The Dryland Eco-Farm: A Potential Solution to the Main Constraints of Rain-Fed Agriculture in the Semi-Arid Tropics of Africa

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Abstract This chapter presents the results of studies on a production system called Dryland Eco-Farm (DEF) that addresses a range of constraints to agricultural productivity in dryland Africa. It combines the use of live hedges and alleys of *Acacia colei*, "demi-lunes" in which are planted domesticated *Ziziphus mauritiania*. Annual crops like pearl millet (*Pennisetum glaucum* (L.) R.Br.), cowpeas and roselle (*Hibiscus sabdariffa*) are planted in rotation. This trial tests the effect of the system on (1) soil erosion control, soil fertility and water use efficiency, (2) crop yield and biomass production, and (3) improving income generation and diversification. Average pearl millet yields in the DEF were twice the control (880 vs. 430 kg ha^{-1}) when no mineral fertilizer was applied. With the application of NPK, millet yields were almost similar under both conditions (950 vs. 780 kg ha^{-1}). Cowpea yields were on average seven times higher than the control without NPK (1,400 vs. 200 kg ha^{-1} total biomass) and three times with NPK (1,850 vs. 650 kg ha^{-1} total biomass). Roselle yield increased four times on average without NPK (205 vs. 60 kg ha^{-1} calices yield) and two times with NPK (234 vs. 114 kg ha^{-1}). Therefore, the system has the potential to produce yield response similar to that of the recommended rate of 100 kg of the 15-15-15 fertilizer per ha. The return to land is estimated at US $224 for the DEF compared to US $77 for the traditional millet–cowpea system. This system has the potential to improve productivity and rural livelihood in the drylands of Africa while sustaining the natural resources base.

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Introduction

The dryland of Africa is the home to the poorest of the world, where about 90% of the population live in rural areas and sustain their livelihood from subsistence agriculture (Bationo et al., 2003). In this zone of Africa, low and erratic rainfall, its poor distribution within the growing period, prolonged dry spells, which usually occur during the season, and the lack of adequate water supply due to soil physical degradation (soil crusting) and nutrient shortage often adversely affect crop growth and yields (Zougmoré, 2003). Indeed, only 2% of the arable lands are irrigated, which means that rain-fed agriculture is the main source of food for the increasing populations in that zone (Parr et al., 1990).

Soil erosion (wind and water), low soil fertility (mining agriculture), low income (vicious circle of low crop yields), low water use efficiency, insufficient supply of animal feed (low biomass production and poor pasture) and poor distribution of the labour force (farmers are busy only 4 months of the year) are some of the constraints to agricultural production in Africa and particularly in the dryland zone. Research work conducted by the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), the International Fertilizer Development Centre (IFDC), the International Institute for Tropical Agriculture (IITA) and national research institutions has led to the development of technologies that

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have proven to be efficient in addressing these constraints individually. But further work in the dryland has shown that to address these constraints a multi-component and multi-disciplinary research is required to increase the productivity of the arable land (Mando, 1997). The Dryland Eco-Farm (DEF) is an innovation that was recently developed at the ICRISAT Sahelian Center (ISC) in Niger in collaboration with the National Agricultural Research and Extension Services (NARES) partners. The DEF combines the use of live hedges of *Acacia colei*, earth bunds that turn into micro-catchments or "demi-lunes", high-value trees such as the domesticated *Ziziphus mauritiania* planted inside the "demi-lunes", and annual crops, each planted in half or a third of the field in rotation each year.

The purpose of the experiment was to test the effect of the DEF system on (1) soil erosion control, soil fertility and water use efficiency, (2) plant biomass production, (3) income generation and diversification and (4) labour productivity compared to the traditional millet–cowpea system.

Materials and Methods

The Experimental Site

This experiment was conducted at the ICRISAT research station at Sadore located at 13° 15′ N, 2° 17′ E, approximately 40 km southwest of the capital city Niamey. The long-term average annual rainfall at this site is 550 mm. The mean monthly temperature varies between 25 and 41°C (Sivakumar, 1993). The soils are classified as Psammentic Paleustalf (West et al., 1984). The experiment started in 2002 on a soil that was left fallow for 10 years, but the evaluation of the yield of the annual crops started in the rainy season in 2004 when the perennials were pruned for the first time at the end of the dry season.

Experimental Layout

The experiment tested the following treatments: land management – DEF vs. no-DEF (also called traditional system or control); cropping system – rotation vs. continuous cropping; mineral fertilizer management – +NPK vs. –NPK; organic amendment management – +mulch vs. –mulch. One hectare DEF was surrounded by a live hedge made out of Australian acacias planted at 2-m intervals. Two rows of *Acacia colei* were planted down the slope from the hedge at a spacing of 10 × 5 m. These two rows were followed by a row of the domesticated *Ziziphus mauritiana* called Pomme du Sahel (PdS) planted at 10 × 5 m spacing. Pomme du Sahel was planted inside 3 × 3 m micro-catchments (demi-lunes) joined by earth bands that diverted the runoff water into the demi-lunes. This configuration of two *Acacia* rows followed by a PdS row was repeated three times in the 1 hectare (100 × 100 m) field. Each of these bands was planted with annual crops. The annual crops were pearl millet – variety Composite Inter-Varietal de Tarna (CIVT); cowpea (*Vigna ungiculata*) (L.) Walp – variety Ecoh-Mali; roselle (*Hibiscus sabdariffa*) – variety Wankoy.

In the no-DEF, three bands were also considered but without tree components and rotation. In both DEF and no-DEF, treatments were laid in a randomized complete block design (RCBD) in four replications. DEF and no-DEF treatments were laid in two separate but adjacent fields. The fertilizer NPK was applied at the rate of 100 kg ha^{-1}, the recommended rate of the Sahel. The plot size was 24 × 5.75 m.

The time table of the cultural practices for both annual and perennial crops are given in Table 1. The trees are pruned every year almost at the same time. The annual crops were planted with the first significant rain. They were kept free of weeds with a traditional hoe called hilaire and harvested at maturity.

Data Collection and Analysis

Characterization of Soil Chemical Properties

Initial soil sampling was done in the field prior to installing the experiment using a stratified random sampling method. For chemical analyses (C, N, P, pH, total N), three cores were sampled, 0–15, 15–30 and 30–60 cm. The present chapter will present the first core, where most of the change in soil chemical properties is expected (Geiger et al.,

Table 1 Activities in the DEF year around

			Time period											
			January	February	March	April	May	June	July	August	September	October	November	December
Annual crops		Planting												
		Care annuals												
	Harvest and processing	Pearl millet												
		Cowpea												
		Hibiscus sabdariffa (roselle)												
Perennials	Acacia sp.	Planting												
		Harvest of seed												
		Prunning												
	Ziziphus	Planting												
		Fertilization (cattle manure)												
		Phytosanitary protection												
		Harvest												
Soil fertility management		Mulch application												
Water harvesting technology		Confect/repare of half-moons												

1992). Soil organic carbon content was determined by the Walkley-Black (1934) method; available P was determined using the Bray P1 method (Bray and Kurtz, 1945); total nitrogen was determined using the Kjeldahl method (Bremner and Mulvaney, 1982); and soil pH was determined in a 1:2.5 suspension with water. At the end of 2004, a second set of soil samples was collected to study the effect of the treatments on the soil characteristics. These samples were analysed for N, P and pH. To study the changes in the levels of these elements over the first 3 years of experimentation, samples were also collected in 2006, but are not reported in the present chapter because these are not yet analysed.

Yield Data

To study the performance of the various annual crops, yield data were collected at harvesting in a plot of 138 m^2. The straw and millet heads were sun-dried and weighed to determine dry weight. The heads of millet were threshed to determine the grain weight per plot which was extrapolated to kg ha^{-1}. The pods of cowpea were collected three times during the season, sun-dried, weighed on plot basis and threshed. The haulm was harvested at the end and weighed. The final yield was determined in the same way as for millet. The calices of *Hibiscus* are used to produce drinks and the grains are used by women to make local ingredients called "sumballa" for sauce. In addition to these products, the fallen leaves and the stalk serve as organic amendments to replenish soil fertility. Calices yield was determined in the following way: the whole fruit was collected to a working area. The calices were separated from the rest of the fruit and both of them were sun-dried. Calices dry weight was recorded on a plot basis and extrapolated to yields per ha. Thereafter, the fruits were threshed to get the grains, whose weight was obtained on a plot basis and then extrapolated to ha. This chapter will focus on grain yield of millet, total biomass of cowpea and calices yield of *Hibiscus* over 3 years. The other data will be reported in another paper.

The data were analysed for Analysis of Variance (ANOVA) using the Genstat v9 statistical package. In the process of statistical analysis, the DEF and no-DEF treatments were considered as nested blocks and there was combined analysis for all the 3 years.

Analysis of Contribution by Trees

On the perennials, firewood and total mulch production data were collected on the *Acacia* trees after pruning. Pomme du Sahel (improved *Ziziphus*) fruits were harvested in December–January. Only mean values of the data of the perennials are presented in the present chapter. Investment, labour and production costs were recorded and served as a basis of economic analysis of the system. Data on soil erosion as well as water use efficiency will be a subject of another paper.

Economic Assessment

An enterprise budget combined with an investment analysis was used to analyse the economic parameters of the DEF. Potential yields and biomass production of the trees had to be estimated since they have never been planted under existing climatic conditions. The lifetime of the PdS is the basis for the economic calculation period, assumed 50 years. Revenues were generated from the annuals (millet and cowpea grains and stover or haulm) and the trees (mainly PdS (improved *Ziziphus*) fruits and *Acacia* firewood). Expenditures included annual costs and fixed costs. Annual costs include seed and seedling costs, and organic and inorganic fertilizers, pesticides and labour costs. Labour costs included all activities from land preparation to harvesting. Fixed costs are mainly depreciation on assets such as PdS and *Acacia colei* trees and some agricultural equipment. The economical analysis of the DEF was compared to a traditional millet–cowpea production system under average conditions in Niger based on expert opinions. Crop prices were those collected by the Systèmes d'Information sur les Marchés Agricoles (SIMA) of Niger. Input prices were gathered from the Central d'Approvisionnement (CA) of Niamey. Wage was proxied by the opportunity cost of labour in rural areas. Data on fruit trees and wood were estimated and weighted using comparable products in Niamey's market. It was assumed that 100% of production was sold.

Results and Discussion

Rainfall Distribution

The cumulative rainfall was similar for the 3 years with a total of 562 mm in 2004, 527 mm in 2005 and 545 in 2006. These values are comparable with the long-term average of 550 mm for Sadore. However, rain distribution varied widely between years. In 2004, rain started in April and continued until the end of June with short dry spells of about 10 days. Another short dry spell of 1 week occurred at the end of August. In 2005, the rain started at the end of May with a long dry spell of 3 weeks from 9 to 29 June. Another dry spell of 10 days occurred in the third week of July. In 2006, the rain started in mid-June with a cumulative rain of 18 mm from 8 June to 6 July which delayed planting during this year. Since millet and cowpeas are short-day species, any delay in planting (as was the case in 2006) negatively affected yields. The effect of water shortage on millet yield was recorded by Kanitkar (1944). Philips and Norman (1967) reported that millet grain yield is adversely affected if rain ceases during the reproductive stage even though the total amount of water received during the cropping season may be adequate (Jensen et al., 1990).

Soil Characteristics

As reported earlier, the experiment was conducted in a field that was under fallow for 10 years. Prior to planting, the P-Bray N° 1 in the top 15 cm soil layer was 20 mg/kg of dry soil, total N was 236 mg/kg and organic carbon was 2.9% (Table 2). This fertility level was better than the level typical to the region (P-Bray N° 1 = 2.1 mg/kg, Org-C 1.7%) reported in Sinaj et al. (2001). From the analysis of the samples collected in October 2004 after 3 years of cropping, Bray N° 1 P as well as total N level decreased in both the DEF and the traditional system. However, the decrease was more pronounced in the control (Table 3). Thus the DEF system maintains a higher level of soil fertility than the traditional system.

Effect of Dryland Eco-Farm on Yield of Annual Crops

Effect on Millet Grain Yield

Average millet grain yield over 3 years in the DEF was about 1,000 kg ha^{-1} (Fig. 1a), which is three times the average grain yield in Niger (Bationo et al., 2003). Grain yields in the DEF were 2–3 times higher than in the traditional system independent of the year and the application of mulch or NPK (Table 4). The application of *Acacia* mulch did not affect grain yield production. This could be due to slow decomposition of the applied mulch. In a separate study (unpublished) at Sadore research station, it was observed that after 1 year, only 50% of the *Acacia* mulch was decomposed even in the presence of termites. Application of NPK in the DEF increased grain yield slightly but this was not statistically significant. In most of the years, grain yield in the DEF without NPK was similar or higher than that in the traditional system with NPK application, which leads to a preliminary conclusion that DEF without fertilizers can produce as much yield as that obtained with the recommended rate of NPK application for the region.

Effect on Cowpea Total Biomass Yield

Cowpea fodder is an important product both as a livestock feed and for income generation. Over the 3 years of experimentation, average cowpea total biomass yield of 2,000 kg ha^{-1} was produced in the DEF which is far above the yield in farmers' field

Table 2 Chemical status of the experimental soil before layout in 2002

Depth (cm)	pH (H_2O)	Bray P1 (mg-P/kg)	Total N (mg-N/kg)	Organic C (%)	Sand (%)	Clay (%)
15	5.2	20.2	236	0.29	93.9	6.1
30	5.0	9.9	126	0.15	93.2	6.9
60	4.9	2.6	87	0.10	92.5	7.6

Table 3 Chemical status of the experimental soil after three seasons in 2004

Depth (cm)	pH	Bray P1	Total N
The dryland eco-farm			
15	5.1	18.7	175
30	4.8	12.5	93
60	4.7	4.7	67
Traditional system (no-DEF)			
15	5.3	10.2	122
30	4.9	6.3	81
60	4.7	3.9	69

(Fig. 1b). Biomass yield in all years in the DEF was 2–3 times higher than in the control, regardless of the year (Table 4).

On average, mulch application did not affect total biomass production. NPK application increased total biomass production, particularly in the control. In the absence of NPK in the DEF as well as in the traditional system, mulch application depressed biomass production whereas with the application of NPK, a 25% yield increase was obtained which was statistically significant.

Effect on *Hibiscus* Calices Yield

Average calices yield of 250 kg ha^{-1} was produced in the DEF, which is far beyond 110 kg ha^{-1} reported by Robert S. McCaleb in *Market Survey: Hibiscus sabdariffa*; http://www.herbs.org/africa/hibiscus.html.

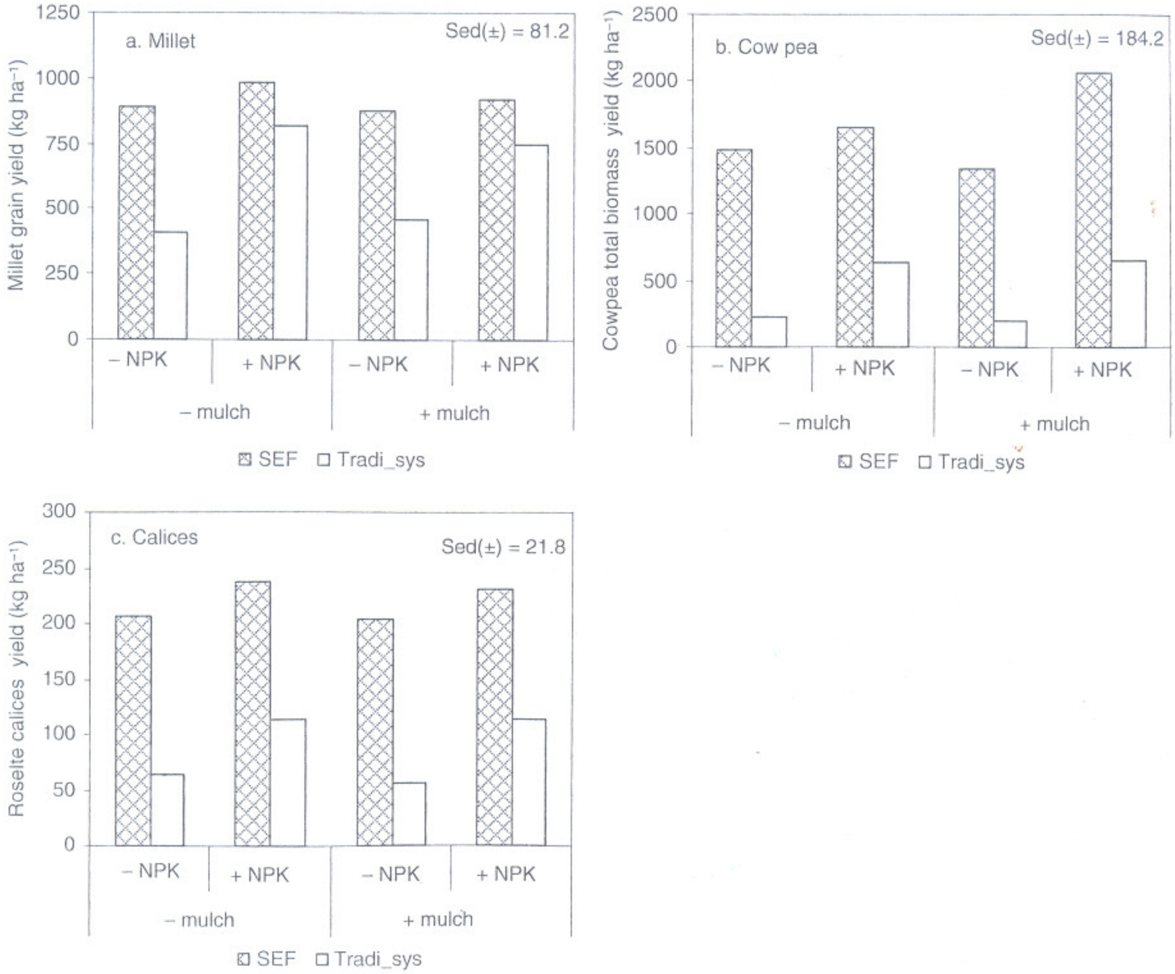

Fig. 1 Effect of the dryland eco-farm system on millet grain, cowpea total biomass and roselle calices yield; mean over 3 years 2004–2006; Sadore ICRISAT Research Station. Sed is standard error of difference between means. Tradi_sys = traditional system

Table 4 Ratio of DEF to traditional system in terms of annual crops for 3 years of cropping

	–Mulch		+Mulch	
Year	–NPK	+NPK	–NPK	+NPK
Millet grain yield				
2004	2.4	1.5	1.9	1.4
2005	2.5	1.1	1.7	1.0
2006	4.1	1.3	3.3	2.6
Cowpea total biomass yield				
2004	6.5	2.0	6.4	2.2
2005	10.0	4.3	10.4	6.5
2006	4.1	1.5	4.4	2.2
Hibiscus calices yield				
2004	2.9	2.4	3.2	2.5
2005	6.4	1.9	2.6	1.5
2006	16.0	14.3	13.6	5.3

This yield level was significantly higher than the control (50–100 kg ha^{-1}) (Fig. 1c). Mulch and NPK application did not significantly affect calices and grain production in the DEF but application of NPK significantly increased yields as compared to the control. Calices yield was 2–16 times higher in the DEF compared to the traditional system, regardless of mulch or NPK application (Table 4).

Effect of Dryland Eco-Farm on Yield of Trees (*Acacia* spp.)

The purpose of planting the *Acacia* trees was to produce firewood for energy and mulch to improve soil fertility, protect the soil against erosion and produce seed which can be used as source of protein for poultry. In the period 2004–2006, firewood production from *Acacia* trees was 2 t ha^{-1} and mulch production was about 2.5 t ha^{-1} (Table 5).

Table 5 *Acacia* firewood and *Ziziphus* fruit production in the DEF

Acacia sp.		
Year	2004	2006
Firewood	1,787	2,137
Mulch	2,575	2,693
Improved *Ziziphus*		
Year	2005	2006
Fruit	241	417

Improved *Ziziphus mauritiana* (PdS)

Pomme du Sahel is the second perennial component of the system providing both food and income. In 2006, the trees were 4 years old and produced 417 kg of fruit ha^{-1} (Table 5). Fruit yields are likely to double over the coming years since the trees had not reached full maturity.

Economical Analysis

The results of the investment analysis of millet and cowpea grown in the DEF are presented in Table 6. The setup costs of US $248 are mainly comprised of the trees, tools and labour. Fruit of the full-grown Pomme du Sahel brings the most income (average 228 US $/year) followed by the pearl millet grains. Annual costs are around 240 US $/year including labour costs at 2 US $/day (Table 6). The results indicate that with a loan with less than 41% as the interest rate, it is advisable to invest in the DEF with millet and cowpea. Credit schemes can help build confidence in the money market by making investing in the DEF less risky for the farmers.

The investment in the traditional system consists mainly of some tools and is so low (US $14) that it is not possible to compare the Internal Rate of Return (IRR) and Net Present Value (NPV) with the investment needed for 1 hectare of DEF. The benefit–cost ratios and return to labour and land can be compared. From Table 7 it can be seen that the benefit–cost ratio is not much higher for the DEF; however, return to labour and capital is much higher than in the traditional system.

Table 6 Set-up costs and Net Present Value (NPV) with different discount rates for millet and cowpea from 1 hectare of DEF

		DEF millet + cowpea
Set-up costs	(US $/ha)	$248
IRR (50 years)		41%
NPV at discount rate (50 years)	10%	$1,673
	20%	$462
	30%	$133
	40%	$5
	50%	–$54

Table 7 Comparing growing millet and cowpea traditionally and in the DEF

	Traditional	DEF
Benefit/cost ratio	1.71	1.93
Return to labour per year	$1.63	$3.35
Return to capital per year	$94	$275

Traditional = no-DEF

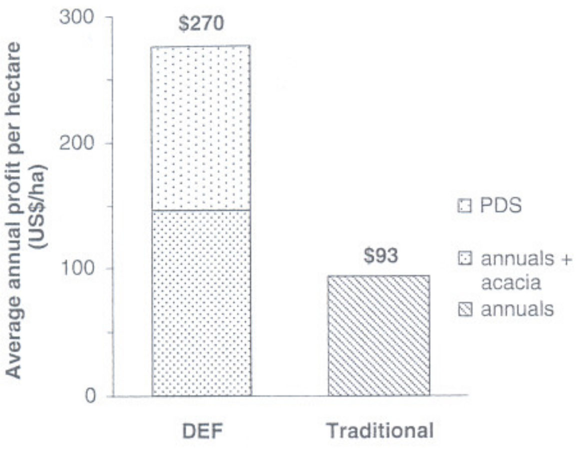

Fig. 2 Average annual profit per ha, contributions from PDS and annuals and acacias separated in the SEF. Traditional = no-DEF

In Fig. 2, the contributions to the average annual profit of the PdS are separated from the acacias and annuals. It can be seen that the incorporation of the PdS in the production system significantly increases the total profit. Besides that, higher yields of the annuals in the DEF translate directly into higher profit from cultivating millet and cowpea.

Conclusions

The Dryland Eco-Farm is an integrated trees–crops–livestock system under development. So far the performance of this system is outstanding in comparison with the traditional rain-fed production system. The incorporation of the Australian acacias results in improved soil fertility and in a corresponding increase in yield. The incorporation of a drought-tolerant fruit tree species significantly increases the profitability of the system. A system that is based on trees needs to be tested over a period of at least 10 years before concrete conclusions can be drawn. It should also be tested in farmer's fields to identify constraints for adoption. Therefore there is a need for further study and development of the system before it can be recommended for mass dissemination. All criteria used to evaluate the economic viability of the DEF in the Sudano-Sahelian zone suggest that it is worthwhile investment as an alternative to the traditional millet cowpea production system. This can be mainly attributed to the consistent fruit and firewood production of the PdS, the most dominant income-generating element of the DEF. From the analysis it was clear that accesses to credit for investment and markets that can absorb the product are very important provisions for viable investments. Institutional financing with fair interest rates and long repayment periods can play a major role in facilitating private farm investments in more intensive rain-fed production systems in the region. Social benefits from decreased erosion, water harvesting, forage production or less wood logging were not taken into account in the economic analysis.

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References

Bationo A, Mokwunye U, Vlek PLG, Koala S, Shapiro BI (2003) Soil fertility management for sustainable land use in the West African Sudano-Sahelian zone. In: M.P. Gichuru, A. Bationo, M.A. Bekunda, H.C. Goma, P.L. Mafongoya, D.N. Mugendi, H.K. Murwira, S.M. Nandwa, P. Nyathi and M.J. Swift (eds.) Soil fertility management in Africa: a regional perspective. Academy Science Publisher & Tropical Soil Biology and Fertility, Nairobi, Kenya, pp 253–292

Bray RH, Kurtz LT (1945) Determination of total, organic, and available forms of phosphorus in soils. Soil Sci 59:39–45

Bremner JM, Mulvaney CS (1982) Nitrogen–total. In: Page AL (ed) Methods of soil analysis. Part 2, 2nd edn. Agron, Monogr. 9. ASA and SSSA, Madison, WI, pp 595–624

Geiger SC, Manu A, Bationo A (1992) Changes in a sandy Sahelian soil following crop residue and fertilizer additions. Soil Sci Soc Am J 56:172–177

Jensen ME, Burman RD, Allen RG (eds) (1990) Evapotranspiration and irrigation water requirement. ASCE manual and reports on engineering practices No. 70. ASCE, New York, NY, 332pp

Kanitkar MV (1944) Dry farming in India. ICAR Sci. Monograph no. 15. New Delhi

Mando A (1997) Effect of termites and mulch on the physical rehabilitation of structurally crusted soils in the Sahel. Land Degrad Devel 8:269–278

McCaleb RS Roselle production manual (*Hibiscus sabdariffa*). In: Market survey: *Hibiscus sabdariffa*; agribusness in sustainable natural African plant productions. http://www.herbs.org/africa/hibiscus.html

Parr JF, Stewart BA, Hornick SB, Singh RP (1990) Improving the sustainability of dryland farming systems: a global perspective. In: Singh RP, Parr JF, Stewart BA (eds) Advances in soil science, vol 13. Dryland agriculture strategies for sustainability. Springer-Verlag, New York, NY, pp 1–8

Phillips LJ, Norman MJT (1967) A comparison of two varieties of bulrush millet (*Pennisetum typhoides* S. & H.) at Katherine. NT Melbourne, CSIRO Aust Div Land Res Tech Memo No 67/18

Sinaj S, Buerkert A, El-Hadjj G, Bationo A, Traore H, Frossard E (2001) Effect of fertility management strategies on phosphorus bioavailability in four West African soils. Plant Soil 233:71–83

Sivakumar MVK (1993) Agroclimatology of West Africa: Niger. Information bulletin no. 5. ICRISAT, Patancheru, AP, p 108

Walkley A, Black IA (1934) An examination of Degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. Soil Sci 37:29–37

West LT, Wilding LP, Landeck JK, Calhoun FG (1984) Soil survey of ICRISAT. Sahelian Center, Niger

Zougmoré RB (2003) Integrated water and nutrient management for sorghum production in semi-arid Burkina Faso. Wageningen University and Research Centre, Wageningen