Chapter 12
Approaches to Reinforce Crop Productivity Under Rain-fed Conditions in Sub-humid Environments in Sub-Saharan Africa

Regis Chikowo, Shamie Zingore, Justice Nyamangara, Mateete Bekunda, Joseph Messina, and Sieglinde Snapp

Abstract Smallholder farming in much of Sub-Saharan Africa is rain-fed and thus exposed to rainfall variability. Among the climate variables, rainfall is projected to decline and have an overriding effect on crop productivity. With little opportunity for supplementary irrigation for the majority of farmers, a plausible strategy to maintain crop production under water-limited conditions includes balanced nutrient management for enhancing efficiency of use of limited soil water. Co-application of judicious rates of organic and mineral nutrient resources, particularly including the use of phosphorus (P) on P-limited soils, will facilitate development of an extensive crop rooting system for efficient exploration and capture of soil water, especially at a depth >0.8 m. This chapter explores case studies across Eastern and Southern Africa where various soil water conservation and nutrient management

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R. Chikowo (✉)
Plant Soil and Microbial Sciences Department, Michigan State University,
East Lansing, MI 48824, USA

Crop Science Department, University of Zimbabwe, Box MP167, Harare, Zimbabwe
e-mail: regischikowo@yahoo.co.uk; chikowor@msu.edu

S. Zingore
International Plant Nutrition Institute (IPNI), Africa Program, ICIPE Compound,
Box 30772, Nairobi, Kenya

J. Nyamangara
International Crops Research Institute for the Semi-Arid Tropics (ICRISAT),
P.O. Box 779, Bulawayo, Zimbabwe

M. Bekunda
International Institute of Tropical Agriculture (IITA), Arusha,
P.O. Box 10, Duluti, Tanzania

J. Messina
Department of Geography, Michigan State University, East Lansing, MI 48824, USA

S. Snapp
Plant Soil and Microbial Sciences Department, Michigan State University,
East Lansing, MI 48824, USA

R. Lal et al. (eds.), *Sustainable Intensification to Advance Food Security and Enhance Climate Resilience in Africa*, DOI 10.1007/978-3-319-09360-4_12

approaches have been used to gain 'extra miles' with limited available soil water. Firstly, an approach is described that varies nitrogen (N) fertilizer application across growing seasons, by adjusting N application rates to match current season rainfall trends. The approach offers opportunities for farmers to increase crop productivity to >6 t ha^{-1} in high agro-potential areas, compared to a ceiling of 4.5 t ha^{-1} for the fixed fertilization model, while minimizing economic losses due to investments in N fertilizer during drought years. Secondly, we deal with the subject of fertilization across nutrient gradients, where a poor agronomic N use efficiency of <18 kg grain kg^{-1} of applied N is demonstrated for soils with <0.4 % organic carbon, compared with >35 kg grain kg^{-1} of N applied when soil organic carbon >0.5 %. Thirdly, the conservation agriculture (CA)-nutrient management nexus is examined, where maize yields in farmers' fields with CA alone were barely 0.5 t ha^{-1} compared to an average of 2.5 t ha^{-1} for CA combined with fertilizers. Fourthly, a novel system that involves intercropping two legumes with contrasting phenology for enhanced cropping system functioning is described. Finally, an approach that can be used for co-learning with farmers on soil fertility management principles for risk management is presented. The data lead to the conclusion that the 'doubled-up' legumes system results in reduced fertilizer requirements for cereal crops grown in sequence, which benefits yield stability over time. Variable use of N fertilizer according to season quality and more tailored targeting of nutrients are vital for profitable investments in fertilizers in Africa. The Africa RISING project in Eastern and Southern Africa is currently harnessing some of these principles as vehicles for intensification of smallholder farming systems.

Keywords Droughts • Nutrient use efficiency • Soil nutrients • Water productivity • Maize

12.1 Introduction

Poor agricultural productivity in much of Sub-Saharan Africa (SSA) is widely linked to soils that are inherently nutrient deficient, particularly for nitrogen (N) and phosphorus (P), and unreliable rainfall characterized by both droughts and flooding conditions (Mazvimavi 2010; IPCC 2007). Compared to other parts of the world where agricultural green revolutions have been stimulated by mechanization and high fertilizer use, SSA soil nutrient balances remain largely negative (Smaling et al. 1997). The capture and utilization of nutrients by crops has been poor, albeit applied in small doses, largely due to nutrient imbalances (Kho 2000).

Efficient nutrient recovery by crops is a function of a multitude of factors—ideally in a balanced state (Janssen 1998). Nitrogen fertilizers are easily lost
ough leaching in light textured soils during periods of high rainfall when
ce times are short (Cadisch et al. 2004; Chikowo et al. 2004). Under water
ement of nutrients from the soil to the plant is curtailed such that any
s are not used efficiently. Conversely, P availability is often acutely
d aluminum oxides, which is common in highly weathered and

Photo 12.1 Severe nutrient deficiencies on maize plants on a sandy soil, Murehwa district, Zimbabwe

acidic tropical soils (e.g., Vanlauwe et al. 2002; Sanchez et al. 1997). These are among the difficult scenarios that resource-constrained smallholder farmers in SSA must grapple with in their production systems.

Short-range spatial variability in soils commonly exists within and among farms due to localized differences in parent material and/or management (Tittonell et al. 2005; Mtambanengwe and Mapfumo 2005), with major implications for water and nutrient use efficiency. In most cases, fields that are poor in N and/or P will yield poor returns even when these nutrients are amply supplied through fertilizers, as nutrients other than N and P may limit production (Janssen 1998; Wopereis et al. 2006; Zingore et al. 2007). Therefore, any fertilization strategy that seeks to optimize resource use efficiencies by crops must recognize the important role of the inherent and distinct capacity of different soils to supply nutrients to the crops (Photos 12.1 and 12.2). In the face of limited external resources, the question of how to efficiently target the available nutrients on the farms in a continuum of conditions becomes critical (Giller et al. 2006).

A key objective of this chapter is to present nutrient management options in SSA agriculture and the associated nutrient use efficiencies—a vital step for identifying cropping systems or system components that offer opportunities for crop intensification under water-limited conditions. The performance of cropping systems in the different regions of SSA is illustrated using case studies for five pathways for crop production intensification and climatic risk management:

I. Rainfall-responsive fertilization strategies
II. Fertilization of spatially heterogeneous farms and nutrient use efficiencies
III. Conservation agriculture and intensification

Photo 12.2 Unfertilized (foreground), and fertilized (background) maize on a sandy soil, Murehwa district, Zimbabwe

IV. Integration of double-up legumes—does that lead to more stable yields?
V. Co-learning nutrient and risk management options with farmers

12.2 Approaches for Enhancing Crop Productivity on Smallholder Farms in SSA

12.2.1 A Flexible N Fertilization Strategy Responsive to Rainfall Season Quality

The erratic and uneven distribution of rainfall makes use of fertilizers by smallholder farmers very risky. Farmers may be reluctant to apply full rates of fertilizers in good rainfall seasons because of the risk of crop failure, and they may apply more fertilizer than is justified by crop returns in drought years (Photo 12.3).

Nutrients such as P and K are usually applied 100 % at planting while N is partially applied at planting, and the remainder is applied as top-dressing. Most N top-dressing recommendations given to farmers are rigid and do not recognize the importance of soil–water interactions regarding N fertilizer use efficiency. Therefore, practical methods of applying proportioned doses of fertilizer dependent on the prevailing rainfall are required to optimize fertilizer use efficiency. To manage variable rainfall environments, Piha (1993) devised and successfully tested a flexible system of fertilization, in which theoretically optimum rates of the nutrients P, K, and S are applied based on yield potential in an average rainfall season, while nitrogen is applied as a series of portioned applications, adjusted

Photo 12.3 Dry spells on soils with low water holding capacity is a major problem even for hardy sorghum, Wedza district, Zimbabwe. Such conditions reduce fertilizer use efficiency

during the season according to the degree of water stress observed. This system optimizes resource use efficiency during good rainfall seasons, while ensuring minimum wastage in case of drought due to the reduced fertilizer inputs. Piha (1993) compared two nutrient management strategies that involved either:

I. A fixed N application rate for specific agro-ecologies, in line with recommendations normally given to farmers by the extension system, or
II. Rainfall-varied N top-dressing that was a function of general agro-ecology as well as current rainfall season quality.

For both systems, maize was supplied with a low dose of N at planting, in the form of compound fertilizers that also contained P, K, and S. The fixed-N treatments received additional N as ammonium nitrate, in three equal portions at 4, 6 and 8 weeks after emergence to result in 50 kg N ha^{-1} and 92 kg N ha^{-1}, for high and low agro-potential areas, respectively. The rainfall-varied treatments received variable amounts of ammonium nitrate on the same dates (0, 17, 34 or 50 kg N ha^{-1} for a high agro-potential area, or 0, 17, or 34 kg N ha^{-1} for a low agro-potential area), resulting in variable top-dressing N being applied at 0–100 kg N ha^{-1} for low potential areas and 0–150 kg N ha^{-1} for high potential areas, respectively (Table 12.1).

This flexible system of fertilization, in which optimum rates of P, K, and S fertilizers are basally applied based on yield potential in an average rainfall season, while N is applied as a series of portioned applications and adjusted according to the evolving rainfall pattern in any one season, results in more efficient maize production (Fig. 12.1). Trials over a 5-year period on farmers' fields resulted in 25–42 % greater yield and 21–41 % more profit than a model based on existing fertilizer recommendations (Piha 1993). These results are significant in that they confirm that

Table 12.1 Fertilizer rates (kg ha^{-1}) used in maize field trials to evaluate a flexible system of N top dressing management in Zimbabwe

	Pre-planting				
	N	P	K	S	Top-dressing N
High potential areas					
Currently recommended rates	24	18	18	18	68
Theoretically optimum rates	24	26	26	26	0–150[a]
Low potential areas					
Currently recommended rates	16	12	12	12	34
Theoretically optimum rates	16	17	17	17	0–150[a]

[a] Variable N top dressing (see text for explanations)

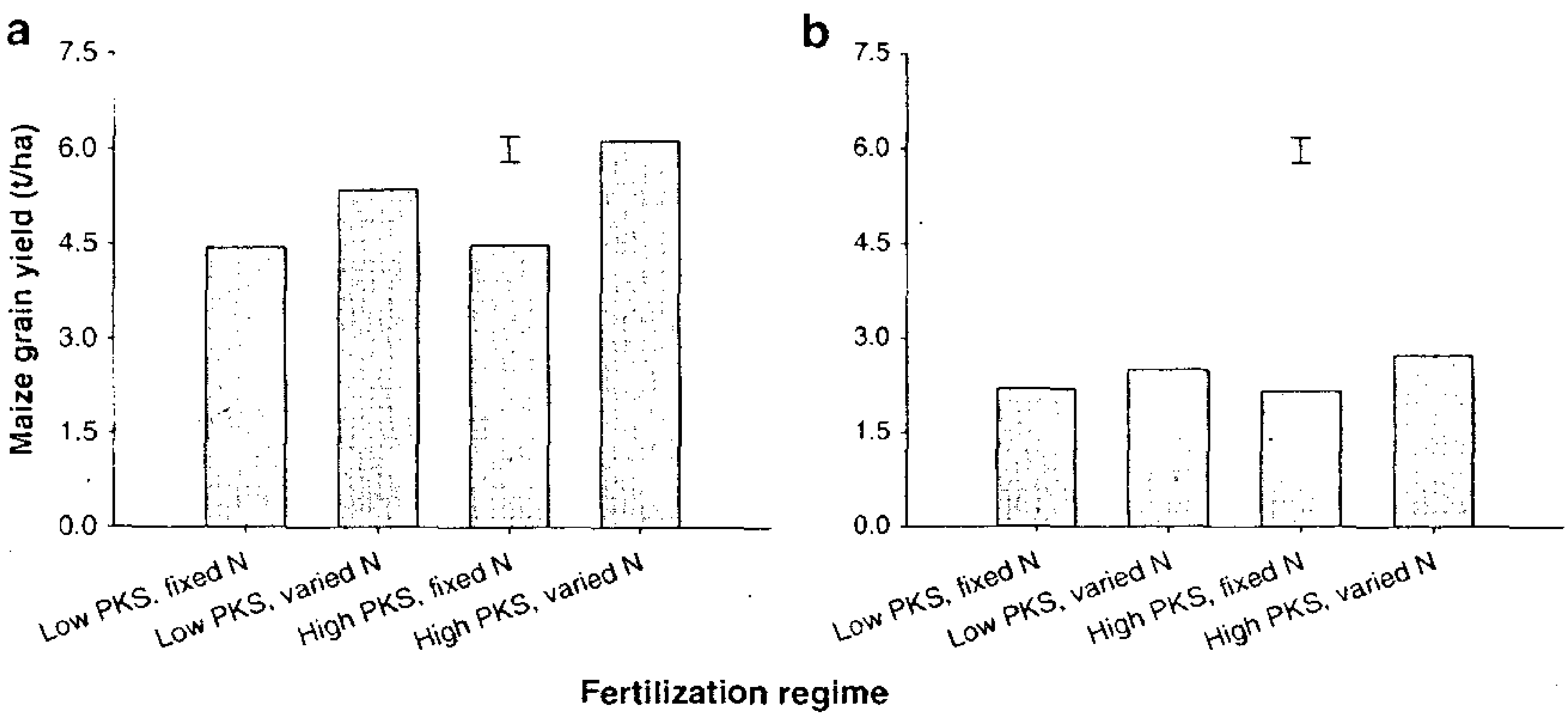

Fig. 12.1 Effects of N, P, K, and S application strategy on maize productivity for (**a**) a high agro-potential site and (**b**) a low agro-potential site in central Zimbabwe (synthesized based on data from Piha 1993). *Vertical bars* represent LSD

productive and profitable agriculture is possible on poor soils, and in semi-arid conditions, with the judicious use of inorganic fertilizers when strategically correct timing and quantities are followed. The fertilization strategy optimizes N use efficiency during good rainfall seasons, while ensuring minimum losses in case of drought as further N top-dressings are withheld under sub-optimal soil moisture.

12.2.2 *Fertilization of Spatially Heterogeneous Farms and Nutrient Use Efficiencies*

Many smallholder farms are known to be spatially heterogeneous in terms of soil quality; therefore, response to applied nutrients varies considerably across fields (Prudencio 1993; Manlay et al. 2002; Masvaya et al. 2010). However, fertilizer recommendations currently accessed by smallholder farmers rarely reflect these circumstances and are based on an assumption of soil resource base homogeneity. For example, in Zimbabwe, fertilizer recommendations are linked to agro-ecological zones that are principally delineated based on rainfall, despite the short-range, wide variability known to exist in soils within the agro-ecological zones (Ncube et al. 2007; Zingore et al. 2007). Differences in nutrient resource management by farmers, which is usually a function of resource endowment and preferential application of nutrient inputs to fields close to the homesteads, has often accentuated variability in soil fertility, creating gradients of fertility across fields and farms (Mtambanengwe and Mapfumo 2005; Zingore et al. 2007; Tittonell et al. 2013). Short range spatial variability in soils also exists within and across farms due to the inherent properties of soils. This spatial variability in soils on smallholder farming systems has largely been trivialized when designing technological interventions, yet it is widely asserted that variability of soil fertility within farms poses a major challenge for efficient use of resources for increased crop productivity (Wopereis et al. 2006; Zingore et al. 2007). Explicitly recognizing that farmers deal with a variable soil resource base is important for the formulation of nutrient management strategies that enhance efficient use of nutrient resources on farms (Janssen et al. 1990). Considering that fertilizer resources are scarce, it is critical that fertilization regimes be tailored to the biophysical environments and socio-economic status of farmers to optimize use efficiency. When robust soil fertility indicators are known, it is possible to use them to tailor fertilizer application strategies for different circumstances, allowing an informed approach that leads to improved farm system functioning (Janssen et al. 1990; Zingore et al. 2011; Nandwa 2001). In this study, soil organic carbon (SOC) is proposed to be a robust indicator for soil fertility status that can potentially be used to predict resource use efficiencies under a range of management regimes.

In order to better understand the influence of SOC on nutrient use efficiencies on granitic sands, 120 smallholder farms in Wedza district, Eastern Zimbabwe, were first surveyed for SOC content, resulting in categorization that recognized three distinct field types (domains):

I. Field Type 1: fields with $\leq$0.4 % SOC—fields that have been poorly managed and have a history of poor yields
II. Field Type 2: fields with >0.4–0.6 % SOC—fields that have received organic amendments intermittently
III. Field Type 3: fields with >0.6 % SOC—a small proportion of fields that have a history of good management, including use of organic manures and mineral fertilizers, with clay content generally >15 %

Within each of the three Field Types (domains), field sites were identified for experimentation during two consecutive cropping seasons. All sites were strategically located within a 2 km radius to eliminate possible confounding effects due to differences in rainfall, because spatial variability in rainfall is known to be high (Table 12.2). The experimental treatments were formulated using widely available fertilizer resources as follows:

Table 12.2 Physical and chemical characteristics of soils (0–20 cm) at establishment of field experiments in Eastern Zimbabwe

Site	Sand (%)	Clay (%)	SOC (%)	Available P (mg kg^{-1})	Soil pH (H_2O)	Total N (%)	Ca	Mg	K
							cmol$_{(+)}$ kg^{-1}		
Field type 1 (≤0.4 % C)									
Chingwa	94	4	0.35	3.3	4.4	0.03	6.2	5.1	0.15
Muriva	94	5	0.40	5.5	5.0	0.03	7.1	6.3	0.23
Field type 2 (>0.4–0.6 % C)									
Makoni	94	4	0.46	5.1	4.9	0.05	12.2	4.2	0.42
Chinhengo	80	10	0.54	7.3	4.9	0.04	7.3	4.4	0.43
Field type 3 (>0.6 % C)									
Mapiye	84	10	0.73	7.4	5.4	0.05	8.3	5.1	0.52
Muhwati	65	19	0.89	10.5	5.2	0.06	7.5	5.3	0.48

(i) Control (no nutrients added)
(ii) NK (muriate of potash and ammonium nitrate)
(iii) NPS (single super phosphate + ammonium nitrate)
(iv) PKS (single super phosphate + muriate of potash), and
(v) NPKS (compound fertilizer + ammonium nitrate)

Across all sites, the target nutrient application rates for Year 1 were 40 kg ha^{-1} P, 60 kg ha^{-1} K, and 120 kg ha^{-1} N. During Year 2, the target N application rate was maintained while only 20 kg P and 30 kg K were re-applied. Practically, N application was deemed a function of rainfall, with a mandatory initial application of 20 kg ha^{-1} N at planting and two subsequent applications of 50 kg ha^{-1} N, if soil moisture permitted. With this rule, only 70 kg ha^{-1} was applied for both seasons, due to terminal season droughts that necessitated withholding the second N top dressing application of 50 kg ha^{-1}. High nutrient application rates for P and K were used, compared with prevalent rates commonly used by farmers, to enable determination of attainable yields for the three soil fertility domains when all other variables were maintained the same, including rainfall. All the P, K, and S were applied at planting, as compound fertilizer, single super phosphate, or muriate of potash (KCl) fertilizer.

These experiments showed that N, P, and K agronomic use efficiencies were primarily influenced by treatment and SOC levels (Table 12.3A). Fertilization with NPKS and NPS produced the highest N agronomic efficiency (AE_N) across sites, ranging from 16 to 37.8 kg grain kg^{-1} N, whereas the NK treatment had an AE_N range of 1.7–20 kg grain kg^{-1} N applied across all sites. Agronomic efficiencies were always lowest for the Field Type 1 domain while AE_N were larger but not significantly different between Field Types 2 and 3. The AE_P for the NPS and NPKS treatments were also comparable for Field Types 2 and 3, ranging between 28 and 67 kg grain kg^{-1} P for the NPS and NPKS treatments, compared to a paltry 0.5–14 kg grain kg^{-1} P applied for the PKS treatment. Application of K had a very small impact on yield across all the field types with the largest $AE_K < 1$ kg grain kg^{-1} K applied (data not shown). Recovery efficiencies (RE) followed the same

Table 12.3 Nitrogen and P agronomic efficiencies [A] and N and P recovery efficiencies [B] as influenced by nutrient management and soil resource base (site) in Dendenyore, Wedza district, Zimbabwe

[A]

	Site %		AE_N			AE_P	
	C	NK	NPS	NPKS	NPS	PKS	NPKS
Site		kg grain kg^{-1} N applied			kg grain kg^{-1} P applied		
Chingwa	0.35	1.7	16.0	17.0	28.0	0.5	29.3
Muriva	0.40	13.7	22.5	26.7	39.5	2.3	41.2
Makoni	0.46	10.3	27.0	31.2	47.5	7.5	50.4
Chinengo	0.54	20.0	32.0	34.8	56.0	2.2	56.3
Mapiye	0.73	17.7	35.8	36.4	62.7	8.7	64.1
Muhwati	0.89	18.5	37.1	37.8	65.0	14.0	67.0
LSD	NA		3.2			5.4	

[B]

	Site %		RE_N			RE_P	
	C	NK	NPS	NPKS	NPS	PKS	NPKS
Site		Fraction N uptake (kg kg^{-1})			Fraction P uptake (kg kg^{-1})		
Chingwa	0.35	0.04	0.31	0.37	0.17	0.18	0.20
Muriva	0.40	0.32	0.47	0.60	0.25	0.10	0.27
Makoni	0.46	0.19	0.61	0.66	0.33	0.02	0.32
Chinhengo	0.54	0.40	0.67	0.73	0.32	0.01	0.33
Mapiye	0.73	0.14	0.75	0.77	0.26	0.03	0.27
Muhwati	0.89	0.44	0.83	0.84	0.30	0.08	0.31
LSD	NA		0.11			0.04	

trend, with a low RE_N for Field Type 1 compared to Field Types 2 and 3 (Table 12.3B). In many cases, RE_N at least doubled when P was co-applied. In one case, the RE_P was as little as 1 % for the PKS treatment, increasing remarkably to 30 % when both N and P were applied. Again, the RE_K were insignificant across all sites, and these results are not reported.

Yields for both NK and PKS treatments were poor across sites as indicated by low water productivity values for the three fields representing the three Field Types (Fig. 12.2), confirming these macronutrients as the most critical. In many cases, no differences existed in yields between the control and the PKS treatment, despite relatively high application rates of 40 kg ha^{-1} P and 60 kg ha^{-1} K. Yield response was only realized when N was added. These results represent a classic example of the law of the most limiting nutrient and crop growth and the indispensable need for balanced nutrient application. This is comparable to results from West Africa, where significant improvements in RE_N were observed upon simultaneous application of N and P (Fofana et al. 2005). Often, smallholder farmers have managed to sustain low maize production levels by managing soil fertility through application of a combination of small quantities of livestock manure, compost and spreading nutrient-rich soils from anthills around the crop fields. Although the concentration

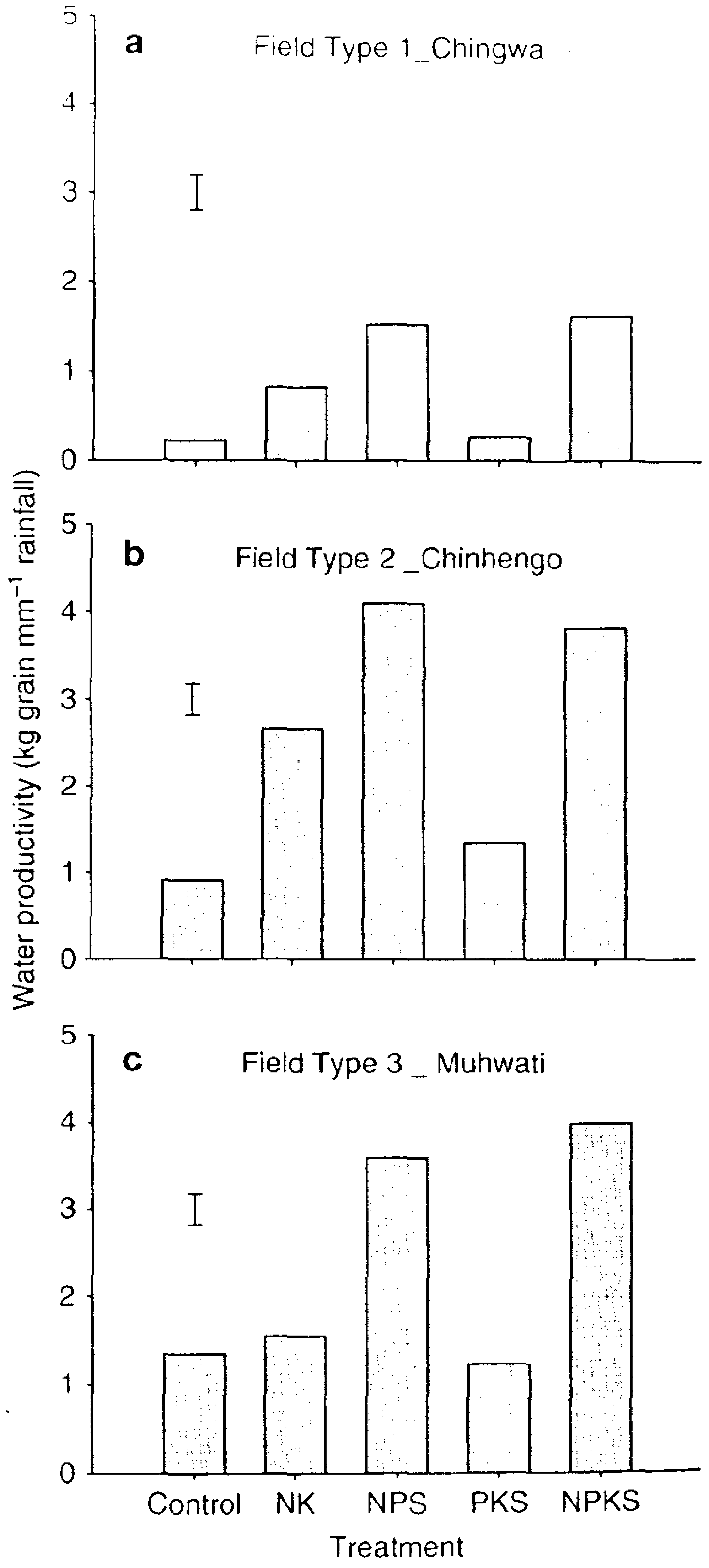

Fig. 12.2 Water productivity (kg grain mm^{-1} rainfall) as influenced by nutrient management across three experimental sites belonging to different soil fertility domains, Dendenyore ward, Hwedza, Zimbabwe. *Bars* indicate least significant differences, LSDs between means

of nutrients in these resources is low, the few macro- and micronutrients that become available avert acute nutrient deficiencies, making production of base yields possible.

Response to fertilizers is a function of the current state of soil fertility, with acutely degraded fields responding poorly to nutrient additions (Kho 2000; Tittonell et al. 2005; Zingore et al. 2007). The long-term lack of adequate mineral and organic nutrient resources has led to the expansion of fields that fall under Field Type 1, as farmers preferentially allocate the limited nutrient resources to a few specific fields. The neglected fields are then cropped without any external nutrient inputs, gradually becoming exhausted of nutrients and concomitantly becoming acidic. Resuscitating these fields to profitable crop production becomes a challenge as they characteristically respond poorly to fertilizers when they become available. Giller et al. (2006) suggested that other nutrients critical to maize growth should be applied to enable greater responsiveness to N and P. Studies have shown that for degraded soils with poor response to fertilizer the process of soil rehabilitation can be kick-started with additions of livestock manure (Zingore et al. 2007). The feasibility of such interventions is, however, doubtful due to the resource constraints faced by smallholder farmers.

12.2.3 Conservation Agriculture and Intensification

Conservation agriculture (CA) has been widely promoted in SSA as a possible solution to control soil erosion and degradation in smallholder arable fields (Bayala et al. 2012; Haggblade and Tembo 2003; Marongwe et al. 2011; Umar et al. 2011), which is largely attributed to conventional tillage using the mouldboard plough. Conservation agriculture as defined by the Food and Agriculture Organization (FAO) consists of three principles: (i) minimal soil disturbance, (ii) maintenance of at least 30 % permanent organic mulch on the soil surface, and (iii) a diversified cropping system. Reduced tillage (RT) is by far the principle adopted by the largest number of smallholder farmers and practices range from hand-hoe dug planting basins to planting furrows opened using ox-drawn or tractor-drawn rippers (Nyamangara et al. 2013). The maintenance of at least 30 % permanent organic mulch on the soil surface is the least adopted principle, due to a combination of low crop yields (less than 1 t/ha) and competing claims to residue use on the farms, primarily for livestock feed during the dry season when grazing is limited and of poor quality (Giller et al. 2009).

Conservation agriculture has had dramatic effects in terms of reducing soil erosion and runoff but has been inconsistent in terms of increasing crop productivity largely due to inherent or declining soil fertility. Ndhlovu et al. (2013) reported 39 % more maize grain yield under conservation agriculture compared to conventional tillage in Zimbabwe, but noted that high labor and fertilizer demands in conservation agriculture present problems in adoption amongst resource-constrained farmers. In a compilation of 23 reports, Wall et al. (2013) reported >10 % higher crop yields under conservation agriculture compared with conventional tillage, but the role of fertilization was not clearly defined. Giller et al. (2009) noted that the empirical evidence is not clear and is inconsistent regarding the contribution of conservation agriculture to yield gains compared with conventional tillage. Nyagumbo (1999) reported that the performance of conservation agriculture relative to existing technologies is highly variable and dependent on site and farmer characteristics.

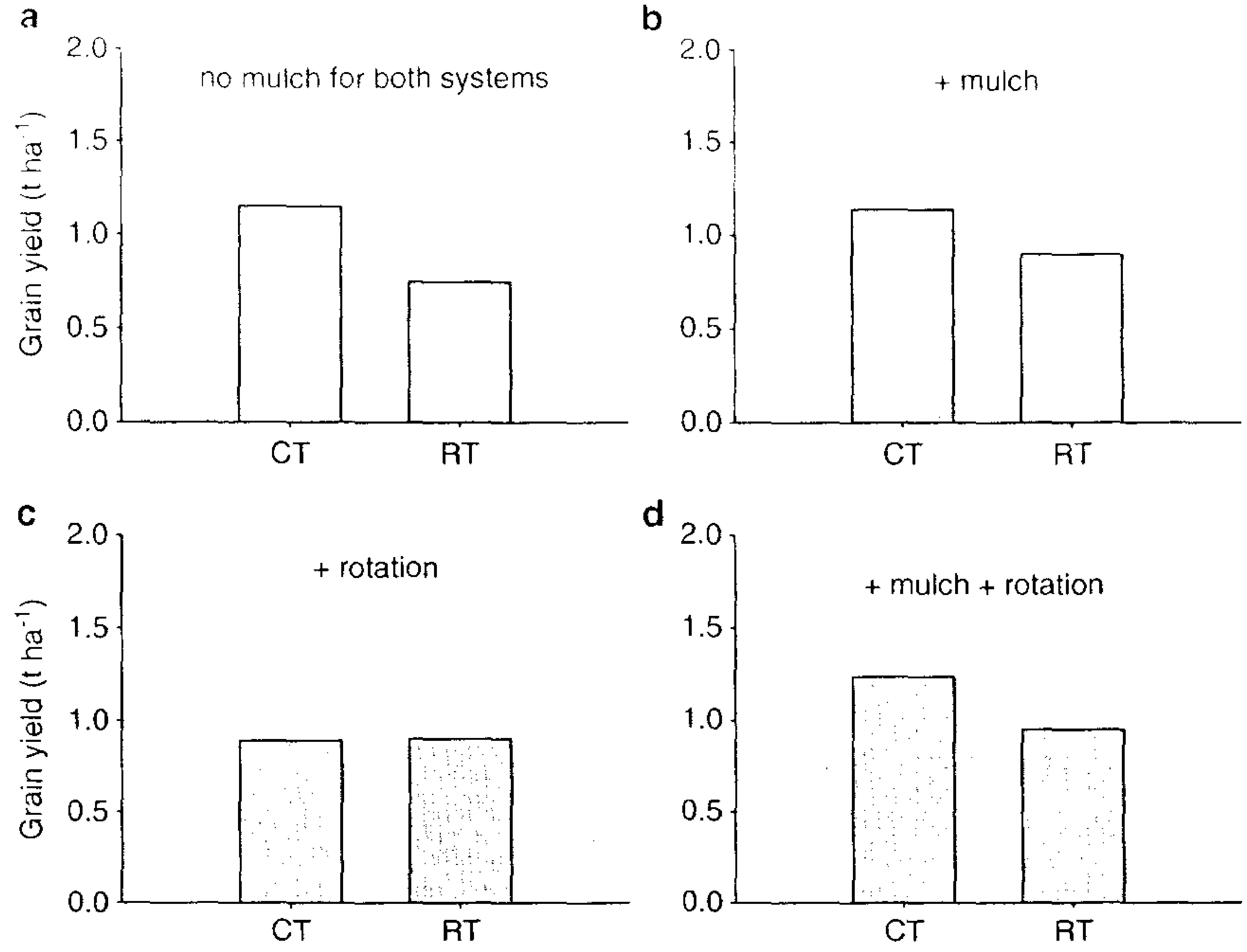

Fig. 12.3 Maize grain yield under conventional tillage (CT) and reduced tillage (RT) during the 2011/2012 cropping season on a sandy soil at the Matopos Research Station, Zimbabwe. *Bars* present standard errors of the difference of the means

An experiment at the Matopos Research Station in a semi-arid part of Zimbabwe demonstrated that maize grain yields were significantly lower under reduced tillage only (RT), RT + mulch, and RT + mulch + rotation (all three CA principles) compared with conventional tillage (CT), but yields were similar between RT + rotation (no mulch) and CT (Fig. 12.3). Mineral fertilizer was applied to both RT and CT treatments. The studies appear to indicate the need to target conservation agriculture promotion according to access to nutrient resources, crop type, soil type and rainfall amount and distribution. It is also clear that benefits from reduced tillage will not be realized in the short term.

Appropriate use of fertilizer has been suggested as the fourth principle of conservation agriculture in SSA in order to increase the likelihood of benefits for smallholder farmers (Vanlauwe et al. 2014). On-farm survey results from Zimbabwe across several farms strongly suggest that appropriate fertilization is critical for benefits of conservation agriculture to be realized in soils that are already poor (Table 12.4). A meta-analysis of major long term conservation agriculture trials conducted worldwide indicated that grain yield was positive when mineral N fertilizer was applied at rates greater than 100 kg N ha^{-1} (Rusinamhodzi et al. 2011). The performance of conservation agriculture under semi-arid conditions is enhanced by the addition of small amounts of N fertilizer and cattle

Table 12.4 Effect of mineral fertilizer application on the yield of maize (kg ha^{-1}) on 92 farms for maize monocropping and 65 farms for maize-legume rotation under CA in smallholder areas across semi-arid and sub-humid conditions in Zimbabwe

Fertilizer use	Maize monocrop (N = 92)	Maize-legume rotation (N = 65)
No fertilizer	520 ± 133	450 ± 61
N fertilizer (top-dressing)	1,760 ± 247	2,420 ± 493
NPKS fertilizer (basal and top-dressing)	2,560 ± 160	3,310 ± 482

Adapted from Nyamangara et al. (2013)
N number of farms

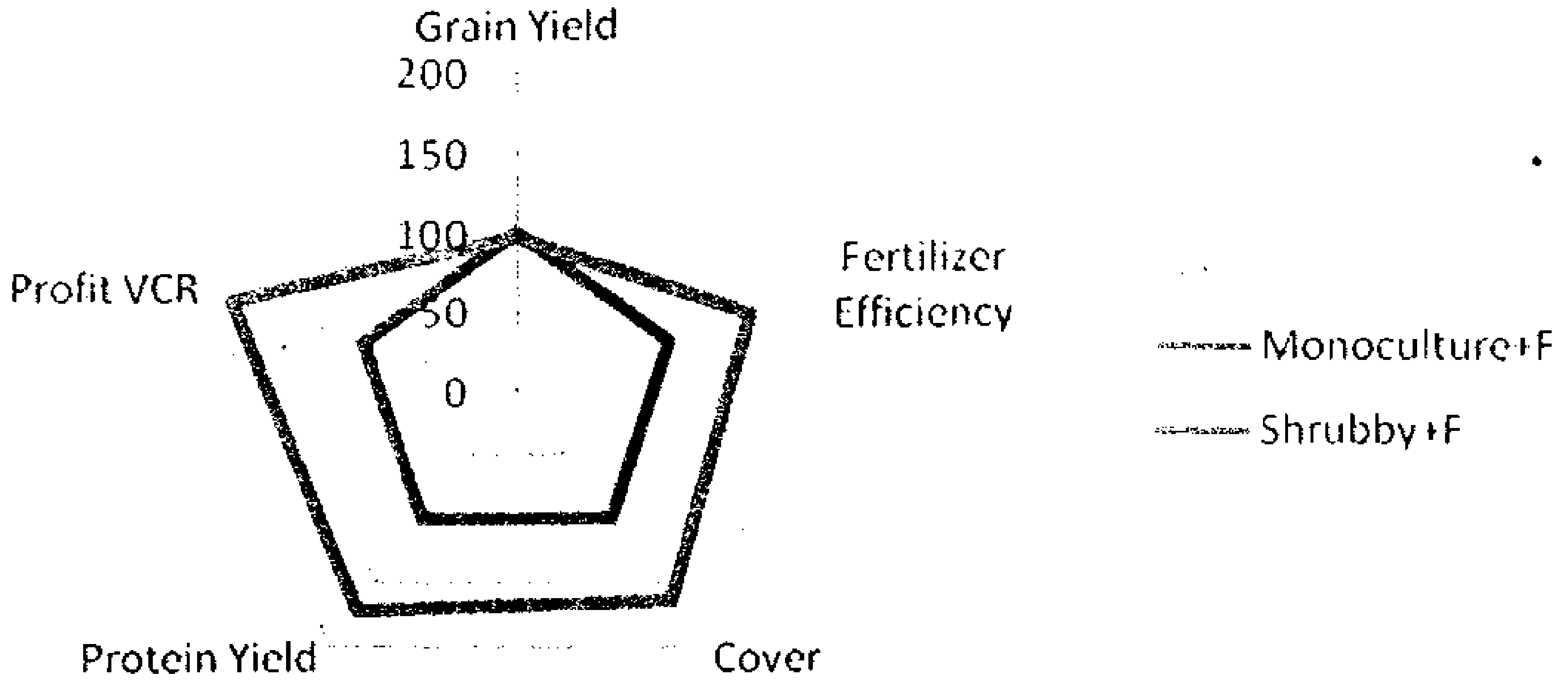

Fig. 12.4 Doubled-up shrubby legumes offer multiple services in cropping systems as compared to monoculture practices, + F = with fertilizer (Modified from Snapp et al. 2010)

manure—the micro-dosing principle. These studies illustrate the pivotal role of optimal application of nutrients in enhancing crop yield under conservation agriculture as opposed to interpreting conservation agriculture as a silver bullet on its own.

12.2.4 Intercropping Legumes: The Doubled-Up Cropping System

Growing two or more crops simultaneously in the same space—known as inter-cropping—is a strategy employed to maximize beneficial interactions while minimizing competition. Where inter-specific competition for resources (nutrients, light, water) is minimal due to the companion crops occupying different ecological niches and thus growing in a complementary manner, intercropping is known to increase biodiversity, stability, and financial diversification on farms (Snapp et al. 2010; Fig. 12.4). The doubled-up legume cropping arrangement involves intercropping two legume crops that have complementary plant architecture, and additional desirable traits such as different maturity dates. For example, groundnut and pigeonpea are ideal 'doubled-up' companion legume crops because groundnut can be grown as a shallow-rooted understory crop intercropped with pigeonpea (*Cajanus cajan L.*) Pigeonpea has a very slow early growth rate, developing into a bushy architecture when groundnut would be maturing. Thus, most of the resources (nutrients, water, light) used by pigeonpea during its late vegetative and reproductive phases are under conditions of 'sole' cropping. Pigeonpea develops a deep rooting system that facilitates capture of leached nutrients or soil moisture at depth at the end of the rainfall season. The resultant large leafy biomass eventually forms a layer of high quality litter on the soil surface—an important nutrient cycling pathway that stabilizes the yields of cereal crops grown in sequence even at reduced fertilizer use. This 'doubled-up' legume system ensures double benefits in form of improved soil fertility and grain harvests for two legume crops. Work with this system has consistently demonstrated superior land productivity compared to rotational systems.

12.2.5 Co-learning Nutrient and Risk Management Options with Farmers

Smallholder farmers in SSA have developed low risk farming management practices in an effort to ensure that their subsistence food needs are met. However, farmers' practices are largely sub-optimal even under favourable climatic conditions, because they are faced with multiple biophysical and socio-economic stresses that are now exacerbated by increased rainfall variability. Evidence from empirical research indicates that it is possible for farmers to increase maize yields from the current $<1\ \mathrm{t\ ha^{-1}}$ to $>3\ \mathrm{t\ ha^{-1}}$ if appropriate technologies are adopted and rainfall is adequate. Recognizing that sustainable solutions should be embedded within the communities, it is hypothesized that vulnerability to food shortages could be partly addressed if a significant proportion of farmers in maize-based farming systems strategically tailored their practices. Among other elements, such practices should employ drought tolerant maize varieties, appropriate responses to rainfall season typologies by timely planting, and integrated soil fertility management (ISFM) to ensure production of high yields in favorable seasons and revert in future bad seasons to the surplus generated. Here, we present a co-learning approach that involves working with farmer groups and implementing adaptive field experiments anchored on the three essential components of ISFM: (1) use of mineral fertilizers (Photo 12.4) (2) use of locally available organic nutrient resources, and (3) use of improved maize germplasm. The approach is a knowledge-based empowerment process that aims to tailor crop production practices to each community and is closely related to farmer resource-endowment circumstances.

Photo 12.4 Timely access to fertilizers is a key adaptation strategy for producing high crop yields during good rainfall seasons

A 3-year study was conducted with six smallholder farming communities in Eastern Zimbabwe to develop crop production strategies that ensure high agronomic efficiency and concurrently respond to the emerging challenges of increased climate variability. Agronomic practices were designed to provide answers to problems related to three rainfall season typologies that were readily identified by farmers:

I. Cropping seasons that are associated with crop yield losses due to delayed planting (late start of the rainfall season),
II. Cropping seasons that experience excessive rains early in the season followed by drought, resulting in poor yields for early planted crops, and
III. Cropping seasons with marked within-season dry spells, with prevailing conditions during the sensitive vegetative stages having the overriding effect on crop productivity.

Farmers prioritized combining inorganic fertilizers and locally available organic resources to improve soil productivity and 'trying out' different maize varieties and staggered planting dates for maize as options to increase maize productivity and simultaneously spread risk. Farmers in different resource endowment categories indicated their preferred rates of fertilizers and organic resources which best suited circumstances, a form of 'best fit—best bet' hybridization (Table 12.5; Mtambanengwe and Mapfumo 2005). Heterogeneity of farming households is an inherent component of smallholder communities, calling for better targeting of technologies, as farmers have different capacities to invest in soil fertility replenishment or maintenance (Giller et al. 2011). Staggered planting of each of three

Table 12.5 Soil fertility management options targeted by different farmer resource groups during participatory field experimentation with farming communities in Eastern Zimbabwe

	Farmer resource group[a]		
Fertilization rates and options	RG1	RG2	RG3
Basal compound fertilizer (kg ha^{-1} P)	26	21	14
Nitrogen fertilizer (kg ha^{-1} N)	120	70	35
Cattle manure (t ha^{-1})	10	6	3
Woodland litter/compost (t ha^{-1})	Optional	3	2

[a] *RG1* resource endowed farmers, *RG2* intermediate resource group, *RG3* resource constrained farmers

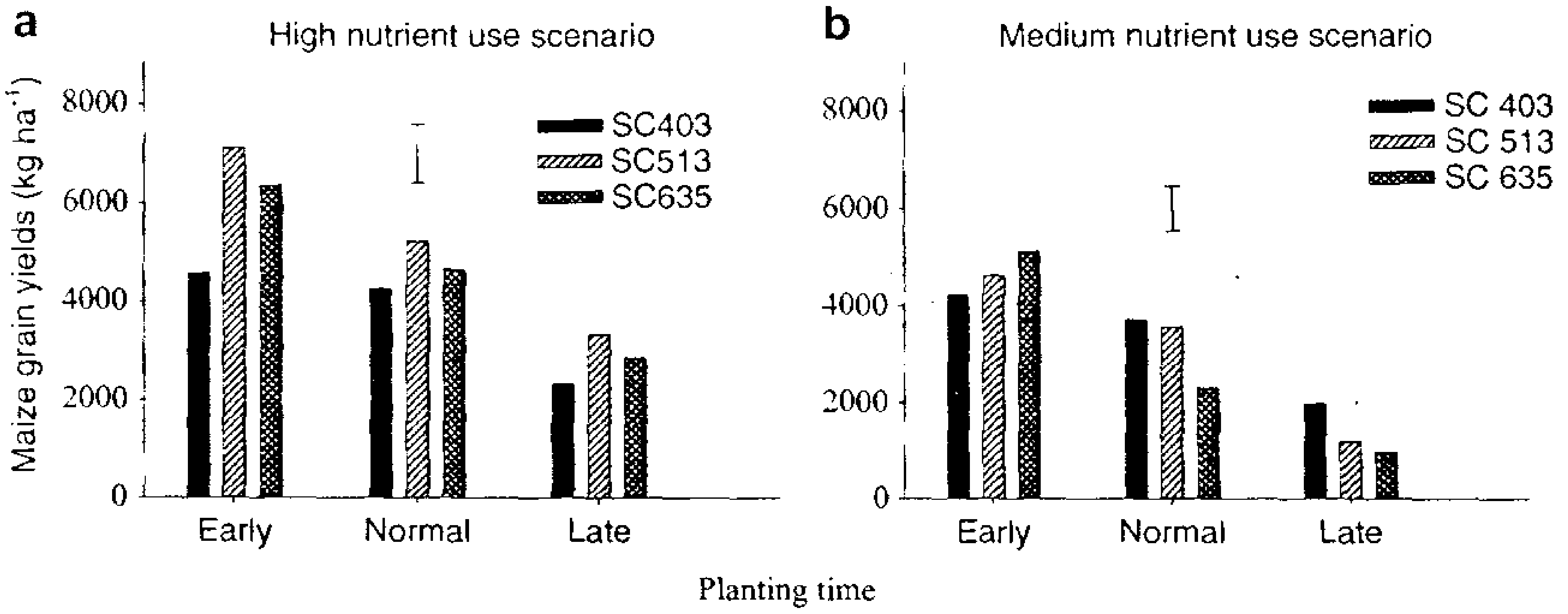

Fig. 12.5 Mean maize grain yields across experimental sites with early, normal, and late planting of three maize varieties at (**a**) high nutrient use levels corresponding to resource endowed farmers, RG1 and (**b**) when medium nutrient application rates were used corresponding to intermediate farmer resource group RG 2. *Vertical lines* are LSDs

maize varieties was agreed upon as a viable strategy to spread and manage climate-related risk. During community workshops, farmers collectively defined planting windows as (i) early planting—before and up to 25 November, (ii) normal planting—26 November to 15 December, and (iii) late planting—16 December to 31 December. Planting beyond year-end was considered too late for maize in Southern Africa because the rainfall normally tails-off by mid April, making this too risky for maize varieties that require 4 months of development to physiological maturity. Actual planting dates depended on soil moisture availability within each of the planting windows, but successive planting events were at least 2 weeks apart.

The study revealed substantial variability in performance of maize varieties across seasons and sites due to excessive rains or prolonged dry spells experienced during the experimentation period. However, it is clear that use of combinations of locally available organic nutrient resources and external fertilizers provided an opportunity to produce yields ranging from 3 to 7 t ha^{-1} when planting was completed during the early and normal planting windows (Fig. 12.5). Late planting was associated with large yield penalties, irrespective of the rate of nutrient application. Despite the increased climate variability, the analyses indicated that it is feasible to stabilize food availability in a community if ISFM components are employed to increase production of food crops, especially during favorable seasons, creating safety-nets that buffer communities against future bad seasons. Development of crop and soil fertility management options based on rainfall season typologies identified by farmers is one of the strategies that could enhance the capacity of smallholders to increase crop productivity and ensure food self-sufficiency against a changing climate.

12.3 Conclusions

Cropping systems in much of SSA are functioning sub-optimally, but approaches exist that can help to reduce the yield gaps and ensure food security, even under variable rainfall environments. Appropriate targeting of nutrient resources to field types that vary widely in soil fertility can be employed by farmers to maintain niches of high crop productivity that buffer overall farm production in an uncertain environment. Nitrogen is one of the most limiting nutrients to cereal production, and its variable use in a manner responsive to rainfall season quality would ensure its profitable utilization and minimize losses during drought seasons. The field experience gained in this research also suggests that the 'doubled-up' legumes system results in reduced fertilizer requirements for cereal crops grown in sequence, and crop yield stability benefits over time.

Acknowledgements The authors gratefully acknowledge funding from USAID through the Africa RISING program being implemented by the International Institute of Tropical Agriculture (IITA). Data for case studies that constitute this chapter are a result of funding from the International Plant Nutrition Institute (IPNI), IDRC, ICRISAT, and the McKnight Foundation.

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