Chapter 7
Effect of Integrated Soil Fertility Management Technologies on the Performance of Millet in Niger: Understanding the Processes Using Simulation

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Résumé La faible fertilité des sols et la rareté des pluies sont les facteurs les plus limitatifs de la production agricole dans la zone soudano-Sahélienne en Afrique de l'Ouest. La région habite les populations les plus pauvres de la planète dont 90% vivent en milieu rural et tirent leur nourriture d'une agriculture de subsistance. Cependant, les rendements des céréales en général et du mil en particulier qui constituent la nourriture de base sont très faibles (300–400 kg/ha). La recherche a développé des technologies de gestion intégrée de la fertilité des sols mais elles n'ont pas été adoptées par les paysans. DSSAT (Decision Support System for Agrotechnology Transfer) est un outil incorporant des modèles de 16 différents types de cultures avec un logiciel facilitant l'évaluation et l'application des modèles de cultures pour différentes utilisations. Mais son utilisation requiert un minimum de données sur le climat, les sols, les cultures et aussi les données expérimentales. Les simulations obtenues à partir de ces données permettront aux chercheurs de développer beaucoup de résultats prometteurs en milieu paysan. Cette étude montre

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les interactions entre la fertilité des sols et les rendements de mil dans trois sites (Banizoumbou, Bengou et Karabedji) au Niger sur une périodes de 5 ans (2001–2005) et une simulation dans DSSAT sur l'azote.

Abstract Low soil fertility and erratic rainfall are the most limiting factors to crop production, in the Sudano-Sahelian zone of West Africa. The region is the home of the world's poorest people, 90% of whom live in villages and gain their livelihood from subsistence agriculture. However, yields of cereals in general, and millet in particular that constitute the staple food of rural people, are very low (300–400 kg/ha). Research has developed technologies of integrated soil fertility management, but resource poor farmers have not adopted them. DSSAT (Decision Support System for Agrotechnology Transfer) is a tool incorporating models of 16 different crops with software that facilitates the evaluation and application of crop models for different purposes. Its use requires a minimum data set on weather, soil, crop management and experimental data. The simulations from these data can help scientists to develop promising management options to improve farmer's conditions. However, requirements for such model use is to evaluate its capabilities under farming situations, soils, and weather that are characteristic of the area where it will be used. This study was conducted to evaluate the DSSAT millet model capabilities for simulating the interactions between soil fertility and millet yields in three sites (Banizoumbou, Bengou and Karabedji) of Niger over 5 years (2001–2005) and different nitrogen management.

Introduction

Soil degradation, loss of organic matter, low soil fertility and yields, poverty, and climatic changes are among the main factors reducing crop production in the world. In the Sahel, low rainfall and its variability and distribution, dry spells and other climatic factors affect crop production. Production losses are mainly due to drought (2/3) and cricket attack (1/3) (Nanga 2005). Water balance in the region is positive only during 3 months of the year; meaning that water is still a limiting factor for crop production in a region where 90% of the population is rural and depend on subsidence rainfall for agriculture. Millet is the main crop in Permanent Inter-State Committee for Drought Control in the Sahel (CILSS) countries with 45% of cereal production followed by sorghum (28%) and maize (11%). Niger is second after Burkina Faso with 27% of cereal production in CILSS. Niger, with a population of 12.94 million in 2006, is one of the food-deficit countries in the world (CILSS/Agrhymet 2005). Only 12% of the country has an annual rainfall of 600 mm or more and only 10% has 350–600 mm. Cereal crop needs at least 300 mm if it is well distributed (Moustapha 2003). Cereal production in 2004/2005 was estimated to about 2.50 million tons with a negative balance of about 0.22 million t, which is equivalent to 7.5% of Niger population needs (Nanga 2005). Niger is the poorest country in the world according to the United Nations Development Program (UNDP) classification based on Human Development Index (HDI). Production was less than demand in Niger in two of the last 5 years. Ninety-eight percent of the cereal production in Niger is from rainwater. Rice, the principal irrigated crop, is less than 2% of the total cereal production. Water availability for irrigation also depends on rainfall, and in 2004 rice production decreased to only 0.5% of cereal production in Niger (FAO 2004). As Sahelian agriculture depends on rainfall, which varies considerably from year to year with considerably effects on crop production. Poor rainfall, high temporal variability and spatial distributions, and other climatic constraints are characteristic of the Sahel. This makes water a principal constraint of crop production in this country.

Population pressure has reduced cultivable area and traditional fallow is no longer feasible in Niger. It's known that millet is a crop adapted to Sahelian climate conditions, but combined with low soil fertility, low rainfall can greatly reduce crop productivity. In this context of soil degradation and poor climatic conditions, recommended farmer's practices are not appropriately adapted. ICRISAT research aims to find and propose to farmers combinations of soil fertility technologies, methods to increase water use efficiency and varieties to significantly improve crops yields.

This study was conducted to help identify improved natural resources management in these poor soils and weather conditions. Phosphorus, nitrogen, manure and rainfall effects on crop production are shown in the study. DSSAT v4.02 (Jones et al. 2003; Hoogenboom et al. 2004) was used to compare simulated and measured data and specific effects of climatic and fertility factors on millet production.

Materials and Methods

Three sites were used for this study due to agronomic and climatic data availability: Banizoumbou, Bengou and Karabédji, where ICRISAT has conducted experiments and where meteorological stations were used to record daily weather data that are needed for the millet model. We used data from 5 years (2001–2005) on trials conducted in the three different sites. Mineral and organic fertilizers were used and comparisons between the control and other treatments show the low productivity of the farmer's system. Among limiting factors, water was included and simulations were done to show its effects on millet production. Many factors are used in DSSAT but only climate and fertility will be used in this study.

Before the rainy season there is always uncertainty of what to be planted, when and how. Climatic data such as rainfall, minimum and maximum temperatures, and solar radiation are necessary inputs to the model. Other data are also used as DSSAT inputs: soil parameters, fertilizer type, manure and other organic fertilizers from the three sites.

There is no significant difference between soils of Karabédji and Banizoumbou but annual rainfall vary from 300 to 500 mm. At Bengou, rainfall is about 800 mm per year and the soils are very different. This large variation in rainfall may result in

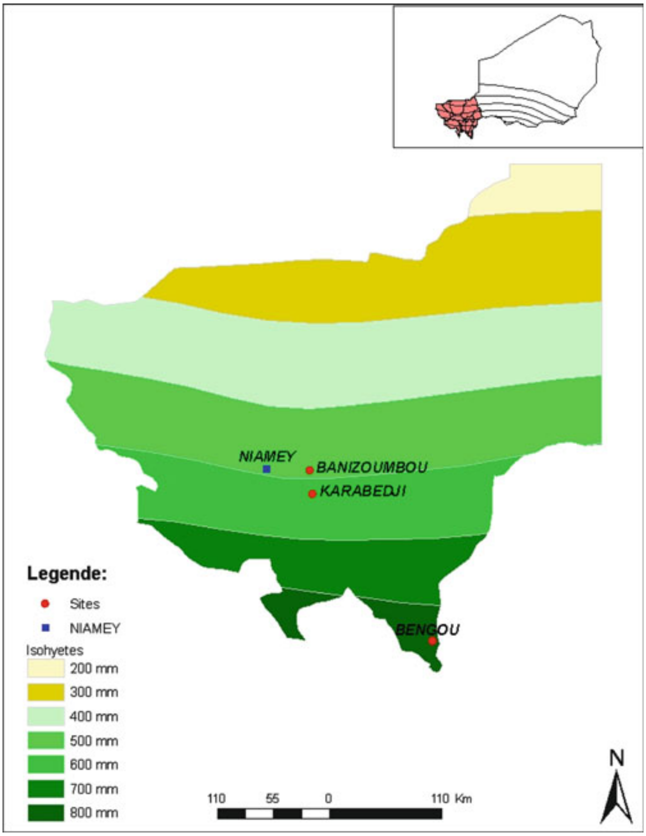

Fig. 7.1 Study sites and annual rainfall isohyets

significant differences in millet production in Niger for production situations where water is the most limiting factor.

Study Sites

Climate

These three sites are in a normal rainfall range for millet production (above 300 mm) but Bengou is more humid with more than 700 mm per year and over 4–5 months of rainfall compared to the two other sites where it rains only 3 months per year. Annual rainfall of Banizoumbou and Karabédji are, respectively, 360 and 450 mm (Fig. 7.1).

Table 7.1 shows that rainfall during the past 5 years exceeded the longterm mean is mentioned but not provided anywhere. At Banizoumbou and Karabédji, only

Table 7.1 Annual rainfall (mm), 2001–2005

Sites	2001	2002	2003	2004	2005	Mean
Banizoumbou	344	345	510	363	444	***401***
Karabédji	368	638	557	524	468	***511***
Bengou	985	732	884	630	784	***803***

Table 7.2 Soils characteristics at the different sites

Sites	pH KCl	C.org (%)	P-Bray1 (mg/kg)	Ca^{2+} Cmol/kg	ECEC Cmol/kg	N_{min} (mg/kg)
Banizoumbou	4.4	0.12	1.5	0.4	0.8	5
Karabédji	4.2	0.16	1.9	0.2	0.8	4
Bengou	4.2	0.33	2.5	0.4	1.3	9

2001 rainfall was under its long-term mean. At Bengou 2 years (2002 and 2004) received less than the normal amounts.

Soils

Soils from Banizoumbou and Karabédji are similar sols ferrugineux tropicaux lessivés. With more than 90% sand, these soils have low organic matter, low ECEC; and are very poor in nutrient contents. Soils from Bengou are slightly better and have higher organic carbon (more than 0.2%) and higher ECEC (Table 7.2).

Fields close to the village receiving high organic matter due to human and animal activities are more productive compared to the outfields. Prudencio (1993) observed such fertility gradients between fields closest to the homestead (home gardens/infields) and those furthest (bush fields/outfields). Soil organic carbon contents of between 11 and 22 g/kg have been observed in home gardens compared with 2–5 g/kg soil in bush fields. Fofana et al. (2006) in a comparative study at Karabédji-Niger on degraded lands (bush fields) and non degraded (infields) have observed that millet grain yield across years and fertilizer levels averaged only 800 kg/ha in bush fields and 1,360 kg/ha on infields. Recovery of fertilizer N applied varied considerably and ranged from 17% to 23% on bush fields and from 34% to 37% on infields. Similarly, recovery of fertilizer P was 18% for bush fields and 31% for infields over 3 years of cropping. It is clear that degraded soils are poor in organic carbon, their responses to fertilizer applications are less, and the recovery of fertilizer applied is very low. Soil degradation was defined by FAO (2002) as the loss of soil productivity capacity in term of decreased fertility, biodiversity and natural resources. Yield loss due to soil degradation in Africa varied from 2% to 50% the last 10 years (Scherr 1999). Bationo et al. (2006a) in Sherr (1992) and in Oldeman et al. (1992) in a description of degradation of arable soils in Africa and in the rest of the world estimated that degraded soil proportions were 38% in the world and 65% in Africa. During the last 30 years, nutrient losses in African soils were equivalent to 1,400 kg/ha N (urea), 375 kg/ha of SSP (phosphorus) and 896 kg/ha of KCl (potassium). In

Niger, Henao and Baanante (2006) estimated nutrient losses of 56 kg/ha (NPK) during the 2002–2004 cropping seasons.

Crops

At Karabédji and Banizoumbou, crops are mainly millet, sometimes intercropped with cowpea. At Bengou, millet is intercropped with sorghum, groundnut or cowpea as it rains up to 5 months per year.

Long-term average millet and sorghum grain yields are, respectively, 400 and 190 kg/ha. In 2002 and 2003, respective cereal production was 3.34 and 3.56 million tons in Niger for millet and sorghum grain yields were respectively 461 and 476 kg/ha (FAO 2004). Research at ICRISAT (1985) showed that in the semi-arid zones of the Sahel where annual rainfall is over 300 mm, nutrients are more limiting than water in crop production. At Sadore (Niger), with 560 mm of annual rainfall, 1.24 kg of millet grain per millimeter of water was harvested without fertilizer and 4.14 kg of millet grain per millimeter of water when fertilizer was used (Bationo et al. 2006).

Experimental Layout

Three sites where ICRISAT conducted studies and where climatic and physical conditions are different were used in this study: Banizoumbou, Bengou and Karabédji. The selected Experiments started in 2001 and are still on going. They are factorial experiments with $3 \times 3 \times 3 = 27$ treatments on 4 replications with 3 levels of phosphorus (0, 13 and 26 kg P/ha), 3 levels of manure (0, 2 and 4 t/ha) and 3 levels of nitrogen (0, 30 and 60 kg N/ha). Climatic data were collected over years: rainfall by using rain gauges at each site and temperature and solar radiation collected from a nearby meteorological station.

The trial was established for calculating the fertilizer equivalency of manure and to compare mineral and organic fertilizers use efficiencies. Manure nutrient composition was analyzed every year and used as inputs in DSSAT. Grain and total dry matter yields were measured in this study and used to compare with simulated data. Because DSSAT v4.02 did not have a phosphorus model, we used GENSTAT to analyze P responses and DSSAT for analyzing the climatic effect on productivity in this study. Effect of fertilizers, sites and years on millet production can be analyzed and climatic effect can be shown through grain and total dry matter yield comparisons.

Initial conditions are characterized by soil analysis for N, P, and K and were used in DSSAT. Simulations were conducted to show the role of water, fertilizers (mineral and organic) and other climatic factors. Water and fertilizer limitations were estimated to compare the results in different cases and their impact in millet production.

Nitrogen effects are included in DSSAT v4.02 and were used to study this nutrient's effects on millet production. Measured and simulated data were compared and differences were interpreted. Growth stages and water and nitrogen stresses were simulated in DSSAT to compare their respective limitations. We also compared the different rainfall amounts in each growth stage to evaluate the effects of water stress at different stages. In this paper, only the Banizoumbou site was used for the DSSAT simulations, but the other three sites results were also used to analyze and interpret results .

Results and Discussions

Effect of Fertilizers in Millet Production

Overall analysis of data from the three sites over the 2001–2005 years showed that phosphorus was more significant than the other nutrients in millet grain production. P alone accounted for 17% in the total variation followed by manure (8%) and nitrogen (4%). These trends of phosphorus, manure and nitrogen were the same for millet stover production (26%, 13% and 8%, respectively) The factor year accounting for 29% of the total grain plus stover yield variation decreased to only 4% for millet grain production and the site factor accounted for 2% in both stover and grain production. This high variation show that stover production varied less than grain production due to grain losses from bird attacks, which reduced 2001 grain production at Bengou. Other factors such as water stress at grain filling can also affect grain yield. Water stress during the grain filling period is highly important for grain yield and should be highlighted in the simulated results.

Soil fertility levels should be increased as nothing can be done to increase rainfall, but rural populations are very poor and fertilizer costs are very high. In Oumou and Ed Heinemann (2006), Africa accounted for only 3% of the world fertilizer consumption with 13% of world's arable soils and 12% of world's population. Sub-Saharan Africa (excluding south Africa) accounted for less than 1% in the world fertilizer consumption, equivalent to 9 kg/ha compared to an amount of 148 kg/ha in Asia and the Pacific region. In 2002, fertilizer consumption in Niger was only 1.1 kg/ha where 1 t of fertilizer cost $400 compared to $90 in Europe whereas average income in Niger was less than $1 per day making fertilizer unaffordable.

Phosphorus

Millet grain production over the 5 years increased with phosphorus rates, but variations were higher per year, especially in 2003 when yields were higher at all P rates (Fig. 7.2b). Millet stover yields also increased with phosphorus; increases were about the same across years (Fig. 7.2a). If fertilizer were affordable for

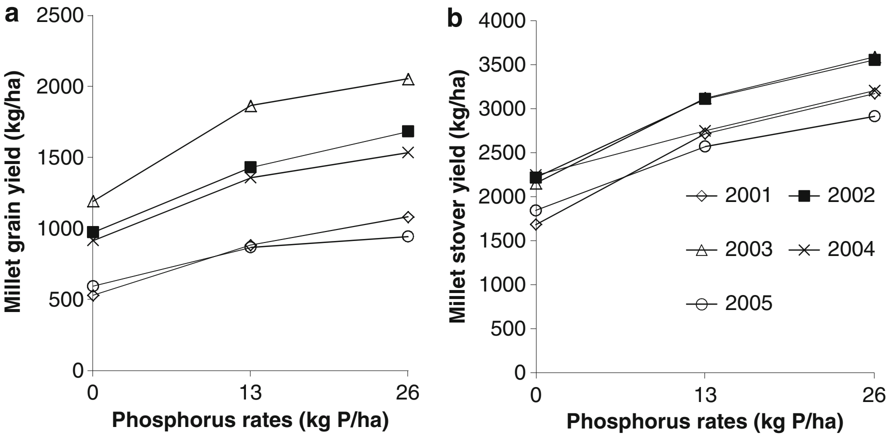

Fig. 7.2 Effect of phosphorus on millet grain (**a**) and stover (**b**) yields

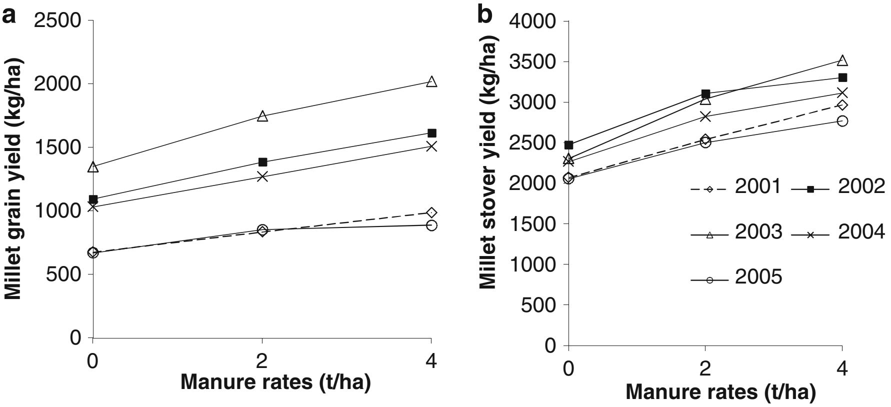

Fig. 7.3 Effect of manure on millet grain (**a**) and stover (**b**) yields

farmers, the hill placement of small quantity (4 kg P/ha) can double millet grain yield. Tabo et al. (2006) showed that a micro-dose of 4 kg P/ha increased millet and sorghum grain yields up to 43–120% and farmer's income were improved by 52–134% in the studied countries (Burkina Faso, Mali and Niger).

Manure

Similar to phosphorus, manure use showed that grain yields varied over years and increased with high manure application rates. In 2003, grain yield was higher but stover yield remained about the same as in other years (Fig. 7.3).

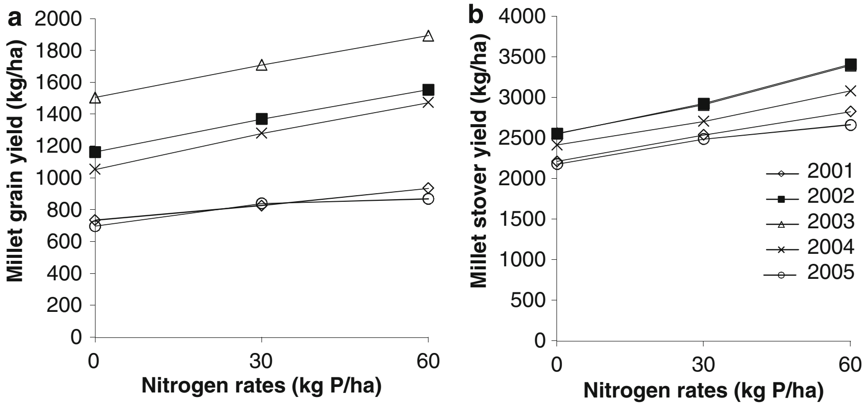

Fig. 7.4 Effect of nitrogen on millet grain (**a**) and stover (**b**) yields

Nitrogen

Nitrogen treatments resulted in the same variability on grain yield as phosphorus and manure and the same trends on millet stover production (Fig. 7.4). The best grain yields were observed in 2003.

Effect of Sites on Millet Production

Overall, the site factor accounted for only 1.6% of the total variation. The same trends were observed in the grain production with 17.8% and 4% of the variation, respectively, for the phosphorus and manure treatments. But the year factor became highly significant with 29% of the total variation and decreased to only 4% for the millet stover while other factors (P, manure and N) accounted for 26%, 13% and 8% of the variation, respectively. Millet stover production was about the same over the years, meaning that only grain yields show a significant year-year variation.

Fertilizers and Sites

Phosphorus

Phosphorus effects on grain production was more important at Bengou than at the others sites where there were similar grain production levels (Fig. 7.5). Stover production was reversed at Bengou, which registered the lowest yield although the annual rainfall was higher.

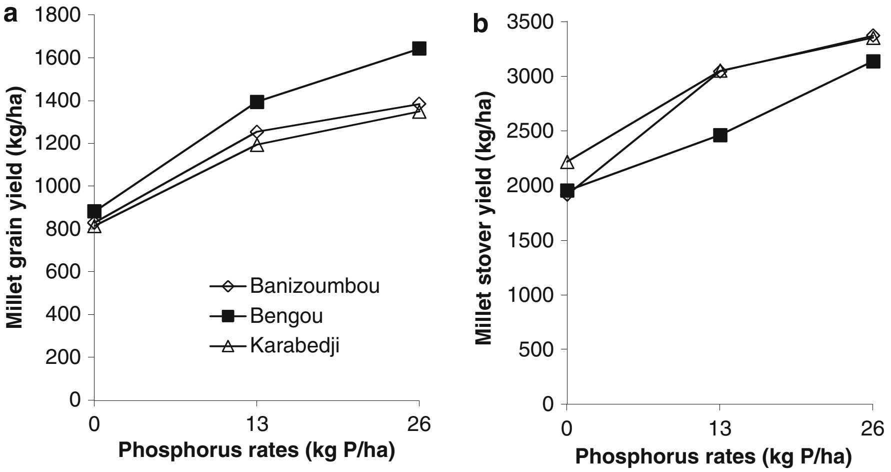

Fig. 7.5 Effect of phosphorus on millet grain (**a**) and Stover (**b**) yields in three sites

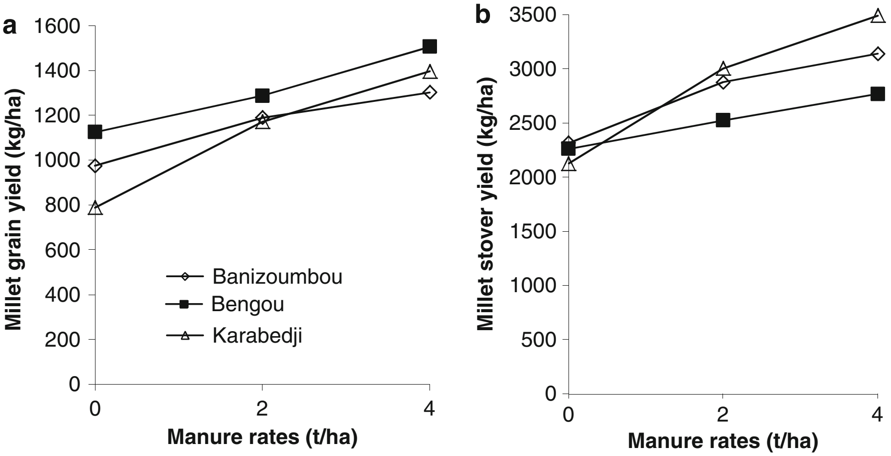

Fig. 7.6 Effect of manure on millet grain (**a**) and stover (**b**) yields in three sites

Manure

Manure effect was the same under the three sites with only a small increase in millet grain production at Bengou (Fig. 7.6).

Nitrogen

Compared to phosphorus and manure effects, the nitrogen effect was lower at Bengou but showed the same effects as the other sites on millet grain production. This effect is reversed in stover production. Fertilizers showed that their effectiveness was higher

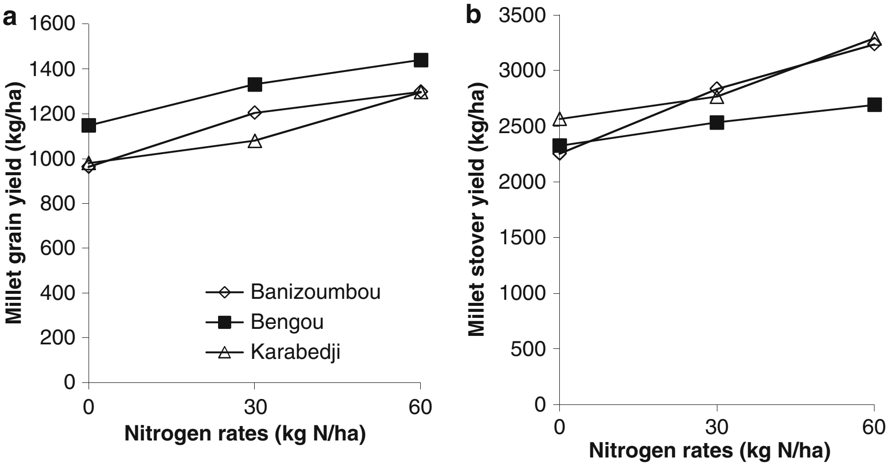

Fig. 7.7 Effect of nitrogen on millet grain (**a**) and stover (**b**) yields in three sites

on grain production at Bengou than at the other sites where the nutrients seemed to be used during vegetative plant growth to produce more biomass (Fig. 7.7).

Water and Fertilizer Use Efficiencies

Water Use Efficiency (WUE)

Water use efficiency (WUE) was increased with fertilizer use. The mean over 5 years was only 0.6 kg of grain per millimeter of water for the control and 2.1–2.6 kg of grain per millimeter of water when fertilizer was used. WUE in 2003 was the best over the 5 years, demonstrating a good correlation between WUE and yields. WUE is higher at Bengou where it increases to 3.6 kg of grain per millimeter of water.

Fertilizer Use Efficiency (FUE)

Compared to WUE, FUE was higher with low rates of fertilizer and the trends were the same at the 3 sites. PUE was 2–3 times higher than NUE (nitrogen use efficiency), confirming that phosphorus was the most limiting factor in millet production at the studied sites. FUE was also higher in 2003 and poorer in 2005 for both phosphorus and nitrogen.

Correlation Between WUE, FUE and Yields

A good correlation of WUE and grain yield was observed with different fertilizer sources ($r^2 = 1$): high WUE gives high yields. But there is no good correlation between FUE and grain yield (Fig. 7.8).

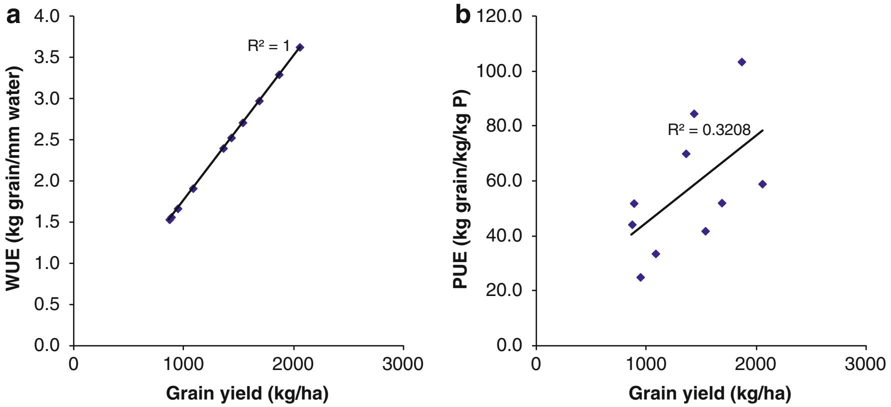

Fig. 7.8 Water (**a**) and phosphorus (**b**) use efficiency

Other Site Factors

Since fertilizer effects vary over the different sites, each one should have its own characteristic such as initial soil conditions. Bengou had higher responses to fertilizer; but no correlation was found to prove that this was due to the high rainfall specific to that site. On all other sites, high yield was not a consequence of high rainfall, but good rainfall distribution did result in high yield in 2003 for all three sites. In addition, Bengou showed higher soil fertility values than the two other sites as was shown in Table 7.2.

Year Effects on Millet Production

As expected, millet yields varied from year to year (Fig. 7.9). Important factors for these include rainfall, temperatures, solar radiation, wind, and crop pests and diseases. The first three factors are used in DSSAT and should be more characteristic of a particular year than the others. The agrometeorological variables are the main data for crop simulation model: minimum and maximum temperatures, solar radiation and total rainfall (Hoogenboom 2000). The other factors can also contribute to yield levels, such as bird attacks that occurred in 2001 at Bengou. Wind, a source of soil degradation and erosion, can also affect crop productivity.

In this sites, millet grain yield varied over years while stover yields were stable. Yields were high in 2003 but annual rainfall was not (except for Banizoumbou). It is clear that rainfall contributes to millet production, but it is not the only important factor affecting millet production.

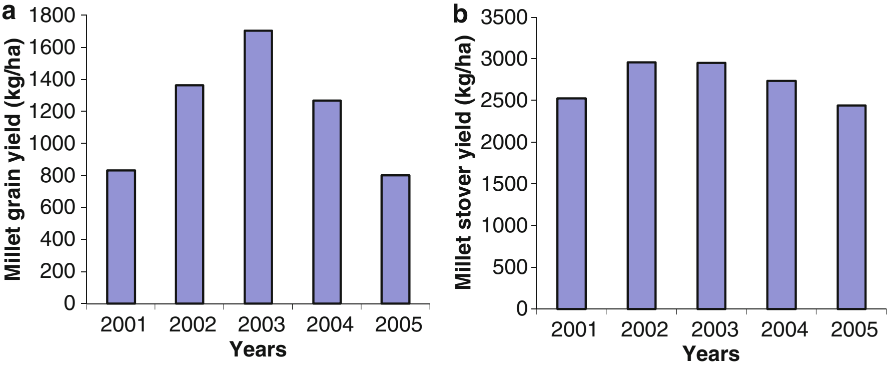

Fig. 7.9 Annual millet grain (**a**) and stover (**b**) yields observed in three sites

Over years, phosphorus, manure and nitrogen accounted for 45%, 22% and 11% of the total variation of millet grain production, respectively. They accounted respectively for 26%, 13% and 8% of the total variability while the site factor accounted for only 4% and 2% for grain and stover production, respectively.

Factors Other Than Rainfall

Temperature

Minimum and maximum temperatures of Katanga used for Karabédji and Banizoumbou followed the same trends over the 5 years. Temperatures were high from March to May, low from June to August, increased in September to October, and decreased again from November to February. In 2003, temperatures varied from the general trends with the lowest temperatures among all years except from July to September when temperatures are generally low but were high in 2003. In 2005 temperatures were in general higher than normal. Grain production was high in 2003 and low in 2005, showing a correlation between temperatures and grain production.

At Bengou, minimum temperatures were higher than the other sites but followed the same trends with long periods of low temperatures during the rainy season. High yields were observed during 2003 when temperatures were low and low yields during 2005 when temperatures were high.

Solar Radiation

No particular effect was observed with solar radiation, but it decreased at Gaya particularly from April to September corresponding to the low temperature period.

In general solar radiation affects panicle initiation duration as shown by Alagarswamy et al. (1998) in the experiment on sorghum varieties where young plants become photoperiod sensitive. When solar radiation is high, panicle initiation occurs more rapidly. But there was not much variation of solar radiation among sites or years in this study. Also, there was no significant variation in panicle initiation among the sites, years, and treatments in this study.

Other Rainfall Factors

Mostly, high rainfall is needed for rainfed crops to produce high yields. But millet yield may not be highly correlated with total seasonal rainfall due to the importance of other factors and due to the timing of rainfall events and related drought periods during a season. For example, at Banizoumbou, from planting to harvest, only 269 mm of rain was received in 2001 but millet yield was higher in 2001 than in 2005 when 353 mm was received. In 2005, more dry spells occurred than in 2001; timing of rain is very important in millet production.

Annual Rainfall

Annual rainfall and crop yield are not well correlated. If so, Banizoumbou, Karabédji and Bengou yields should have been highest in 2002, 2002 and 2001, respectively. However, for the three sites, 2003 had the highest yield even though rainfall that year was not the highest.

Rainy Season Length

When rainfall and monthly rain frequency and season length were analyzed, it was clear that high variations in grain yield were due to dry spells during the grain-filling period. Local varieties with long cycles of 110–120 days started their grain filling around 70–80 days after sowing, and any dry spell after this time can affect negatively millet grain production. ICRISAT research on millet varieties comparing grain filling in drought conditions has shown lower grain weights by 22% in 1988 and 27% in 1989. Treatments under water stress have shown a short grain filling period compared to irrigated ones.

At Banizoumbou and Karabedji, some dry spells occurred during the grain filling period (10–13 days) and during the whole cycle. In 2003, the longest dry spell was only 5 days during the grain filling period and grain yield was high compared to the other years. At Bengou, a long dry spell occurred in 2005, from 58 days after sowing (DAS) until harvest, and grain yield was considerably decreased.

Soil fertility affects millet production more than climatic factors at these sites, although it varies over years. 2003 and 2005 have shown some particular maximum and minimum yields due to some particular low and high temperatures, affecting water balance during the crop cycle.

Growth Development and Water Stress

Water and nitrogen stress analyses showed that farmers' practice (no fertilizer or manure applications) was not affected by water stress, but that nitrogen stress started at 20 DAS to harvest. It's clear that water was not the most limiting factor for farmers' practice, but that fertilizer was in this study.

In West Africa, drought risks are more related to the mean annual rainfall. With increasing annual rainfall, the percentage frequencies of short dry spells increases while the frequencies of long dry spells decreases. In general, dry spells around panicle initiation are higher than those during the flowering phase, particularly for locations with low rainfall. The dry spells become progressively longer at some point during the grain-filling phase. At low-rainfall locations, this occurs much earlier than at locations with higher rainfall (Sivakumar 1991).

Water stress was particularly high for the 60 kg/ha N treatment in 2001, 2004 and 2005. Annual rainfall for these years showed durations of 98, 75 and 107 days, respectively. The shortest rainfall duration was observed in 2004 but the lowest yield was in 2005, meaning that high temperatures in 2005 also affected water balance and yields.

Yields and Plant Growth Simulations

Simulations showed biomass development and grain formation during the growth cycle. Simulated yields were higher than observed ones except for farmers' practice (N0) where the simulated yields were sometimes lower (Tables 7.3 and 7.4). The higher simulated yields may be explained by the inability of the model to simulate phosphorus since the millet model in DSSAT did not have a P component. Phosphorus is an important nutrient in western Africa and Bationo et al. (2006) showed that nitrogen and manure applications are more efficient when combined with P.

Conclusion

There is always risk in rainfall crop production. In millet, crops under fertilizer treatments are more affected by water stress as shown by DSSAT simulations. During the 5 years of experiments, crops were never destroyed by water stress and yield was increased by the use of fertilizer in all cases. The farmer's practice was not

Table 7.3 Grain yields simulated (*S*) and measured (*M*) of treatments N0, N30 and N60 (Banizoumbou, 2001–2005)

Year	2001		2002		2003		2004		2005	
Trts	S	M	S	M	S	M	S	M	S	M
N0	104	290	353	339	264	365	201	354	433	328
N30	1,145	520	1,401	750	1,256	500	710	615	1,285	542
N60	1,300	635	2,522	542	2,372	584	965	908	1,996	526

Table 7.4 Stover yields simulated (*S*) and measured (*M*) of treatments N30 and N60 (Banizoumbou, 2001–2005)

Year	2001		2002		2003		2004		2005	
Trts	S	M	S	M	S	M	S	M	S	M
N0	293	1,275	1,671	1,238	1,147	1,458	858	1,523	1,862	1,523
N30	4,421	2,040	8,202	2827	7,376	1,937	5,313	2,289	6575	2,289
N60	6,046	2,280	13,025	2,867	12,266	2,575	8,585	2,508	9,397	2,508

Trts treatments

affected by water stress caused by dry spells because of the more limiting effects on nutrients. This means that annual rainfall was enough for millet crops under farmer's practices, and fertilizer (especially P) is more limiting since crop yields under fertilizer were improved even though some dry spells occurred during the cropping season. It was also shown that only water stress during the grain filling period affected millet grain yield and stover production was not affected by dry periods during grain filling. Farmer's practice was always deficient in nutrients with and without water stress.

Water stress affecting crop yield occurred in September corresponding to the end of the rainy season. Although we cannot control weather, we can adapt our cropping systems to get the maximum benefit from rainfall. If millet production is low in Niger, it is mainly because high producing technologies adapted to the weather conditions are not adopted by farmers. Simulations on nitrogen have showed that simulated yields were always better than yields under farmer's practice, indicating that there is potential to increase millet yields by adding N fertilizer. However, the simulated responses to N were higher than measured, mainly due to the fact that P is a major limiting factor in these studies and the DSSAT model did not include this factor. This highlights the fact that there is a need to incorporate a soil P model to address the major nutrient limitation in these soils.

If water is limiting to crop production, others factors also contribute in the Sahelian context. Although annual rainfall was sometime higher in the studied sites, yields were still lower. DSSAT is a tool that can be used to determine which factors most affect crop production, especially N fertilizer and water. Simulated and measured data can be compared to select high productive systems. It would be also good to extend the study area to other agro-climatic zones.

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