulphur (S) in addition to known deficiencies of macronutrients such as nitrogen (N) and phosphorus (P) (Table 3). New widespread deficiencies of secondary and micronutrients are apparently the reason for holding back the productivity potential (Sahrawat et al. 2007, 2011; Wani et al. 2012b; Chander et al. 2013a, b, 2014a, b) and declining response to macronutrients and so decreasing nutrient use efficiency. In view of observed deficiencies, the application of major nutrients N, P and K as currently practiced is important for the SAT soils (El-Swaify et al. 1985; Rego et al. 2003), but very little attention has been paid to diagnose and take corrective measures for deficiencies of secondary nutrients and micronutrients in various crop production systems (Rego et al. 2005; Sahrawat et al. 2007, 2011; Wani et al. 2012b) followed in millions of small and marginal farmers' fields in the rainfed SAT. The role of soil organic carbon (C) in maintaining soil health is also well documented (Wani et al. 2012c). 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; Chander et al. 2013a). Soil organic matter, an important driving force for supporting biological activity in soil, is very much in short supply, particularly in tropical countries. Management practices that augment soil organic matter and maintain it at a threshold level are needed (Chander et al. 2013a). Therefore, there is need to identify and promote management interventions with high carbon sequestration potential to promote soil organic carbon storage which is very critical for optimum soil processes to enhance nutrient use efficiency.

7.2.2 Soil Health Management: An Important Driver for Enhancing Nutrient Use Efficiency

Often, soil fertility is the limiting factor to increased yields in rainfed agriculture. With experiences of green revolution and in a quest to get higher yields, farmers have started adding macronutrients in quantities higher than required and getting declining response to nutrient inputs. Based on soil analysis results, ICRISAT-led consortium has designed and is promoting balanced nutrient management practices which also include deficient secondary nutrients and micronutrients. Soil test-based fertilizer recommendations are designed at cluster of villages called block, a lower administrative unit in a district, by considering practical aspects like available infrastructure, human power and economics in research for impact for smallholders in the Indian SAT. Fertilizer recommendations at block level cater well to soil fertility needs in contrast to current blanket recommendations at state level. We recommend to apply full dose of a particular nutrient if its deficiency was on >50 % farms in a block and half dose of a nutrient if its deficiency was on <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. Scaling up of such soil test-based balanced fertilization through farmer participatory trials in rainfed systems in India and particularly in Karnataka through extensive government support has shown substantial increase (~20–70 %) in crop yields after micro- and secondary nutrient amendments and at same levels of primary macronutrients indicating enhanced use efficiency of macronutrients (Fig. 4).

Based on diagnosed deficiencies and using soil test-based nutrient management, on-farm trial results indicated improvements in soil fertility parameters in spite of getting higher yields (Fig. 5). In simple terms soil test-based balanced fertilization not only enhances nutrient use efficiencies of macronutrients through increased yields under same levels of macronutrients but also captured more nutrients in the soil system. On-farm studies have shown residual benefits of soil test-based applied secondary nutrients and micronutrients as increased yields over farmers' practice plots up to three succeeding seasons (Chander et al. 2013a, 2014a), and thereby enhancing use efficiencies of macronutrients on a sustainable basis.

7.2.3 Nitrogen and Phosphorus Use Efficiency Under Balanced Nutrition

Nitrogen is often the most limiting nutrient for crop yield in many regions of the world and, in a quest to achieve high yields, is applied in large quantity from external sources resulting in low-N use efficiency. Along with N, the deficiencies of P are common in SAT soils (Sahrawat et al. 2007, 2010), and P is the next nutrient added in large quantities. On these soils, it can be necessary to apply up to fivefold more P as fertilizer than is exported in products (Simpson et al. 2011) due to extensive fixation in the soil.

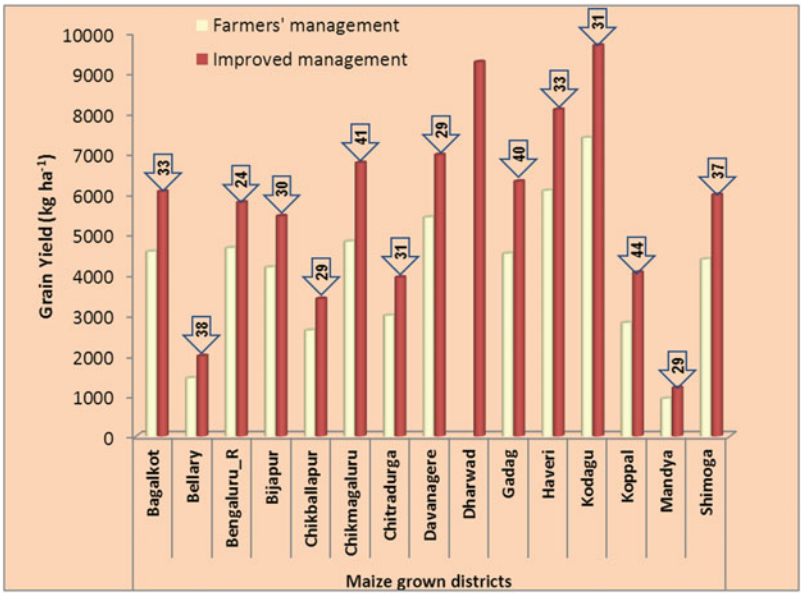

Fig. 4 Maize grain yield response to improved management and farmers' management practices in various districts of Karnataka during 2011 rainy season

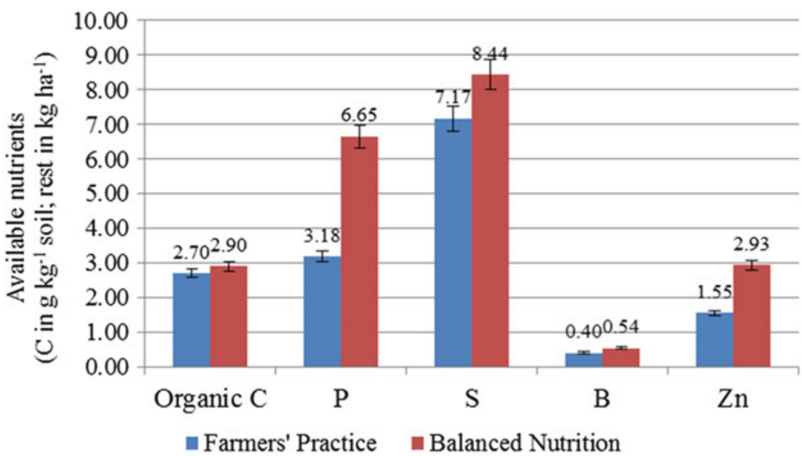

Fig. 5 Postharvest soil fertility status after 2010 rainy season groundnut in Nalgonda (Source: Chander et al. 2014a)

Phosphorus fertilizer is expensive for smallholder farmers, and given the finite nature of global P sources, it is important that such inefficiencies be addressed. Plant nutrients rarely work in isolation. Interactions among nutrients are important because a deficiency of one restricts the uptake and use of another. We hypothesized that multiple nutrient deficiencies could result into low-nutrient use efficiency in N and P and therefore studied different aspects of it.

Nutrient uptake efficiency (NUpE/PUpE) reflects the efficiency of the crop in obtaining it from the soil (Rahimizadeh et al. 2010). Uptake of supplied nutrient is the first crucial step and an issue of concern worldwide, and hence, increased nutrient uptake efficiency has been proposed as a strategy to increase nutrient use efficiency by Raun and Johnson (1999). Nutrient utilization efficiency (NUtE/PUtE) reflects the ability of the plant to transport the nutrient uptakes into grain (Delogu et al. 1998). The nutrient harvest index (NHI/PHI), defined as nutrient in grain to total nutrient uptake, is an important consideration in cereals. The NHI/PHI reflects the grain

Table 4 Effects of balanced nutrient management strategies on nitrogen efficiency indices in maize at ICRISAT, Patancheru, India, 2010 rainy season

Treatment	NUpE	NUtE	NUE	NHI
Control	1.00	60.2	60.2	46.8
NP	0.37	80.7	30.1	67.3
NP + SBZn (every year)	0.46	78.5	36.0	60.5
NP + 50 %SBZn (every year)	0.51	92.5	47.3	65.8
NP + SBZn (alternate year)	0.47	84.4	39.7	69.3
NP + 50 %SBZn (alternate year)	0.42	80.8	34.1	67.0
LSD (5 %)	0.11	17.4	8.85	11.3

Source: Chander et al. (2014b)

Table 5 Effects of balanced nutrient management strategies on phosphorus efficiency indices in maize at ICRISAT, Patancheru, India, 2010 rainy season

Treatment	PUpE	PUtE	PUE	PHI
Control	1.00	172	172	60.4
NP	0.49	228	111	83.5
NP + SBZn (every year)	0.41	328	134	83.9
NP + 50 %SBZn (every year)	0.51	343	176	87.9
NP + SBZn (alternate year)	0.53	281	146	90.1
NP + 50 %SBZn (alternate year)	0.44	299	125	84.9
LSD (5 %)	0.15	83.7	38.6	9.40

Source: Chander et al. (2014b)

nutritional quality (Hirel et al. 2007). The results showed that the addition of deficient S, B and Zn recorded the highest uptake efficiency, utilization efficiency, use efficiency and harvest index in N and P in maize (Tables 4 and 5). The treatment N, P plus 50 % S, B and Zn added every year proved best over generally followed 100 % S, B and Zn addition once in 2 years. The nutrient uptake efficiency is positively correlated with plant dry matter and grain yield (Lee et al. 2004), which were favourably affected under S, B and Zn addition and explain the increase in NUpE. The findings showed that the balanced nutrition is the best strategy to increase cereal nitrogen uptake efficiency and thereby minimize N loss and environmental damage. Similar findings were also recorded in case of P. The study proved here that balancing N and P with deficient nutrients (Potarzycki 2010), which in current context are S, B and Zn in the SAT soils, is an important strategy to improve utilization efficiency, use efficiency and harvest index in both N and P.

7.2.4 Recycling Nutrients in On-farm Wastes

In view of widespread low levels of soil organic carbon in rainfed soils, additions through organic sources of nutrients are very important to maintain optimum soil processes and enhance nutrient use efficiencies. Presently in India, about 960 million tonnes of solid wastes are 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 et al. 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 vermicompost is an enriched source of nutrients with additional plant growth promoting properties and vermicompost application can improve nutrient availability, crop growth, yield and nutrient uptake (Nagavallemma et al. 2004). So, the on-farm produced vermicompost can enhance soil health and save costs of chemical fertilizers leading to nutrient use efficiency and economic productivity improvement.

Enriched vermicompost may be prepared from on-farm organic wastes and cow dung. Rock phosphate being a cheap source of P is added at 3 % of composting biomass to improve P content in vermicompost due to solubilization action of humic acids and phosphate solubilizing bacteria (Hameeda et al. 2006) during the vermicomposting process. *Eudrilus eugeniae* and *Eisenia foetida* species of earthworms are used for vermicomposting. The mature vermicompost is contained on an average of 1.0 % N, 0.8 % P, 0.7 % K, 0.26 % S, 110 mg

Table 6 Effects of nutrient managements on soybean (Glycine max) grain yield, benefit/cost ratio under rainfed conditions in Madhya Pradesh, India, during 2010 rainy season

District	Grain yield (kg ha^{-1})			LSD	Benefit/cost ratio	
	FP	BN	INM	(5 %)	BN	INM
Guna	1,270	1,440	1,580	34	1.31	4.58
Raisen	1,360	1,600	1,600	115	1.85	3.55
Shajapur	1,900	2,120	2,410	69	2.99	10.2
Vidisha	1,130	1,410	1,700	640	2.16	8.43

Source: Chander et al. (2013a)
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 + vermicompost)

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

	Total nutrient uptake					
	N	P	K	S	B	Zn
Treatment	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

Source: Chander et al. (2013a)
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 + vermicompost)

B kg^{-1}, 60 mg Zn kg^{-1} and 14 % organic C (Chander et al. 2013a).

On-farm results showed that with the use of vermicompost, the use and cost of chemical fertilizers can be reduced up to 50 % while getting higher productivity as compared to balanced nutrition solely through chemical fertilizers (Table 6), thereby enhancing nutrient use efficiency. More nutrients are captured as plant uptake under BN and INM practices due to enhanced contents and yields (Table 7). This is expected due to synergy created through nutrient balancing and specific roles of roles of nutrients like B which is necessary to maintain membrane integrity (Cakmak et al. 1995) and hence can enhance the ability of membranes to transport available nutrients. The INM practice results in economic benefits and efficient resource utilization including on-farm wastes and so is a sound-scalable technology.

7.3 Landform Management

Through efficient in situ water management using landform management like broad bed and furrow (BBF) or conservation furrow (CF) in poorly drained Vertisols, nutrient and other inputs can be efficiently utilized to get higher crop yields (Dwivedi et al. 2001; Sreedevi et al. 2004; Wani et al. 2003a). Rainwater management practices in rainfed agriculture are very critical particularly when most rainfall occurs in a limited period of the year. Initial downpours distort soil structure and also adversely affect water infiltration into soil and thereby ultimately negatively affect crop productivity and thereby resource use efficiency. Participatory evaluation clearly showed that landform management like BBF and CF keeps soil surface intact for more effective infiltration and safely allows excess run-off through furrows. The landform management practices in Sujala watersheds in Karnataka, India, increased crop yields over the farmers' practice of cultivating on flatbed by 12–20 % with CF and 30 % with BBF (Table 8).

7.4 Supplemental Irrigation

Water scarcity is a major limiting factor under rainfed agriculture, and thus the role of lifesaving one or two irrigations through harvested water in enhancing crop productivity and nutrient use efficiency is well understood and documented. However, studies have indicated micro-irrigation practices more effective than traditional flood irrigation practices in enhancing yields, nutrient and water use efficiency. On-station experiments at ICRISAT headquarter at Patancheru recorded significantly higher yields under drip irrigation as compared to flood irrigation (Table 9). The drip irrigation practice proved economically more remunerative while saving water resources also.

Table 8 Effects of land form management practices on crop yield in Sujala watersheds, Karnataka, India, 2006–2007

District/watershed	Crop	Crop yields (kg ha^{-1}) Farmers practice	Cultivation across slope with conservation furrow	Broad bed and furrow
Haveri				
Aremallapur	Maize	3,110	3,610 (16)*	–
Hedigonda	Maize	4,030	4,560 (13)	
Dharwad				
Parsapur	Soybean	1,500	1,800 (20)	
Kolar				
Diggur	Groundnut	1,010	1,200 (19)	–
Venkatesh Halli	Groundnut	950	1,070 (12)	–
Chitradurga				
Toparamalige	Maize	3,530	–	4,560 (30)

Source: ICRISAT (2007)
*Note: Figures in () indicate per cent increase over the farmers' practice

Table 9 Pooled data on yield of maize-chickpea cropping system (2009–2011) at ICRISAT, Patancheru

Treatment	Maize (t ha^{-1})	Chickpea (t ha^{-1})	Maize equivalent yield (t ha^{-1})	B:C
Flood irrigation	3.87	1.99	9.15	2.97
Drip irrigation	3.97	2.24	9.91	3.26
LSD (5 %)	NS	0.14	0.33	

Source: Sawargaonkar et al. (2012)

7.5 Integrated Genetic and Natural Resource Management

Cultivation of low-yielding cultivars in rainfed semi-arid tropics is one of the major factors for low yields leading to inefficient use of nutrient resources. This is a big opportunity to enhance nutrient use efficiencies through replacing low-yielding cultivars with high-yielding ones. On-farm research showed enhanced nutrient use efficiencies with high-yielding cultivars (Table 10). However, nutrient imbalances do not allow the high-yielding varieties to show potential, and participatory trials showed the highest yields and use efficiency of nutrients under integrated approach of improved variety and balanced nutrition.

Table 10 Integrated improved crop cultivar and balanced nutrient management enhance maize grain yield and RWUE in different districts of Rajasthan during 2009 rainy season

District	Yield (kg ha^{-1}) FP	IC	IC + BN	LSD (5 %)	B:C ratio
Tonk	1,150	1,930	3,160	280	4.26
Sawai Madhopur	1,430	2,030	3,000	420	3.33
Bundi	1,380	2,180	4,240	714	6.05
Bhilwara	2,990	4,340	6,510	860	7.45
Jhalawar	2,550	3,520	4,960	316	5.11
Udaipur	2,530	3,090	6,320	509	8.03

Source: Chander et al. (2013b)

7.6 Improved Genotypes and Nutrient Use Efficiency

7.6.1 Need for Exploring Genotypic Diversity

Nitrogen use efficiency is a fundamental issue when discussing crucial topics related to yield improvements with fertilizer nitrogen application in an eco-friendly manner. The efficient use of nitrogen is important for the economic and environmental sustainability of production systems. Improving nitrogen uptake and partitioning to grain reduces the amount of nitrogen at risk of loss to the environment (Raun and

Johnson 1999). Enhanced grain N recovery is important for maintaining protein concentrations in high-yielding crops (Cox et al. 1986). In cereal cropping systems, nutrient use efficiency can be improved through two main strategies: by adopting more efficient farming techniques and by breeding more nutrient use-efficient cultivars (Ortiz-Monasterio et al. 1997). The efficient crop management practices have been discussed. Breeding strategies include identification and selection of desirable traits which increase the uptake and/or utilization efficiency of the crop (Foulkes et al. 2009) and identifying quantitative trait loci for NUE (Hirel et al. 2007). Therefore, development of N-efficient cultivars is needed to sustain or increase yield and quality while reducing the negative impacts of crop and fertilizer production on the environment (Hirel et al. 2007).

7.6.2 Genotypic Diversity for NUE Components

Genotypic diversity for NUE is well documented in wheat (Cox et al. 1985; Gooding et al. 2012), corn (Chevalier and Schrader 1977), sorghum (Maranville et al. 1980) and pearl millet (Wani et al. 1992; Uppal et al. 2014). As discussed earlier NUE can be expressed by two components NUpE and NUtE which express differently at various N input conditions. Various studies worldwide have identified genetic association between cereal grain yield and NUE components under contrasting conditions of high and low-N input supply. Some studies indicate that NUpE accounts for more genetic variations in NUE under low-N supply (Ortiz-Monasterio et al. 1997; Le Gouis et al. 2000), some indicate NUtE accounts for NUE in low-N supply (Wani et al. 1992; Alagarswamy and Bidinger 1982), whereas some studies conclude that both NUpE and NUtE contribute equally to NUE at all levels (Dhugga and Waines 1989). For NUE, genetic variability and genotype × nitrogen interactions reflecting differences in responsiveness have been observed in several studies on maize (Moll et al. 1982; Bertin and Gallais 2000), pearl millet (Wani et al. 1992) and sorghum. In addition, it has been found that correlations among various agronomic traits such as grain protein yield and its components are different according to the level of nitrogen fertilization. At high N input, genetic variation in NUE was explained by variation in N uptake, whereas at low-N input, NUE variability was mainly due to differences in nitrogen utilization efficiency. This suggests that the limiting steps in N assimilation may be different when plants are grown under high or low levels of nitrogen fertilization.

Millets are staple food for millions of people in semi-arid tropics of Asia and sub-Saharan Africa which are generally grown on poor soils and low rainfall conditions with low fertilizer inputs. Genotype screening and selection for tolerance to low N and low P is an important strategy to increase productivity in nutrient-stressed environment. Various experiments on fertility management in pearl millet indicate that response of pearl millet varies widely among N studies with optimum rates from 0 to greater than 150 kg ha^{-1} N (Gascho et al. 1995). Most of the studies concluded that genotype × fertility interaction for grain yield and N utilization efficiency depends on grain production efficiency, i.e. cultivars yielding ability at a given level of fertilizer. A study conducted at two sites in ICRISAT with 12 genotypes and two N and P levels reported that millet hybrids have higher N, P and K use efficiency than composites and landraces which are conferred by higher harvest index and translocation of nutrients to developing grain in hybrids (Wani et al. 1992). The correlation between grain yield and NUtE suggests that direct selection for NUE may have value in improvement of yielding ability under low-fertility conditions (Alagarswamy and Bidinger 1982). A recent attempt to resynthesize earlier data sets from strategic research experiments on pearl millet reveals that NUtE is a more important contributor to NUE than NUpE under low to medium N supply (Uppal et al. 2014) (Fig. 6).

Similarly in a study at different agroecological systems, 15 genotypes of sorghum were evaluated for N and P concentrations at different growth stages in low-N or low-P Alfisols. Hybrids and improved varieties produced higher

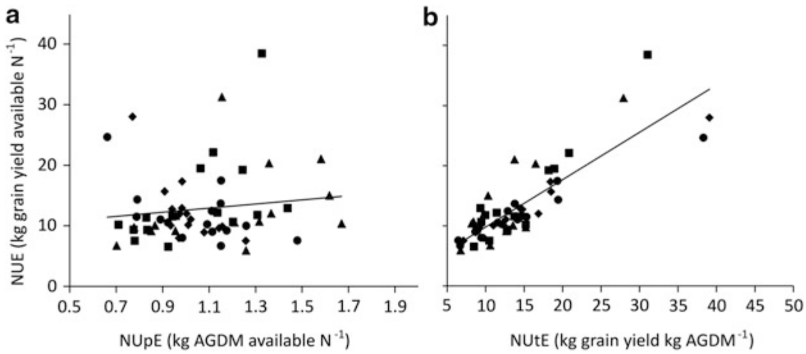

Fig. 6 Linear regression of N uptake efficiency (NUpE) (y = 3.39 + 9.189; R^2 = 0.016) and N utilization efficiency (NUtE) (y = 0.788 + 1.93; R^2 = 0.72) on nitrogen use efficiency among four pearl millet cultivars. Symbols represent cultivar means over N rates (◆) = 700256, (■) = BJ 104, (▲) = Ex-Bornu and (●) = GAM 73. Regression was significant for **b**

Table 11 Sorghum grain yield (GY, kg ha^{-1}), aboveground dry matter (AGDM, kg ha^{-1}), harvest index (HI), N uptake efficiency (NUpE = kg aboveground dry matter kg soil available N^{-1}), N utilization efficiency (NUtE = kg grain yield kg aboveground dry matter^{-1}) and nitrogen use efficiency (NUE = NUpE × NUtE = kg grain yield soil available N^{-1}) in a long-term trial (1978–1986)

Cultivar	GY	AGDM	HI	NUpE	NUtE	NUE
FLR101	1,899	3,913	0.33	1.03	46.06	47.48
CSV5	1,017	4,690	0.18	0.94	26.95	25.43
CSH5	2,173	5,037	0.30	1.11	48.97	54.33
IS889	1,405	2,203	0.39	0.84	41.84	35.13
DIALL	1,666	4,101	0.29	0.98	42.39	41.65

biomass and grain yield. In P-stressed situations, P from leaves and stem reserves is rapidly and efficiently translocated to support grain filling (Adu-Gyamfi et al. 2002). A P32 study revealed that in low-P conditions, P-efficient genotype translocates more P from roots to flag leaves (Adu-Gyamfi et al. 2002). In a study three maize genotypes that were grown in two sites with different soil types revealed that N-efficient trait of genotype is closely related to its adaptability to soil characteristics and water availability. ICRISAT's long-term experiments on sorghum reveal that genotypic diversity for NUE and its components exist among sorghum genotypes and genotypes with higher yield potential have higher NUE in Alfisols which are low in N and P (Table 11).

There is a lot of controversy about the performance of landraces, and farmers preferred varieties compared to hybrids and improved varieties in a low-nutrient environment. Various studies have showed that hybrids and new cultivars have more yield potential than landraces and old cultivars due to improved efficiency to fertilizer application (Wani et al. 1992; Adu-Gyamfi et al. 2002). On the contrary, some studies (Bationo et al. 1989; Payne et al. 1995) reported that local landraces or farmer-selected local lines of sorghum and pearl millet are better adapted to low-fertility regimes. There are various biotic and abiotic factors that influence the adaptation of crop plants to low-nutrient environments. Also crop response to nutrients depends on agronomic traits of the cultivar which contribute to grain yield and nitrogen use. Improvement in grain yield is more closely associated with grain N uptake in pearl millet (Fig. 7) leading to higher NHI (Uppal et al. 2014). Wani et al. (1992) found that selection for improved HI in modern pearl millet cultivars has inadvertently improved traits for NUE resulting in improved nutrient use efficiencies and nutrient translocation indices (Fig. 8).

Selection for nutrient-efficient cultivars is typically conducted under favourable field conditions with only the difference in soil nutrient availability. However, in practical field conditions, variation in soil types and/or seasonal weather conditions may have a strong influence on soil nutrient dynamics and plant growth and, therefore, nutrient uptake and its subsequent utilization in plants. Screening should take into

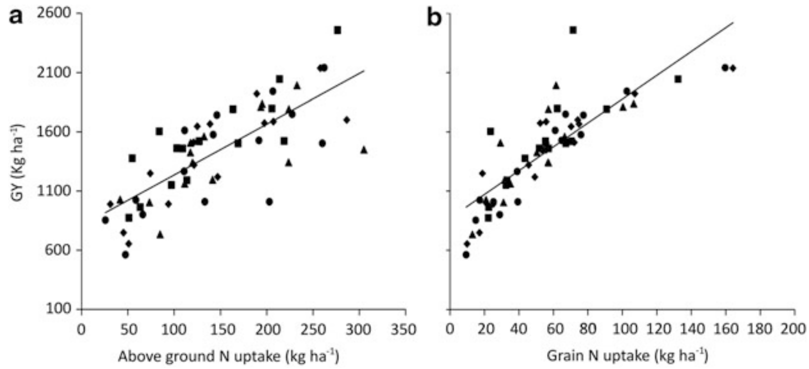

Fig. 7 Linear regression of aboveground N uptake (y = 4.28x + 806.79; $R^2 = 0.58$) and grain N uptake (y = 10.06 + 869.8; $R^2 = 0.70$) on grain yield among four pearl millet cultivars. Symbols represent cultivar means over N rates (◆) = 700256, (■) = BJ104, (▲) = Ex-Bornu and (●) = GAM 73

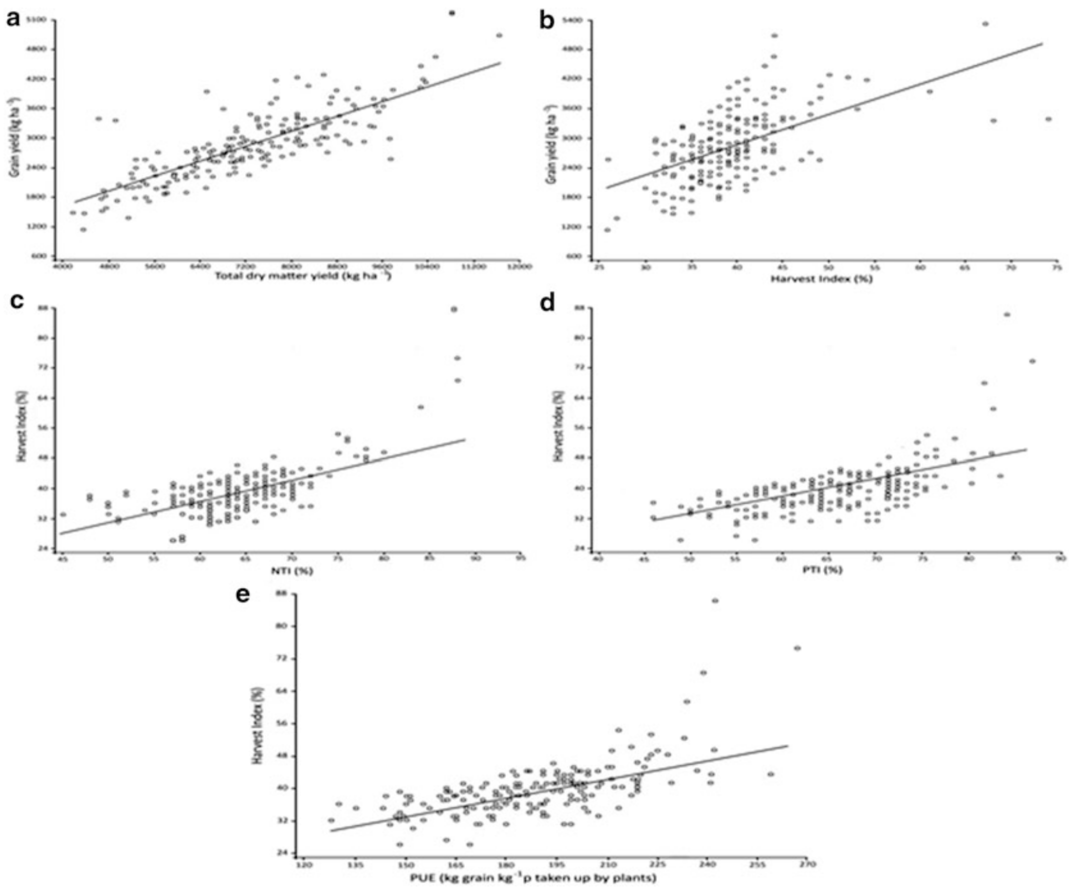

Fig. 8 Relationship between (**a**) grain yield and total dry matter (y = 84 + 0.380x; $R^2 = 0.67$), (**b**) grain yield and harvest index (y = 472 + 60.10x; $R^2 = 0.28$), (**c**) harvest index and nitrogen translocation index (NTI) (y = 1.41 + 0.589x; $R^2 = 0.44$), (**d**) harvest index and phosphorous translocation index (PTI) (y = 7.86 + 0.478x; $R^2 = 0.38$) and (**e**) harvest index and phosphorous use efficiency (y = 8.64 + 0.162x; $R^2 = 0.48$) of pearl millet genotypes

Table 12 Severity of foliar diseases, pod and haulm yields of IDM and non-IDM plots in a watershed in Dharwad District, Karnataka, 2006 rainy season

	FD score 1–9 scale		Pod yield (kg ha^{-1})		Haulm yield (kg ha^{-1})	
District	IDM	Non-IDM	IDM	Non-IDM	IDM	Non-IDM
Dharwad	5.5	8.3	860	660	1,530	1,140

Source: ICRISAT (2007)

Note: FD = foliar diseases; IDM = improved dual purpose cultivar ICGV 91114; seed treatment with bavistin + thirum (1:1) @ 2.5 g kg^{-1} seed; foliar application of fungicide kavach/bavistin at 60–65 DAS; Non-IDM = farmers' practice

consideration the interaction of nutrients, water, soil type, climatic variables and cropping system.

7.6.3 Candidate Traits for High NUE and Mechanism

Promising traits for selection by breeders to increase NUE have been identified which include increased root length density, higher N uptake, low-leaf lamina N concentration, more efficient post-anthesis N remobilization to developing grain and reduced N concentration in feed crops may be of particular value for increasing NUE. We will be discussing N remobilization in detail as it affects the nitrogen harvest index of the crop.

During leaf senescence NH3 is liable to be lost from plants by volatilization. This loss can be reduced by high glutamine synthetase (GS1) activity (Mattsson et al. 1998). A positive relationship between GS1 activity and NUtE and grain yield has been reported in maize grown under low-N conditions (Masclaux et al. 2001), and QTLs for NUE and a structural gene for GS1 are co-localized (Hirel et al. 2007). Over 80 % of the aboveground N at harvest can be present in the aboveground crop at flowering and can account for 50–80 % of the nitrogen accumulated in the grains at maturity depending on crop species (Hirel et al. 2001). N remobilization is an important trait affecting the utilization of canopy N, and the efficiency of the N remobilization from aboveground parts to the grain can be measured by the nitrogen harvest index (NHI). The NHI is a heritable characteristic (Cox et al. 1985). The nitrogen harvest index has a positive association with N uptake by grain and a negative trend with straw N concentration and quantity (Tripathi et al. 2004).

7.7 Integrated Pest Management

Crop diseases, insects, weeds are one of the major constraints to increase food production and higher resource use efficiency. Though reliable estimates on crop losses are limited, Oerke et al. (1995) brought out about 42 % loss in global output due to insect pests, diseases and weeds despite the use of plant protection options. In India, the pre-harvest loss was up to 30 % in cereals and pulses, and it can be up to 50 % in cotton and oilseed crops (Dhaliwal and Arora 1993).

In rainfed systems, unawareness about and lack of good agronomic practices is leading to low yields resulting in poor nutrient use efficiency. Participatory trials in Dharwad District of Karnataka, India, showed that foliar disease severity was low in holistic integrated disease management (IDM) plots of groundnut variety ICGV-91114 than non-IDM plots of local cultivar. Its mean severity was 5.5 on a 1–9 rating scale in IDM plots compared to an 8.3 rating in non-IDM plots (Table 12). Under IDM plots, pod yield was significantly higher as compared to non-IDM plot under the same level of nutrient use.

The agricultural sector in India or elsewhere has long been recognized for its dependence on chemical control for the management of biotic stresses (insects, diseases and weeds). The excessive dependence on chemical pesticides led to the development of resistance in pests to pesticides, outbreaks of secondary pests and pathogens/biotypes and occurrence of residues in the food chain (Ranga Rao et al. 2009). To overcome such situations and minimize damage to human and animal health, several organizations have started advocating the concept of IPM with better profits. Studies have indicated that crop- and need-based IPM technologies which are very effective tools to reduce chemical use, also result into better pest control (Ranga Rao et al. 2009; Chuachin et al. 2012) to get higher productivity and nutrient use efficiency.

8 Conclusions and Way Forward

The rising use of nutrient inputs to meet future food security is unavoidable. However, in current scenario as discussed in this chapter, there is lot of scope to improve nutrient use efficiency through optimizing crop-growing environment and other inputs to get the maximum productivity. Scientific awareness and solutions to most problems are available and, however, have not reached on farmers' fields particularly in rainfed systems. Ensuring implementation of holistic solutions at farm level through consortium of technical institutions should be the priority of all stakeholders. Strengthening of on-farm research for impact and innovative extension systems is a very important aspect that needs immediate attention to see changes on ground.

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