ON-FARM YIELD AND WATER USE RESPONSE OF PEARL MILLET TO DIFFERENT MANAGEMENT PRACTICES IN NIGER

A Dissertation

by

COMFORT MANYAME

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

December 2006

Major Subject: Soil Science

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Approved by:

Co-Chairs of Committee,	William A. Payne James L. Heilman
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ABSTRACT

On-farm Yield and Water Use Response of Pearl Millet to Different Management Practices in Niger. (December 2006)
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M.Phil., University of Zimbabwe
Co-Chairs of Advisory Committee: Dr. William Albert Payne
Dr. James L. Heilman

Pearl millet [*Pennisetum glaucum* (L.) R.Br.] production under subsistence farmer management on the sandy soils of southwestern Niger is faced with many challenges, including declining soil fertility, highly variable and scarce rainfall and poor resource base of the peasant farmers in the region. This study was conducted to evaluate the potential of management to increase yield and water use efficiency of pearl millet grown on two farmers' fields in Niger during two growing seasons, 2003 and 2004.

The management practices tested were: 1) Five manure treatments (no manure, transported manure, current corralling, a year after corralling, and two years after corralling); 2) The microdose technology (20 kg di-ammonium phosphate ha^{-1}, and 20 kg di-ammonium phosphate ha^{-1} + 10 kg urea ha^{-1}); and lastly, 3) Three different pearl millet cultivars (Heini Kirei, Zatib, and ICMV IS 89305).

In both growing seasons, manure had the greatest effect on the yield and water use of pearl millet at both sites. In 2003 grain yields were 389 kg ha^{-1} in the NM treatment and 1495 kg ha^{-1} in the C0 treatment at Banizoumbou whereas at Bagoua, the NM treatment had 423 kg ha^{-1} vs. 995 kg ha^{-1} in the C0 treatment. In 2004, the NM treatment at Banizoumbou had 123 kg ha^{-1} grain yield and the C0 treatment had 957 kg ha^{-1} whereas at Bagoua the NM treatment had 506 kg ha^{-1} vs. 1152 kg ha^{-1} in the C0 treatment. Residual effects of manure led to grain yields in the C1 and C2 treatments which were more than twice as high as in the NM treatment. The improved cultivars were generally superior for grain yields, whereas the local landrace was superior for straw yields at both sites. Root zone drainage was decreased by between 50 to 100 mm, and water use increased by the same amount in the current corrals at the two sites during the two growing seasons. Increased water use under corralling and presence of residual profile moisture at the end of each of the two seasons suggested that water did not limit pearl millet production at the two sites.

DEDICATION

To my parents Naphtali and Julia, this one is for you…..

Ndinotenda!

ACKNOWLEDGEMENTS

I would like to thank my major professor, Dr. ‘Bill’ Payne for giving me the opportunity to attend Texas A&M University’s graduate school, and for his consistent guidance and help with my research and dissertation write up. His advice and support were invaluable throughout the course of this study.

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CHAPTER I

INTRODUCTION

The Sahel is a region stretching from Senegal to Chad between latitudes 11^o and 15^o south of the Sahara desert. Rainfall in the Sahel is variable, undependable, falls in high intensity storms, and increases threefold from 400 mm in the northern limit to 1200 mm in the extreme south near 12^o N (Sivakumar, 1989; Sivakumar, 1993; D'amato and Lebel, 1998).

Niger is one of the countries situated in the Sahel. The population growth rate of Niger (3.3 %) is one of the highest in the world and 60 % of the population lives below the poverty line (UN World Food Program, 2006). Farmers in Niger rely on rain-fed agriculture to grow pearl millet [*Pennisetum glaucum* (L.) R.Br.] and sorghum (*Sorghum bicolor* L.) as monocrops or intercropped with cowpea [*Vigna unguiculata* (L.) Walp]. Rainfall in Niger is distributed in a single rainy season from May to October, and an annual rainfall average (1921-1990) in the capital city Niamey of 575 mm.

One of the most intensely cropped and productive areas of Western Niger is the Dallol Bosso, which is the fossil valley of the section of the ancient Azaouk River, which runs north-south in Western Niger from 15^o to 12^o N latitude along 3^o E longitude (Wilding and Daniels, 1989). Located between the Niger River Valley to the west, and the Dallol Bosso to the east, is a natural region called the Fakara.

Soils in the Fakara, like in most of the uplands of Western Niger, are generally sandy and prone to forming surface crusts (Casenave and Valentin, 1992).

This dissertation follows the style of Agronomy Journal.

They have low cation exchange capacity (CEC), low organic matter content and have kaolinitic mineralogy (West et al., 1984; Casenave and Valentin, 1992; Manu et al., 1996; Rockström et al., 1998).

Soil properties in farmers' fields are notoriously variable (Scott-Wendt et al., 1988a; Scott-Wendt et al., 1988b; Geiger and Manu, 1993; Wendt et al., 1993; Manu et al., 1996; Voortman et al., 2004) and this translates to variable crop growth and yields. Phosphorus has been singled out as the most important limiting macronutrient for plant growth in these soils (Pieri, 1985) and yield responses to phosphate fertilizer have been shown to be strong with and without nitrogen (Bationo, 1982).

Pearl millet constitutes up to 90 % of Niger's cropped area (Bationo and Mokwunye, 1991a) but average grain yields under subsistence farmer management remain low, varying from 150 to 550 kg ha^{-1} (McIntire and Fussel, 1989; Sivakumar and Salaam, 1999). Efforts to raise millet yields under subsistence farmer management need to address both water and nutrient management because their interaction has been shown to be of paramount importance. Because of prohibitive cost, fertilizer use is very limited making manure the primary source of soil nutrients (Wezel and Haigis, 2002; Schlecht and Buerkert, 2004). However, manure applied on farmers' fields has been shown to be of poor quality (de Rouw and Rajot, 2004a) and to be in small quantities because of poor pasture quality and low number or cattle per cropped area (Ayantunde, 1988). Under the context of subsistence farmer management, others have proposed applying very little amounts of fertilizer under a technology called microdose. Studies evaluating the microdose technology (AgJournal, 2001; NUTMEN/GEMS, 2002) have so far concentrated only on its effect on millet yields and not on the water balance. Given the poor resource base of most subsistence farmers in Niger and the fact that manures are not always applied especially to fields far from the homestead (Prudencio, 1983), it seems appropriate to study the residual effects of manure on millet yields and water balance of farmers' fields.

In light of this, this study evaluated millet yield and water use response to different soil and crop management practices on farmers' fields in two villages in the Fakara during 2003 and 2004. The main objectives of the study were:

1. To evaluate millet yield response to microdose, millet cultivar, manure, and residual effects of manure, one and two years after application.
2. To evaluate the effects of manure, millet cultivar and microdose on the water balance of sandy soils grown to pearl millet, on farmers' fields in the Fakara region.

CHAPTER II

PEARL MILLET RESPONSE TO FERTILIZER AND MANURE UNDER SEMIARID CONDITIONS OF NIGER

Pearl millet is the staple cereal of Niger, constituting up to 90 % of the cropped area (Bationo and Mokwunye, 1991a), yet average grain yields under subsistence farmer management remain low, varying from 150 to 550 kg ha^{-1} (McIntire and Fussel, 1989; Krogh, 1997; Sivakumar and Salaam, 1999). The low grain yields are a result of a myriad of factors including nutrient losses via wind erosion (Bielders et al., 2002), declining and inherent poor soil fertility (West et al., 1984; Manu et al., 1991; Casenave and Valentin, 1992; Manu et al., 1996; Rockström et al., 1998; Bielders et al., 2002), unimproved pearl millet cultivars, and unreliable and erratic rainfall which usually falls in high intensity storms (Sivakumar, 1989; Sivakumar, 1993; D'amato and Lebel, 1998).

Subsistence farmers in Niger have traditionally fallowed their fields and/or applied manures to replenish soil fertility (Bationo et al., 1993; Powell and Williams, 1993). However, fallows have been shortening or disappearing altogether (Berger, 1996; Wezel and Boecker, 1998; Wezel and Haigis, 2002; Schlecht and Buerkert, 2004) because of growing food demand imposed by a rapidly increasing population which is not being met with a proportional increase in cereal production (Garba and Renard, 1991; Sanders et al., 1996; Subbarao et al., 2000). Manures have since become the most important soil fertility management option for subsistence farmers in this Sahelian country (Powell and Williams, 1993). A common practice of manure application amongst the subsistence farmers is corralling (de Rouw and Rajot, 2004a; Schlecht and Buerkert, 2004), during which animals are left overnight to graze recently harvested pearl millet fields. The practice has been shown to lead to deposition of between 3 and 14 Mg manure ha^{-1} or roughly 43-199 kg N ha^{-1} and 4.8-22.4 kg P ha^{-1} (Brouwer and Powell, 1995; Brouwer and Powell, 1998; Gandah et al., 2003; Schlecht et al., 2004). Corralling has been shown to have residual effects on soil nutrient levels and pearl millet yields under controlled conditions (Powell et al., 1998), yet only a few studies e.g. Schlecht et al., (2004) have tested this on-farm.

Whilst the benefits of using organic and/or inorganic fertilizers in the subsistence farming systems of Niger have long been recognized (Bationo and Mokwunye, 1991b; Bationo et al., 1992; Bationo et al., 1993; Powell et al., 1998; Bationo and Buerkert, 2001), prohibitive fertilizer costs (Bationo et al., 1997; Haigis et al., 1999; Abele and von Oppen, 2000) and limited access to manure (Wezel and Haigis, 2002; Schlecht and Buerkert, 2004) have hindered their widespread use. It is against this backdrop that others have proposed using very small quantities of inorganic fertilizer, or the so called "microdoses", to raise the yields of pearl millet under subsistence farmer management. The microdose technology was jointly developed and field-tested by the University of Hohenheim in Germany, ICRISAT, the International Fertilizer Development Center (IFDC), the UN Food and Agriculture Organization (FAO), and Niger's Institute for National Agricultural Research (AgJournal, 2001; NUTMEN/GEMS, 2002). Whether application of fertilizer at rates that are far less than the recommended rates of 15-20 kg P ha^{-1} and 30 kg N ha^{-1} (Bationo and Mokwunye, 1991a; Bationo et al., 1992; Abele and von Oppen, 2000) can substantially raise yields in the absence of manure has yet to be extensively tested on farmers' fields.

The main objective of this study was to compare on-farm pearl millet yield under different manure and fertilizer treatments which included the "microdose" and the "no input system" practiced by some subsistence farmers. The specific objectives were; 1) To evaluate the residual effects of corrals, one and two years after application; 2) To test the effectiveness of "microdoses" of inorganic fertilizer in raising pearl millet yields under conditions of high and low soil fertility at two village sites; and 3) To test pearl millet cultivar effects on grain and straw yields under subsistence farmer management in the Fakara region by comparing the local landrace to two improved cultivars.

Materials and Methods

Banizoumbou and Bagoua village territories

The two study sites in the Fakara were Banizoumbou and Bagoua. Banizoumbou is a village located at coordinates $13^{o}31$'N and $2^{o}39$'E, 65 km east of Niger's capital city, Niamey. The second village, Bagoua, is located at $2^{o}46$' E and $13^{o}29$' N, 12 km south east of Banizoumbou. The climate of the Fakara is hot and semi-arid with a unimodal rainfall distribution. Most of the rain falls between June and September, with an average annual amount of 500 mm (Le Barbe and Lebel, 1997). Soils in the study sites are classified as Psammentic Kandiustalfs (Soil Survey Staff, 1975; Heil et al., 1997). Pearl millet, [*Pennisetum glaucum* (L.) R.Br.] is the major crop grown in the two villages. Rainfall at Banizoumbou was 473 mm in 2003 and 472 in 2004. Bagoua received 452 mm in 2003 and 432 mm in 2004.

Characterization of soil chemical properties

Soil sampling of a farmer's fields in each of the two villages was done using a stratified random sampling method. For chemical analyses (C, N, P, pH, CEC) only the surface 20 cm of soil were considered since this is where most of the change in soil chemical properties is expected (Geiger et al., 1992). Soil organic carbon content was determined by the Walkley Black method (Walkley and Black, 1934); available P was determined using the Bray No 1 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.

Field experiment

A factorial experiment in a randomized complete block design was set up in farmers' fields (and managed by the farmer under the supervision of an ICRISAT technician) at both Bagoua and Banizoumbou during the 2003 growing season and maintained throughout the 2003 and 2004 seasons. Experimental factors were manure, fertilizer, and cultivar. The five different manure treatments were: Two years since last corralling, *C2*; 1 year since last corralling, *C1;* current corralling, *C0*; transported manure, *TM*; and finally, no manure, NM. The three fertilizer treatments were: a control with no fertilizer application; 20 kg ha^{-1} di-ammonium phosphate (DAP) supplying 3.6 kg N ha^{-1} and 3.85 kg P ha^{-1}; and 20 kg ha^{-1} DAP + 10 kg ha^{-1} Urea supplying 8.2 kg N ha^{-1} and 3.85 kg P ha^{-1}. Finally, the three pearl millet cultivars were the local landrace, Heini Kirei, and two improved cultivars Zatib and ICMV IS 89305. In the field layout of the experiment, each of the manure treatments constituted a block, individual plot size was 10 x 10 m, and each treatment was replicated thrice.

In 2003, sowing was done after the first major rains greater than 20 mm on day of year (DOY) 165 at both sites. For the 2004 season, sowing was done on DOY 139 at Bagoua and on DOY 181 at Banizoumbou. The delayed sowing at Banizoumbou was due to labor constraints. Poor emergence led to replanting in the NM, C2 and C0 treatments, 33 days later on DOY 172, at Bagoua. Plants were thinned to 3 plants per hill (30 000 plants ha^{-1}) 14 days after sowing at both sites. Weeding was done twice during the season at both sites using the traditional hand hoe (hilaire). Plots were harvested on DOY 281 at Banizoumbou and DOY 287 at Bagoua in 2003 and in 2004 harvesting was done on DOY 287 at Banizoumbou and DOY 270 at Bagoua. The border rows in each plot were not harvested and hence the harvested area per plot was 81 m^2. The pearl millet heads and straw from each plot's two diagonal rows (the sample) were harvested, set aside, and the fresh weight recorded. The heads and straw from the rest of the plot were also harvested and the fresh weight recorded. Samples (grain plus straw) were then left to dry in the sun and the dry weight recorded. The same was done to the rest of the plot. The heads from the sample were then thrashed and grain weight obtained. The head and straw weight per plot were then calculated as the ratio of the sample dry to fresh weight multiplied by the total fresh weight per plot. The ratio of the sample's grain to head weight was multiplied by the total head weight per plot to obtain the grain weight per plot.

Statistical analyses

Differences in pearl millet yields due to treatments were determined using the analysis of variance (ANOVA) of the general linear model (GLM) procedures (SPSS for Windows, Release 12.0, 2004, Chicago: SPSS Inc.) and effects were considered as significant at a probability level of ≤ 0.05. For ANOVA, the model used was:

$$\text{Yields} = \text{Constant} + \text{Manure} + \text{Fertilizer} + \text{Cultivar} + \text{Fertilizer} * \text{Cultivar} + \text{Error} \qquad [2.1]$$

and for the within-manure treatment analyses the following model was used:

$$\text{Yields} = \text{Constant} + \text{Fertilizer} + \text{Cultivar} + \text{Fertilizer} * \text{Cultivar} + \text{Error} \qquad [2.2]$$

where Manure represents the block effect, and Fertilizer*Cultivar represents the interactive effect of fertilizer and cultivar.

Results

Soil chemical properties

The analytical data in Table 2.1 agree well with those previously reported in either the same villages or within their vicinity (de Rouw, 2004; de Rouw and Rajot, 2004a; de Rouw and Rajot, 2004b). The acid pH of these soils has been attributed as one of the main causes for poor pearl millet growth (Wendt, 1986). Available P was less than the critical level of 8 mg kg^{-1} (Bationo et al., 1989b); only at Bagoua did the maximum P content exceed 8 mg kg^{-1}. Organic C was also very low, as anticipated under high temperature conditions and in sandy soils where organic matter decomposes rapidly (Feller and Beare, 1997) and also due to the generally low organic inputs into the soil under subsistence farmer management. Bagoua had higher maximum total N whereas Banizoumbou had higher CEC.

Pearl millet yields at Banizoumbou in 2003 and 2004

Table 2.2 shows the ANOVA for treatment effects on grain and straw yields during both seasons at Banizoumbou. Pearl millet yields responded only to manure in 2003 and to manure, fertilizer, and cultivar in 2004. In both growing seasons, manure had the largest effect on yields as shown by its large sum of squares, followed by fertilizer and lastly pearl millet cultivar. Individual ANOVA of the manure treatments (Appendix A-1) revealed that in 2003 grain yields did not respond to either fertilizer or pearl millet cultivar in all but the NM treatment where yield responded only to fertilizer.

Grain yields responded to microdose only in the NM treatment in the ICMV IS 89305 cultivar where yields were increased by about 300 kg ha^{-1} (Fig. 2.1). Generally there was very little to no yield response to fertilizer at this site probably because of the small quantities of fertilizer applied. Studies in the region have shown that pearl millet yields respond to N fertilization only if the critical P requirements are met (Bationo and Mokwunye, 1991a; Muehlig-Versen et al., 2003). Whilst small quantities of fertilizer were used in the fertilizer treatments (4 kg P and N ha^{-1} vs. the recommended 15 – 20 kg P ha^{-1} and 30 kg N ha^{-1}) high quantities of manure were applied in the corralling and TM treatments (up to 8 Mg ha^{-1}) further confounding the effects of fertilizer as has been previously shown (Ikpe and Powell, 2002).

In 2004, pearl millet yields responded significantly ($p<0.05$) to fertilizer in the low fertility treatments C2 and NM as well as the TM treatment (Appendix A-1). This response, was greatest (~ 200 kg ha^{-1} more) in the C2 and TM treatments and small in the NM treatment where yields were lowest as reflected in Fig. 2.2. Yield response to pearl millet cultivar was observed only in the TM and C0 treatments.

Pearl millet straw yields responded only to manure in the 2003 growing season. Manure had very large sum of squares and explained most of the yield variation. In the subsequent season straw yields responded to manure and fertilizer treatments but not to pearl millet cultivar and once again manure accounted for most of the yield response.

Table 2.1. Analytical data of soil at 0-20 cm for Banizoumbou and Bagoua at the beginning of the 2003 season.

	Banizoumbou				**Bagoua**			
Soil property	**min.**	**mean†**	**max.**	**sd**	**min.**	**mean**	**max.**	**sd**
pH	**4.7**	**4.8**	**5.3**	**0.2**	**4.5**	**5.1**	**5.6**	**0.4**
CEC (Cmol$_c$ kg^{-1})	**0.7**	**1.0**	**1.4**	**0.2**	**0.2**	**0.7**	**1.2**	**0.3**
Organic C (g kg^{-1})	**1.0**	**1.3**	**1.7**	**0.2**	**1.1**	**1.5**	**2.2**	**0.3**
N (mg kg^{-1})	**116**	**143**	**179**	**19**	**115**	**155**	**210**	**33**
P (mg kg^{-1})	**1.8**	**3.4**	**7.2**	**1.5**	**2.3**	**4.3**	**8.9**	**2.1**

†Means and standard deviations are for five data points each representing a manure treatment.

Table 2.2. ANOVA for treatment effects on grain and straw yields at Banizoumbou in 2003 and 2004.

	Year	Source of variation	SS	df	MS	F	Sig.
Grain	**2003**	**Manure**	**18092572**	**4**	**4523143**	**42.7**	**0.000**
		Fertilizer	**176389**	**2**	**88194**	**0.8**	**0.437**
		Cultivar	**477052**	**2**	**238526**	**2.3**	**0.109**
		Fertilizer * Cultivar	**1064791**	**4**	**266198**	**2.5**	**0.045**
		Error	**12911630**	**122**	**105833**		
	2004	**Manure**	**11836188**	**4**	**2959047**	**47**	**0.000**
		Fertilizer	**1832182**	**2**	**916091**	**14.6**	**0.000**
		Cultivar	**1108503**	**2**	**554251**	**8.8**	**0.000**
		Fertilizer * Cultivar	**205680**	**4**	**51420**	**0.8**	**0.516**
		Error	**7675261**	**122**	**62912**		
Straw	**2003**	**Manure**	**312622454**	**4**	**78155613**	**50**	**0.000**
		Fertilizer	**2729869**	**2**	**1364934**	**0.9**	**0.491**
		Cultivar	**9536248**	**2**	**4768124**	**3**	**0.051**
		Fertilizer * Cultivar	**14104677**	**4**	**3526169**	**2.3**	**0.066**
		Error	**1070586155**	**122**	**1559705**		
	2004	**Manure**	**16162251**	**4**	**4040563**	**39.8**	**0.000**
		Fertilizer	**1903498**	**2**	**951749**	**9.4**	**0.000**
		Cultivar	**317396**	**2**	**158698**	**1.6**	**0.214**
		Fertilizer * Cultivar	**359452**	**4**	**89863**	**0.9**	**0.476**
		Error	**12396644**	**122**	**101612**		

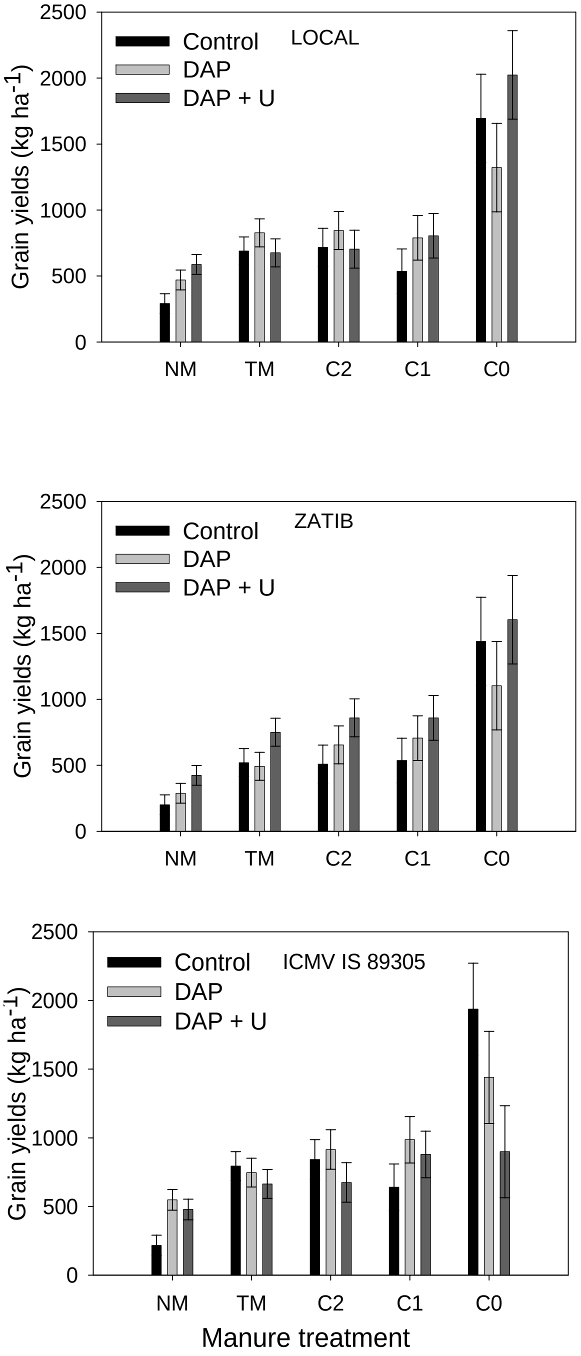


Figure 2.1. Manure and fertilizer effects on grain yields at Banizoumbou in 2003. NM is no manure; TM is transported manure; C2 is two years after last corralling; C1 is one year after last corralling; C0 is the current corral; DAP is di-ammonium phosphate; and DAP + U is di-ammonium phosphate + urea.

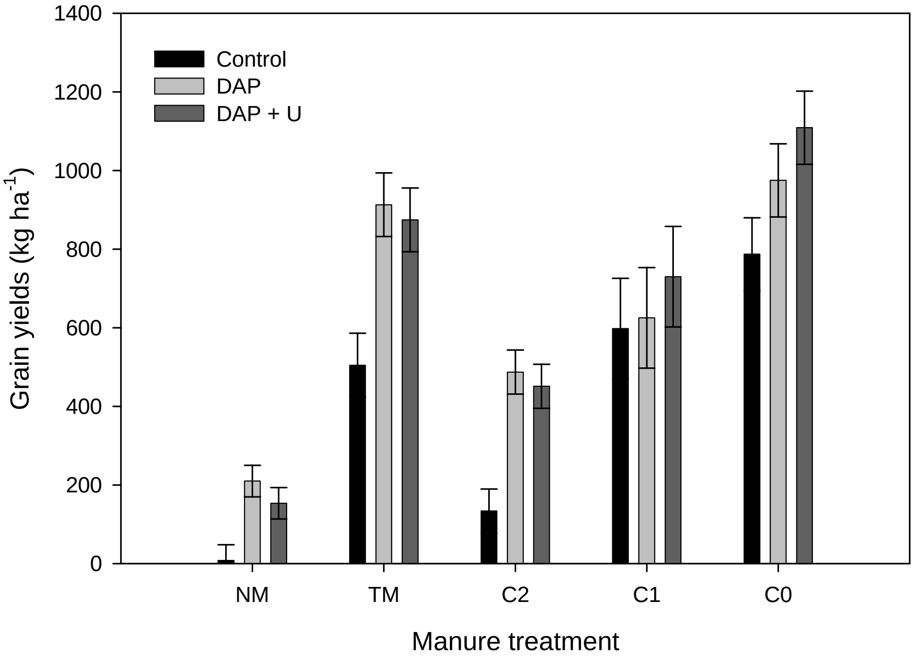


Figure 2.2. Manure and fertilizer effects on grain yields at Banizoumbou in 2004. NM is no manure; TM is transported manure; C2 is two years after last corralling; C1 is one year after last corralling; C0 is the current corral; DAP is di-ammonium phosphate; and DAP + U is di-ammonium phosphate + urea.

Individual ANOVA of the manure treatments showed no straw yield response to either fertilizer or pearl millet cultivar in all but NM in 2003 (Appendix A-2). In 2004, straw yields responded to fertilizer in all but the C0 treatment but did not respond to pearl millet cultivar in any of the manure treatments.

Combined ANOVA (Table 2.3) at Banizoumbou revealed significant differences in grain yields due to year, manure, pearl millet cultivar and fertilizer. Again, the manure treatment explained most of the yield differences as shown by its large sum of squares. This was followed by the effect of year or growing season which may have emanated from the fact that 2004 was not as favorable as 2003. Interaction effects (fertilizer * cultivar; cultivar * year) were significant at this site. This may also be attributed to the difference in the length of the growing seasons and the fact that 2003 received slightly more total rainfall (~40 mm more) after day of planting compared with the 2004 season. For straw, only the manure and year factors led to significant yield differences.

Whilst 2003 was a 'normal' growing season at this site, planting was delayed by 30 days and less total rainfall fell between the day of planting and harvesting in 2004. Pearl millet grain and straw yields in 2004 were consequently lower than in 2003. The response of pearl millet yields to manure treatment in 2003 and 2004 at Banizoumbou is presented in Table 2.4. During 2003, grain yields in the most fertile treatment, C0, were four times higher than in the control, NM, which is representative of some farmers' fields, e.g. those far from the homestead (Schlecht and Buerkert, 2004; Schlecht et al., 2004). In 2004, the C0 treatment resulted in grain yields almost ten times higher than the NM treatment.

The C1 and C2 treatments which measured the residual effects of corrals on pearl millet yields one and two years after last corralling had grain yields twice as high as the control treatment in 2003. In the subsequent season, the C1 treatment had grain yields almost seven times higher than the control whereas grain yields in the C2 were three times higher than the control.

Table 2.3. Combined ANOVA for treatment effects on grain and straw yields at Banizoumbou in 2003 and 2004.

Yield parameter	Source of variation	SS	df	MS	F	Sig.
Grain	Manure	26766453	4	6691613	69.9	0.000
	Year	3961779	1	3961779	41.4	0.000
	Fertilizer	1496263	2	748132	7.8	0.001
	Cultivar	588730	2	294365	3.1	0.048
	Fertilizer * Cultivar	1076170	4	269042	2.8	0.026
	Fertilizer * Year	512307	2	256154	2.7	0.071
	Cultivar * Year	996826	2	498413	5.2	0.006
	Error	23749199	248	95763		
Straw	Manure	213750848	4	53437712	41.7	0.000
	Year	252240782	1	252240782	196.9	0.000
	Fertilizer	4185732	2	2092866	1.6	0.197
	Cultivar	3446888	2	1723444	1.3	0.262
	Fertilizer * Cultivar	447635	2	223817	0.2	0.840
	Fertilizer * Year	6406757	2	3203378	2.5	0.084
	Cultivar * Year	6748940	4	1687235	1.3	0.264
	Error	317714569	248			

The residual effects of corrals were more pronounced under less favorable growing conditions (low rainfall and a shorter growing season) compared with the normal season, 2003. In a study on similar soils in Niger, Schlecht et al., (2004) reported residual effects of corrals on pearl millet yields which lasted for four years and were linear with the amount of manure applied. Powell et al., (1998) evaluated the effects of corralling vs. dung application on sandy soils in Niger and reported higher pearl millet yields in fields which had been corralled once every three years compared with dung only fields. The authors observed that corralled fields benefited from both urine and dung, unlike the dung only treatments. Generally, yield reduction in the corralled fields may be attributed to fast nutrient release and organic matter decomposition reported for Sahelian conditions (Brouwer et al., 1993; Brouwer and Powell, 1998; Esse et al., 2001). However, even with these reductions, yields were still higher in the corralled fields compared with the control, NM, emphasizing the impoverished nature of the soils in the study sites.

For straw yields, the NM and C0 treatments consistently resulted in the lowest and highest yields respectively in both 2003 and 2004. Straw yields in the C0 treatment were five times higher than the control. Fertilizer and cultivar effects on pearl millet yields in 2004 are shown in Table 2.5. Addition of fertilizer was associated with a slight increase in yields but there were no differences between the DAP and DAP + U treatments. The lack of difference between the two fertilizer additions suggests that P may have been more limiting since the additional N supplied by the DAP + U treatment did not seem to lead to higher yields. The improved pearl millet cultivars were also associated with higher grain but not straw yields in 2004.

Table 2.4. Manure treatment effects on pearl millet yields at Banizoumbou. NM is no manure; C2 is two years after corralling; C1 is one year after corralling; C0 is the current corral; and TM is transported manure.

	Grain yields		Straw yields	
Manure treatment	**2003**	**2004**	**2003**	**2004**
		kg ha^{-1}		
NM	**389 a**	**123 a**	**1076 a**	**243 a**
C2	**747 b**	**357 b**	**2462 b**	**441 a**
C1	**749 b**	**651 c**	**2586 b**	**883 b**
C0	**1495 c**	**957 d**	**5802 c**	**1167 c**
TM	**684 b**	**763 cd**	**1791 ab**	**983 bc**

†Mean yields followed by the same letter and in the same column are not significantly different with LSD test at 5 % confidence level.

Table 2.5. Fertilizer and pearl millet cultivar effects on pearl millet yields at Banizoumbou in 2004. DAP is di-ammonium phosphate and DAP + U is di-ammonium phosphate + urea.

Treatment		Grain yields	Straw yields
		kg ha^{-1}	
Fertilizer	Control	406 a	577 a
	DAP	642 b	846 b
	DAP + U	664 b	806 b
Cultivar	Local	452 a	686 a
	Zatib	589 b	737 a
	ICMV IS 89305	672 b	805 a

†Mean yields followed by the same letter and in the same column are not significantly different with LSD test at 5 % confidence level.

Pearl millet yields at Bagoua in 2003 and 2004

ANOVA for treatment effects on pearl millet yield at Bagoua in 2003 (Table 2.6) showed yield response to manure and pearl millet cultivar but not to fertilizer. During the subsequent season, pearl millet yields responded to manure, fertilizer and cultivar treatments. Manure however had the largest effect on grain yields as shown by its large sum of squares.

Individual ANOVA of the manure treatments during the 2003 growing season (Appendix A-3) showed no grain yield response to either fertilizer or pearl millet cultivar in NM, C0, and TM treatments. Pearl millet yields responded only to cultivar in C2 and to both fertilizer and pearl millet cultivar in C1. However, the grain yield response to fertilizer during 2003 was very small as shown in Fig. 2.3. In the following season, pearl millet yields responded to fertilizer in the low fertility treatments NM and C2 (yielding ~ 100 kg ha^{-1} more with fertilizer application) as well as in the TM treatment as shown in Fig. 2.3, whereas response to pearl millet cultivar was observed only in the C2 and C0 treatments. The microdose system tended to increase yields only under conditions of very low soil fertility as persisted in the NM and C2 treatments, but not under high soil fertility conditions e.g. C0.

Straw yields responded to manure and pearl millet cultivar in 2003 with most of the yield variation being attributable to manure. The following season, manure, fertilizer and pearl millet cultivar treatments all had significant effects on pearl millet straw yields. Manure still had the largest influence on yield response.

Individual ANOVA of the manure treatments (Appendix A-4) for the 2003 season showed no straw yield response to fertilizer or pearl millet cultivar in the NM and TM treatments. Yield responded to fertilizer in the C1 treatment and only to cultivar in the C0 and C2 treatments. The interactive effects of fertilizer and cultivar were significant in the C2 treatment. In 2004, straw yields responded to both fertilizer and pearl millet cultivar in the low fertility treatment C2, whereas NM responded only to fertilizer. As observed for grain yields during the 2004 growing season, the low fertility treatments (C2 and NM) benefited more from fertilizer applications.

Table 2.6. ANOVA for treatment effects on pearl millet grain and straw yields at Bagoua in 2003 and 2004.

	Year	Source of variation	SS	df	MS	F	Sig.
Grain	**2003**	**Manure**	**4131123**	**4**	**1032781**	**30.9**	**0.000**
		Fertilizer	**11953**	**2**	**5976**	**0.2**	**0.836**
		Cultivar	**480212**	**2**	**240106**	**7.2**	**0.001**
		Fertilizer * Cultivar	**28942**	**4**	**7236**	**0.2**	**0.929**
		Error	**3837557**	**115**	**33370**		
	2004	**Manure**	**6462679**	**4**	**1615670**	**33.4**	**0.000**
		Fertilizer	**787631**	**2**	**393815**	**8.1**	**0.003**
		Cultivar	**483111**	**2**	**241555**	**5**	**0.008**
		Fertilizer * Cultivar	**99686**	**4**	**24922**	**0.5**	**0.725**
		Error	**5902536**	**122**	**48381**		
Straw	**2003**	**Manure**	**49177133**	**4**	**12294283**	**26**	**0.000**
		Fertilizer	**554477**	**2**	**277238**	**0.6**	**0.557**
		Cultivar	**10264800**	**2**	**5132400**	**10.9**	**0.000**
		Fertilizer * Cultivar	**2069430**	**4**	**517358**	**1.1**	**0.361**
		Error	**57492829**	**122**	**471253**		
	2004	**Manure**	**20464371**	**4**	**5116093**	**24**	**0.000**
		Fertilizer	**4478666**	**2**	**2239333**	**10.5**	**0.000**
		Cultivar	**3810892**	**2**	**1905446**	**8.9**	**0.000**
		Fertilizer * Cultivar	**819305**	**4**	**204826**	**0.96**	**0.432**
		Error	**26035494**	**122**			

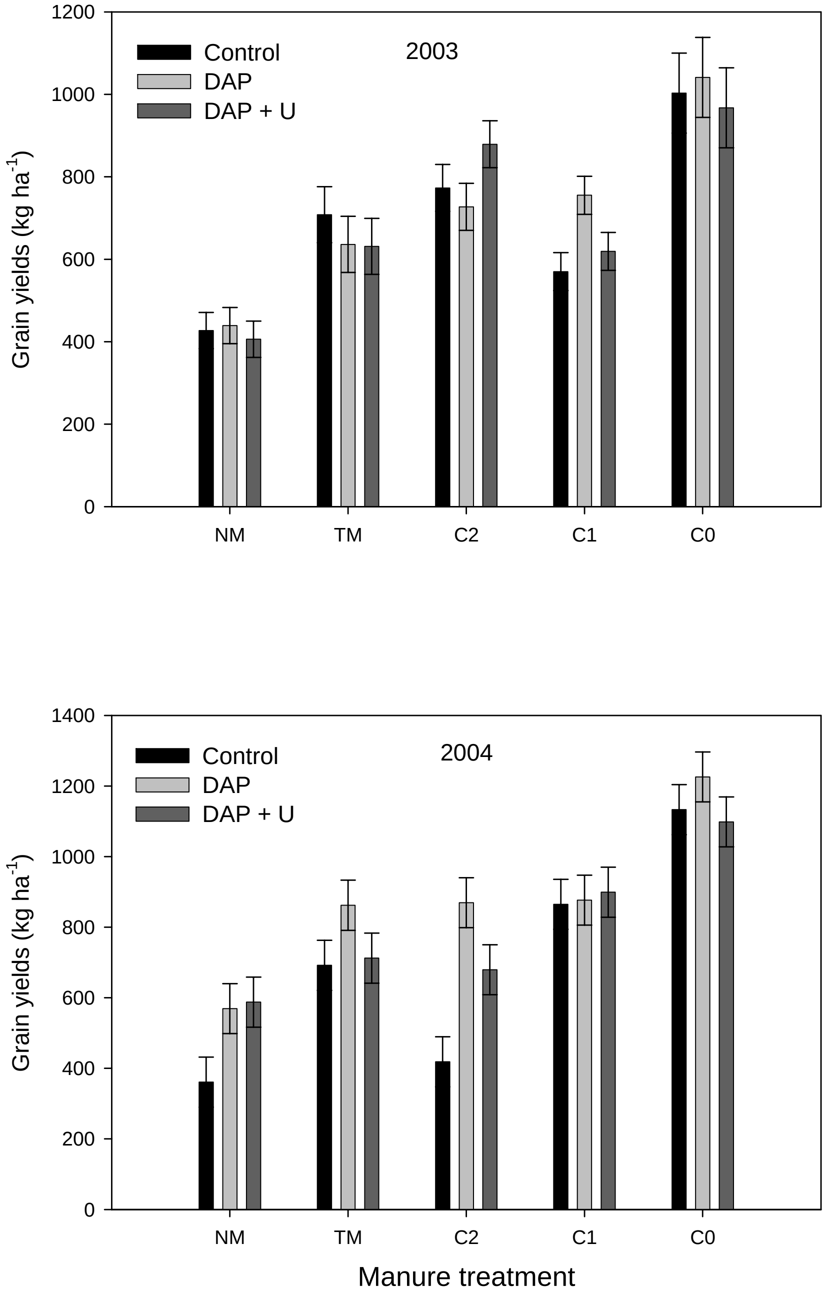


Figure 2.3. Manure and fertilizer effects on grain yields at Bagoua in 2003 and 2004. NM is no manure; TM is transported manure; C2 is two years since last corralling; C1 is one year since last corralling; C0 is the current corral; DAP is di-ammonium phosphate; and DAP + U is di-ammonium phosphate + urea.

Combined ANOVA for the two growing seasons (Table 2.7) showed grain yield response to manure, growing season, fertilizer, pearl millet cultivar and the interactive effects of year * fertilizer and year * pearl millet cultivar. Straw yields also responded to manure, growing season, fertilizer and cultivar but did not respond to their interactive effects.

Treatment effects on pearl millet yields at Bagoua are shown in Table 2.8. The C0 and NM treatments were associated with the highest and lowest grain yields respectively across fertilizer and cultivar treatments for both the 2003 and 2004 growing seasons. Grain yields in C0 were twice as high as in the control, NM. The C1 and C2 treatments on the other hand, resulted in grain yields about one and a half times higher than the control in both seasons.

Grain yield response to the residual effects of corralling at this site was high and yields in the C1 and C2 treatments were similar in both years. This temporal stability of yields contrasted with the Banizoumbou site where yields in 2004 were reduced to half their 2003 levels. On the other hand, straw yields were reduced to half their previous year’s level in the C2 and C1 treatments but were still higher than the control treatment.

Pearl millet yield response to manure at Bagoua was not as high as at Banizoumbou, possibly because the fields used at Bagoua were located close to the farmer’s homestead and may have been manured more frequently from household and animal waste (Prudencio, 1983). Analytical data at the beginning of the 2003 season (Table 2.1) showed higher maximum P, N, and soil pH at Bagoua compared with Banizoumbou.

In the 2003 growing season, which was normal, pearl millet yields (grain and straw) did not respond to fertilizer. As at Banizoumbou this may be explained by the fact that under conditions of high soil fertility and a normal growing season, the fertilizer amounts in the microdose system were not sufficient enough to cause any yield increases.

Table 2.7. Combined ANOVA for treatment effects on grain and straw yields at Bagoua in 2003 and 2004.

Yield parameter	Source of variation	SS	df	MS	F	Sig.
Grain	Manure	9572711	4	2393178	53.6	0.000
	Year	460941	1	460941	10.3	0.001
	Fertilizer	473084	2	236542	5.3	0.006
	Cultivar	517018	2	258509	5.8	0.004
	Year * Fertilizer	303033	2	151517	3.4	0.035
	Year * Cultivar	447195	2	223597	5	0.007
	Fertilizer * Cultivar	23506	4	5877	0.13	0.971
	Error	10761184	241	44652		
Straw	Manure	52790006	4	13197502	32.6	0.000
	Year	19722926	1	19722926	48.7	0.000
	Fertilizer	3827821	2	1913911	4.7	0.010
	Cultivar	12681395	2	6340698	15.7	0.000
	Year * Fertilizer	1205322	2	602661	1.5	0.228
	Year * Cultivar	1394297	2	607148	1.7	0.181
	Fertilizer * Cultivar	585205	4	146301	0.4	0.836
	Error	100379820	248			

Table 2.8. Treatment effects on average pearl millet yields at Bagoua. NM is no manure; C2 is two years after corralling; C1 is one year after corralling; C0 is the current corral;TM is transported manure; DAP is di-ammonium phosphate; and DAP + U is di-ammonium phosphate + Urea.

Treatment		Grain yields 2003	Grain yields 2004	Straw yields 2003	Straw yields 2004
			kg ha^{-1}		
Manure	**NM**	**423 a**	**506 ab**	**1081 a**	**1001 a**
	C2	**793 b**	**656 b**	**2139 b**	**1050 a**
	C1	**648 c**	**880 c**	**1940 b**	**1849 b**
	C0	**995 d**	**1152 d**	**2979 c**	**1773 b**
	TM	**658 bc**	**755 bc**	**2070 b**	**1832 b**
Fertilizer	**Control**	**695 a**	**693 ac**	**1959 a**	**1247 a**
	DAP	**717 a**	**881 bc**	**2115 a**	**1590 b**
	DAP + Urea	**699 a**	**795 c**	**2052 a**	**1666 b**
Cultivar	**Local**	**741 a**	**716 a**	**2423 a**	**1690 a**
	Zatib	**618 b**	**790 ab**	**1781 b**	**1282 b**
	ICMV IS 89305	**753 a**	**863 b**	**1920 b**	**1532 a**

†Mean yields followed by the same letter and in the same column are not significantly different with LSD test at 5 % confidence level.

The following season, pearl millet grain yield response was not consistent with what may have been expected. Response to DAP and DAP + U treatments was similar and the control treatment had similar grain yields as the DAP + U treatment. Straw yields responded positively to DAP and DAP + U treatments. The benefit of urea in the DAP + U treatment was not evident at this site. Minimal response to fertilizer may be explained by the low fertilizer quantities used in the study and better previous management. The local landrace outperformed the two improved cultivars Zatib and ICMV IS 89305 for straw yields but had similar grain yields with ICMV IS 89305. In 2004, Zatib gave the lowest straw yields, and the local landrace and ICMV IS 89305 had similar straw yields.

When the two sites (Banizoumbou and Bagoua) were combined, the ANOVA results (Appendix A-5 and A-6) showed grain and straw yield response to site, manure and cultivar in 2003 and response to site, manure, fertilizer and pearl millet cultivar in 2004. The different response to yields between the two sites may well be attributed to the fact that Bagoua was better managed. This resulted in lower yield response to both manure and fertilizer at this site compared with Banizoumbou.

Table 2.9 summarizes treatment effects on pearl millet harvest indices at the two sites during the two growing seasons. The harvest indices were low, ranging from 0.20 to 0.38, yet common for pearl millet grown under dry land agriculture in the Sahel (Oluwasemire et al., 2002; de Rouw, 2004). The 2004 season had higher harvest indices especially at Banizoumbou. The corralled fields generally gave higher pearl millet grain and straw yields at both sites during the two seasons compared with fields with transported manure. Higher pearl millet yields in the corralled fields can be attributed to two important factors. The first one has to do with the possibility of having more N in corralled fields emanating from both dung and urine (Powell et al., 1998) and the second has to do with more likelihood of leaching and/or volatilization losses of N from manure in the cattle kraals before its transportation to the fields. Manure quality and quantity in the TM treatment varied between farmers. For example, at Banizoumbou in 2004, 90% of the TM was composed of straw and hence may have had little nutritional value.

Table 2.9. Manure, fertilizer and pearl millet cultivar treatment effects on harvest index. NM is no manure; TM is transported manure; C2 is two years since last corralling; C1 is one year since last corralling; C0 is the current corral; DAP is di-ammonium phosphate; and DAP + U is di-ammonium phosphate + urea.

		Banizoumbou		Bagoua	
Treatment		**2003**	**2004**	**2003**	**2004**
Manure	**NM**	**0.24 a**	**0.21 a**	**0.26 a**	**0.29 a**
	C2	**0.21 b**	**0.36 b**	**0.25 ab**	**0.33 b**
	C1	**0.21 b**	**0.35 b**	**0.24 ab**	**0.28 a**
	C0	**0.20 b**	**0.38 b**	**0.23 ab**	**0.34 b**
	TM	**0.25 a**	**0.36 b**	**0.22 b**	**0.26 a**
Cultivar	**Local**	**0.21 a**	**0.30 a**	**0.22 a**	**0.26 a**
	Zatib	**0.21 a**	**0.34 a**	**0.24 b**	**0.33 b**
	ICMV IS 89305	**0.24 b**	**0.35 a**	**0.26 c**	**0.31 b**
Fertilizer	**Control**	**0.22 a**	**0.28 a**	**0.25 a**	**0.30 abc**
	DAP	**0.22 a**	**0.36 b**	**0.24 a**	**0.32 b**
	DAP + U	**0.22 a**	**0.36 b**	**0.24 a**	**0.28 c**

†Mean yields followed by the same letter and in the same column are not significantly different with LSD test at 5 % confidence level.

In general, manure application at both sites, whether through corralling or transported manure, led to higher yields than the control where no manure was applied. Applying dung and urine to the poorly buffered sandy soils of Niger can improve the soil nutrient status as well as soil physical properties (Powell et al., 1998; Ikpe and Powell, 2002). Whilst dung deposits have been shown to mechanically protect the soil by trapping mobile sand during storms thus reducing surface crusting, (de Rouw and Rajot, 2004b) urine has been shown to raise the soil pH, increasing P availability and its subsequent uptake by pearl millet (Powell et al., 1998; Ikpe et al., 1999; Ikpe and Powell, 2002; Muehlig-Versen et al., 2003).

Despite the fact that the experimental design did not allow for formal testing of interaction effects between manure and fertilizer, graphical inspection of Fig 2.1 to Fig. 2.3 suggest no interaction especially at Bagoua in both years and at Banizoumbou in 2003. In the 2004 growing season at Banizoumbou response to the microdose technology seemed to depend on the native fertility of the soil where the NM, TM and C2 treatments had significant yield increases with microdose. Other studies in the region e.g. Bationo et al., (1989a) and Bationo et al., (1993) have shown interaction between organic and inorganic fertilizers.

Discussion

Yield data from this study have confirmed the importance of manure in the subsistence farming systems of south-western Niger which other studies have already shown (Bationo et al., 1989a; Bationo and Mokwunye, 1991b; Bationo et al., 1993; Powell et al., 1998; Ikpe and Powell, 2002; de Rouw and Rajot, 2004a). However, manure quantities as high as those used in this study (up to 8 Mg ha^{-1}) can not be consistently applied year to year by most subsistence farmers in the region. Corralling has been shown to concentrate manure on small areas of the field leading to nutrient losses via leaching (Gandah et al., 2003; Schlecht and Buerkert, 2004; Schlecht et al., 2004). To avoid such losses, farmers can moderate manure quantities by shortening and increasing corralling duration and frequency, but both depend on access to cattle and demand more labor.

Residual effects of corrals were still effective in raising pearl millet yields two years after last corralling. However, in order to sustain high pearl millet yields, frequent corralling may still be required (e.g. after every two or three years) especially under low fertility conditions like at Banizoumbou.

The microdose technology caused significant yield increases but only under harsh conditions (e.g. a shorter growing season, less total rainfall, and no manure applied). At Banizoumbou for example, microdose caused grain yield increase up to 250 kg ha^{-1} in the low fertility treatments (NM, C2 and TM) in 2004 and about the same increase for the ICMV IS 89305 cultivar in the NM treatment in 2003. It is interesting to note that although the transported manure used at Banizoumbou was of poor quality yield increase under TM reached 500 kg ha^{-1} in 2004. If the cost of DAP is assumed to be 240 CFA $kg^{-}1$ and the cost of pearl millet grain to be 100 CFA kg^{-1}, then the microdose technology demands that the farmer invest about 4800 CFA per ha^{-1} of pearl millet grown, a cost which may not be incurred by using transported manure. From this standpoint it appears that farmers at both sites may be better of applying the low quality transported manure than investing in microdose. Initial results of an earlier extensive study on improving crop-livestock productivity through efficient nutrient management in mixed farming systems of semi-arid West Africa (NUTMEN/GEMS, 2002) showed that the increase in yield resulting from microdose (NPK 15-15-15 at 6 g $hill^{-1}$ or 9 kg N, P, and K ha^{-1}) did not pay for the cost of the fertilizer. The same study also showed that on the contrary, increase in yield measured over three years following application of 6 Mg of manure ha^{-1} in corralling largely paid for the cost of corralling and for the impact of corralling on the cropping labor cost leading to a marginal rate of return of the labor investment of 165 %.

The local landrace was generally superior for straw yields and the improved cultivars superior for grain yields at both sites and especially in 2004 which had a shorter growing season.

CHAPTER III

MODELING HYDRAULIC PROPERTIES OF SANDY SOILS OF NIGER USING PEDOTRANSFER FUNCTIONS

Soil hydraulic properties such as the moisture retention curve and hydraulic conductivity (K) control the flux and storage of water in soil making them crucial input parameters in water and solute transport modeling. Knowledge of these properties is needed in many field studies dealing with irrigation and drainage management. Field determination of K and moisture retention curves is often laborious and costly (van Genuchten and Leij, 1992) whilst the K values so determined do not capture the spatial variability under field conditions (Warrick and Nielsen, 1980; Wilding, 1984). This has led to the development and widespread use of indirect methods (Campbell, 1974; van Genuchten, 1980; Rawls et al., 1982; Haverkamp and Parlange, 1986; Vereecken et al., 1989; van Genuchten and Leij, 1992; Rawls et al., 1998; Elsenbeer, 2001; Sobieraj et al., 2001; Suleiman and Ritchie, 2001; Wösten et al., 2001) which are classified as pedotransfer functions (PTFs), which were intended to translate easily measured soil properties like bulk density, particle size distribution and organic matter content into soil hydraulic properties.

PTFs can be categorized into three main groups namely *class* PTFs, *continuous* PTFs and *neural networks* (Schaap, 1999). Class PTFs calculate hydraulic properties for a textural class e.g. sand, by assuming that similar soils have similar hydraulic properties; continuous PTFs on the other hand, use measured percentages of clay, silt, sand and organic matter content to provide continuously varying hydraulic properties across the textural triangle (Wösten et al., 1995). Neural networks are an "attempt to build a mathematical model that supposedly works in an analogous way to the human brain" (Minasny and McBratney, 2002) and were developed to improve the predictions of empirical PTFs (Schaap and Bouten, 1996; Sobieraj et al., 2001; Minasny and McBratney, 2002). In brief, a neural network consists of an input, a hidden, and an output layer all containing “nodes”. The number of nodes in input (soil bulk density, soil particle size data) and output (soil hydraulic properties) layers corresponds to the number of input and output variables of the model (Schaap and Bouten, 1996). The major advantage of neural networks over the two classes described earlier is that they do not require an a-priori concept of the relations between input and output data (Schaap and Leij, 1998). The optimal relations that link input data to output data are obtained and implemented in an iterative calibration procedure (Schaap et al., 2001).

An apparent limitation with the Class PTFs is the fact that they provide an average value of a hydraulic characteristic for each textural class when, in fact, there may be a considerable range of characteristics within a single textural class (Hodnett and Tomasella, 2002). Some PTFs have been incorporated into computer programs like ROSETTA (Schaap et al., 2001) and SOILPAR (Acutis and Donatelli, 2003) where users can choose a PTF based on their level of available inputs.

In general, the performance of PTFs has been shown to be largely dependant on the data used for their calibration (Schaap and Leij, 1998), and caution should always be exercised when using them. This is especially true if predictions are being made for soils that are outside the range of soils used in deriving the PTFs. This has been shown to lead to poor or even inaccurate predictions (Cornelis et al., 2001; Wagner et al., 2001; Wösten et al., 2001; Hodnett and Tomasella, 2002). Spatial variability in soil properties may also decrease the accuracy of predictions made by PTFs as has been shown for saturated hydraulic conductivity, Ks (Tietje and Hennings, 1996; Sobieraj et al., 2001).

Although progress has been made in the development and use of PTFs to estimate soil hydraulic properties in general, to our knowledge there has been very little evaluation of PTFs on the sandy soils of the West African Sahel. Substantive studies of soil hydraulic properties of these soils are available, however, (Vachaud et al., 1978; Hartmann and Gandah, 1982; Vauclin et al., 1983; Payne et al., 1991a) such that evaluation of PTFs for this region should be possible.

This study was carried out to evaluate the performance and suitability of three published PTFs (van Genuchten, Vauclin, and Campbell) for estimating the moisture retention curves and unsaturated K of sandy soils in the Fakara region of southwestern Niger by comparing them to published values on similar soils. The hydraulic properties so determined, would then be an important resource for modeling and understanding the water balance of farmers' fields in the Fakara.

The van Genuchten and Campbell PTFs were selected for this study because they have been widely used and evaluated for a wide range of soil types (Khaleel et al., 1995; Rockström et al., 1998; Schaap and Leij, 2000; Cornelis et al., 2001; Wagner et al., 2001; Amayreh et al., 2003). The Vauclin PTF model was originally developed for sandy soils of Senegal (Vauclin et al., 1983) and later successfully used for similar soils in Niger (Klaij and Vachaud, 1992). The direct method of estimating K from neutron probe measurements (Green et al., 1986), as modified by Klaij and Vachaud (1992), was used as a reference to evaluate the prediction accuracy of the Vauclin, van Genuchten and Campbell PTF models in estimating K.

Pedotransfer function theory

van Genuchten function

Using the van Genuchten (1980) equation, the moisture retention curve function can be represented by

$$\theta(\psi) = \theta_r + (\theta_s - \theta_r) \Big/ \left[1 + (\alpha\psi)^n\right]^{1-1/n}, \qquad [3.1]$$

where $\theta(\psi)$ is the measured volumetric water content (cm^3 cm^{-3}) at suction ψ (cm); θ_r and θ_s are residual and saturation moisture content respectively; α (cm^{-1}) is related to the inverse of the air entry suction, ψ_e, where large values of α indicate a sudden change in water content with some pores emptying under very small negative heads typical of sands; n (>1) is a dimensionless measure of the pore-size distribution (van Genuchten, 1980) and determines the rate at which the S-shaped retention curve turns towards the ordinate for large values of ψ, thus reflecting the steepness of the curve (Wösten et al., 1995). The parameters θ_r, and θ_s, α, and n for moisture retention were estimated from neural networks using the ROSETTA model (Schaap et al., 2001).

Combination of Eq. [3.1] and Mualem's (1976) pore-size model results in the following expression for K (van Genuchten, 1980)

$$K(S_e) = K_o S_e^L \{1 - [1 - S_e^{n/(n-1)}]^{1-1/n}\}^2 \ , \tag{3.2}$$

where the effective saturation, S_e, is given by

$$S_e = \theta(\psi) - \theta_r / (\theta_s - \theta_r) \ . \tag{3.3}$$

In Eq. [3.2], K_o is a fitted matching point at saturation (cm day^{-1}) which is similar but not necessarily equal to K_s, while L is an empirical parameter. For this study, K_o and L were estimated using ROSETTA (Schaap and Leij, 1998; Schaap et al., 2001) from the measured bulk density and soil particle size data.

Vauclin model

The Vauclin model (Vauclin et al., 1983) was derived from a study on Senegalese sandy soils with clay plus fine silt contents ranging from 3.5 to 12.0 %. K (θ) values obtained from the instantaneous profile method (Watson, 1966) were used to model K using the following function,

$$K(\theta) = K_o(\theta / \theta_o)^\beta , \tag{3.4}$$

where $K(\theta)$ is the hydraulic conductivity at moisture content θ, K_o is the hydraulic conductivity at final infiltration, β is a shape parameter and θ_o is the apparent saturated soil moisture content at final infiltration. K_o and β are calculated using the following equations,

$$K_{o_{(cm/h)}} = 28.42 - 1.534(Clay + FineSilt) \qquad [3.5]$$

and

$$\beta = 3.67 + 0.437(Clay + FineSilt) \qquad [3.6]$$

where K_o is in cm hr-1, Clay is the clay content (< 2.0.µm fraction, %) and FineSilt is the fine silt content (2.0 to 20.0 µm fraction, %).The Vauclin model has been used in water balance studies on sandy soils in Nigeria (Grema and Hess, 1994), and in Niger (Klaij and Vachaud, 1992) yielding hydraulic conductivities very close to measured values.

Campbell model

The Campbell model uses particle size distribution and bulk density data to estimate points on the moisture retention curve from which K_s can also be estimated. The SOILPAR program (Acutis and Donatelli, 2003) was used to estimate the Campbell parameters. The Campbell equation for the moisture retention curve is

$$\psi_m = \psi_e(\theta/\theta_s)^{-b}, \qquad [3.7]$$

where θ is volumetric water content, and θ_s is the saturation water content. The parameters ψ_m and ψ_e are soil matric potential and air entry water potential respectively and b is the slope of log$_e$ ψ_m vs. log$_e\theta$. Campbell (1998) also proposed a function for determining K as

$$K(\theta) = K_s(\theta/\theta_s)^{2b+3}, \qquad [3.8]$$

where $K(\theta)$ and K_s are unsaturated and saturated hydraulic conductivities respectively, and b is the same as in Eq. [3.7].

Materials and methods

Site description

The two study sites were Banizoumbou and Bagoua in the Fakara region of southwestern Niger. Banizoumbou is a village located at coordinates 13^{o}31'N and 2^{o}39'E, 65 km east of Niger's capital city, Niamey. The second village, Bagoua, is located at 2^{o}46' E and 13^{o}29' N, 12 km south east of Banizoumbou. The climate of the Fakara is hot and semi-arid with a unimodal rainfall distribution. Most of the rain falls between June and September, with an average of 500 mm (Le Barbe and Lebel, 1997). Soils in the study sites are classified as Psammentic Kandiustalfs (Soil Survey Staff, 1975; Heil et al., 1997) and pearl millet is the major crop grown in the two villages.

Soil sampling strategy

Soil sampling in farmers' fields was done using a stratified random sampling method where each of five manure treatments (see Chapter II) was divided into three equal squares measuring 30 x 30 m. For particle size distribution, soils were sampled randomly from each of these squares using a push augur with 5 cm diameter, at the following depths; 0-30 cm at 10 cm intervals; and 30-210 cm at 30 cm intervals. The samples were then bulked according to depth resulting in nine samples per stratum.

Soil bulk density samples were collected using a 100 cm^3 core from profile pits dug at the two sites and from the same depths as for particle size analysis.

Composite soil samples for moisture retention were collected from the no-manure (NM) stratum at each site. Because clay content increased with depth, especially at Banizoumbou, soil profiles at the two sites were divided into three horizons based on clay content resulting in the following depth intervals; 0 – 30; 30 – 120; and > 120 cm at Bagoua; 0 – 30; 30 – 60; and > 60 cm at Banizoumbou.

Soil physical and hydraulic properties

Particle size distribution was measured on the following fractions, 2000 – 200, 200 – 50, 50 – 20, 20 – 2 , and finally < 2 μm using the pipette method (Gee and Bauder, 1986). Soil bulk density and particle size data were used to estimate the moisture retention curves and K(θ) for the two sites using the van Genuchten function (Mualem, 1976; van Genuchten, 1980), Campbell functions (Campbell, 1974; Campbell and Norman, 1998), and the Vauclin model (Vauclin et al., 1983). The prediction accuracy of the PTFs was tested by comparing the derived moisture retention curves with those determined in the lab using the hanging water column method (Klute, 1986) on 100 cm^3 soil cores repacked to a bulk density of 1.5 g cm^{-3} for the low suction range (0, 1, 2, 3, 4, 5 and 6 kPa) and published pressure plate data for high suction ranges (33, 300 and 1500 k Pa) for similar soils in Niger (Payne, 1987). To evaluate the performance of the different PTFs, the root mean square error (RMSE) between the calculated and measured values was also calculated by:

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{n}(\xi_i - \xi_i^{'})^2}, \qquad [3.9]$$

where ξ_i is measured value, $\xi_i^{'}$ is the predicted value and N is the number of data points.

Soil moisture measurements and estimation of K(θ)

An aluminum access tube was installed to a depth of 1.8 m in the center of each 10 x 10 m experimental plot before pearl millet was planted in 2003. Soil profile volumetric moisture content was then measured to a depth, Z_m, of 1.8 m in each of the plots using a field calibrated neutron probe (IH II Probe, Didcot Instrument Co., UK). A calibration curve was developed for each of the following depths; 0-15 cm; 15-30 cm and > 30 cm. Although neutron probes are known to lose resolution near the surface because of escaping neutrons (Holmes, 1956), satisfactory curves were obtained near the surface (r^2 = 0.99 for 15 cm; 0.98 for both the 15-30 cm and > 30 cm depth). Soil volumetric moisture content (%) was calculated by

$$\theta_v = a + b(C / C_s)\,, \tag{3.10}$$

where θ_v is volumetric moisture content (%); a is the intercept of the calibration curve; b is the slope of the curve; C is the neutron count read by the neutron probe; and C_s is the standard count. The standard count was obtained at the beginning of each measurement date by taking a neutron probe reading in a drum full of pure water. The amount of water stored in the profile was calculated by the trapezoidal integration of the soil moisture content values over the depth of the profile.

Unsaturated hydraulic conductivity was then directly estimated at the maximum rooting depth (1.4 m) using the two stage method proposed by Klaij and Vachaud (1992). Knowledge of unsaturated K for this depth is needed to calculate root zone drainage other soil water balance terms e.g. Payne (1997). In Klaij and Vachaud (1992), stage one represents the beginning of the season when the wetting front had not yet passed the bottom of the soil profile (1.8 m) and stage two is the period when the wetting front had reached the bottom of the profile. If, during a time interval for conditions of stage one the moisture content held between the maximum rooting depth (1.4 m) and the bottom of the profile, S_{rm}, increased by ΔS, then the same amount of water must have drained through that plane. A single K-θ value of the soil hydraulic function can be estimated using the following equation:

$$K(\theta)_a = -D_r \nabla H \Delta t \qquad [3.11]$$

where θ_a is the arithmetic mean of the soil water content at the beginning ($t = t_1$) and end of the time interval ($t = t_1 + \Delta t$) measured at $Z = Z_r$; D_r is the same as S_{rm}; ∇H is the hydraulic head gradient, which was assumed to be (-1) at both sites based on results from earlier work in the region (Hartmann and Gandah, 1982; Klaij and Vachaud, 1992). Vachaud et al., (1991) found excellent correlation between K(θ) functions obtained with and without the unit gradient assumption (i.e., with and without tensiometric data) for coarse soils of Côte d'Ivoire, Mali, and Senegal. By using Eq. [3.11] and repeating the calculation for several time intervals per neutron probe during stage one allowed for the regression of the K vs. θ to give

$$K(\theta)_a = a\theta^b, \qquad [3.12]$$

where *a* and *b* are constants.

Results

Soil physical properties

Tables 3.1 and 3.2 summarize the soil particle size distribution and bulk density data at the two sites. Generally, soil profile clay content at the two sites was low, and did not reach 90 g kg^{-1} with Banizoumbou having higher clay content than Bagoua.

Table 3.1. Particle size and bulk density data at Banizoumbou.

Depth	2000 – 200 µm	SE	200-50 µm	SE	50-20 µm	SE	20-2 µm	SE	<2 µm	SE	Bulk density
cm	g kg^{-1}										g cm^{-3}
0-10	449.3	9.7	490.5	9.4	19.3	2.3	9.7	1.1	31.6	3.5	1.40
10-20	429.6	9.7	497.2	7.8	14.7	2.8	15.7	2.7	42.6	2.4	1.43
20-30	425.9	11.8	482.4	12.7	15.7	1.8	12.6	1.9	63.4	2.7	1.49
30-60	429.4	6.4	467.5	8.9	13.7	2.9	12.0	1.0	77.4	3.2	1.41
60-90	424.5	9.6	469.6	10.8	13.2	2.4	10.7	2.5	82.0	4.6	1.50
90-120	425.2	10.0	470.4	12.5	10.0	1.3	7.6	0.9	86.9	5.8	1.48
120-150	420.9	15.2	475.4	15.8	11.7	1.5	10.6	1.4	81.6	6.2	1.48
150-180	402.8	8.6	489.8	11.2	14.1	1.2	7.8	1.2	85.6	5.3	1.50
180-210	400.2	7.0	494.9	5.7	11.5	1.3	9.9	1.3	83.6	4.8	1.53

†Particle size data are averages of the five manure treatments (NM, TM, C0, C1 and C2)
‡Standard error is for the five manure treatments

Table 3.2. Particle size and bulk density data at Bagoua.

Depth	2000 – 200 µm	SE	200-50 µm	SE	50-20 µm	SE	20-2 µm	SE	<2 µm	SE	Bulk density
cm	$g\ kg^{-1}$										$g\ cm^{-3}$
0-10	488.3	16.1	463.3	14.1	14.3	1.4	9.5	1.0	25.4	1.6	1.54
10-20	471.8	6.9	469.2	6.4	14.0	0.8	9.3	0.8	35.9	1.8	1.64
20-30	450.5	10.3	481.3	9.3	12.5	0.9	8.9	0.5	47.2	2.2	1.55
30-60	456.2	4.4	469.0	5.9	12.8	0.6	7.7	0.6	55.0	1.9	1.55
60-90	446.2	6.4	479.7	5.2	12.3	1.7	7.3	0.6	55.0	2.0	1.49
90-120	455.1	10.8	474.5	11.6	12.1	1.6	6.0	0.5	52.6	1.7	1.54
120-150	435.2	11.3	497.2	10.0	12.4	0.8	6.0	0.3	50.1	2.0	1.44
150-180	416.6	9.5	517.4	8.8	13.7	1.3	6.2	0.2	47.3	2.0	1.52
180-210	401.1	12.9	535.4	13.0	13.5	1.7	5.8	0.5	44.9	2.5	1.43

†Particle size data are averages of the five manure treatments (NM, TM, C0, C1 and C2)
‡Standard error is for the five manure treatments

Table 3.3. Input parameters for moisture retention curves for Banizoumbou and Bagoua.

		Banizoumbou			Bagoua		
Soil property	**Depth (cm)**	**0 – 30**	**30 – 60**	**> 60**	**0 – 30**	**30 - 120**	**> 120**
	Sand (g kg^{-1})	925.0	896.9	894.7	941.5	926.9	934.3
	Silt (g kg^{-1})	29.2	25.7	21.4	22.8	19.4	19.2
	Clay (g kg^{-1})	45.9	77.4	83.9	36.1	54.2	47.4
	Bulk density (g cm^{-3})	1.41	1.41	1.50	1.58	1.53	1.46
van Genuchten	**θ_r (cm^3 cm^{-3})**	0.05	0.06	0.06	0.05	0.06	0.06
	θ_s (cm^3 cm^{-3})	0.42	0.42	0.40	0.36	0.38	0.40
	α (cm^{-1})	0.03	0.03	0.03	0.03	0.03	0.03
	L	0.84	0.80	0.84	0.91	0.90	0.88
	n	2.85	2.39	2.37	3.19	2.91	3.05
	K_o (cm d^{-1})	23.74	21.14	17.22	19.91	17.95	20.35
Campbell	**ψ_e (-j kg^{-1})**	0.69	0.78	0.90	0.75	0.79	0.71
	b	2.17	2.71	2.83	1.97	2.25	2.13
	K_s (mm h^{-1})	73.43	56.65	42.94	61.39	56.27	68.98

Table 3.4. Input parameters for unsaturated hydraulic conductivity at 1.4 m soil depth for Banizoumbou and Bagoua.

Model	Parameter	Banizoumbou	Bagoua
van Genuchten	L	0.84	0.87
	n	2.40	2.98
	K_o (cm d^{-1})	17.76	20.70
Campbell	ψ_e (-j kg^{-1})	0.87	0.70
	b	2.78	2.18
	K_s (mm h^{-1})	46.28	70.03
Vauclin	b	7.50	5.90
	K_o (cm h^{-1})	15.10	20.40

At Banizoumbou bulk density was lower, possibly because of the higher clay content and also due to observed termite activity, which has been shown to lower the bulk density (Mando, 1997).

Moisture retention curves

The parameter values required by the van Genuchten and Campbell models to estimate the moisture retention curves are presented in Table 3.3 and parameter values for hydraulic conductivity are presented in Table 3.4. Parameters for the van Genuchten model were derived from ROSETTA (Schaap et al., 2001) and those for the Campbell model were derived from SOILPAR (Acutis and Donatelli, 2003).

The moisture retention curves for the three depth intervals at the two sites (Fig. 3.1 and Fig. 3.2) are typical of the sandy soils which dominate most of south-western Niger (Hoogmoed and Klaij, 1990; Payne et al., 1991a). Field capacity of these soils, which ranges from anywhere between 0.12 to 0.16 $m^3 m^{-3}$ depending on clay content (Payne, 1987; Payne et al., 1990a), was reached at a suction (h) below 10 kPa with further increases in h up to 50 kPa draining the soils rapidly to $\theta < 0.05$ $m^3 m^{-3}$.

The Campbell model performed well for the 0 – 30 cm soil depth at Banizoumbou and had an RMSE 0.05 $m^3 m^{-3}$ (Fig. 3.1). For depths below 30 cm, the Campbell model tended to overestimate h for θ between 0.05 and 0.20 $m^3 m^{-3}$ and had RMSE of 0.05 and 0.04 $m^3 m^{-3}$ for 30 – 60 cm and > 60 cm soil depth respectively. At the dry region of the moisture retention curve, the Campbell model predicted a more gradual change in θ with change in h, which in fact is not typical of these sandy soils which have been shown to rapidly drain with small changes in h (Hoogmoed and Klaij, 1990; Payne et al., 1991a). The van Genuchten model overestimated moisture retention in the dry region for the three depth intervals but performed well for the wet range especially for the 0 -30 and 30 – 60 cm depth intervals. The RMSE for the van Genuchten model for the 0 -30 and 30 – 60 cm depth intervals at Banizoumbou was 0.07 $m^3 m^{-3}$ and for the > 60 cm depth interval it was 0.06 $m^3 m^{-3}$.

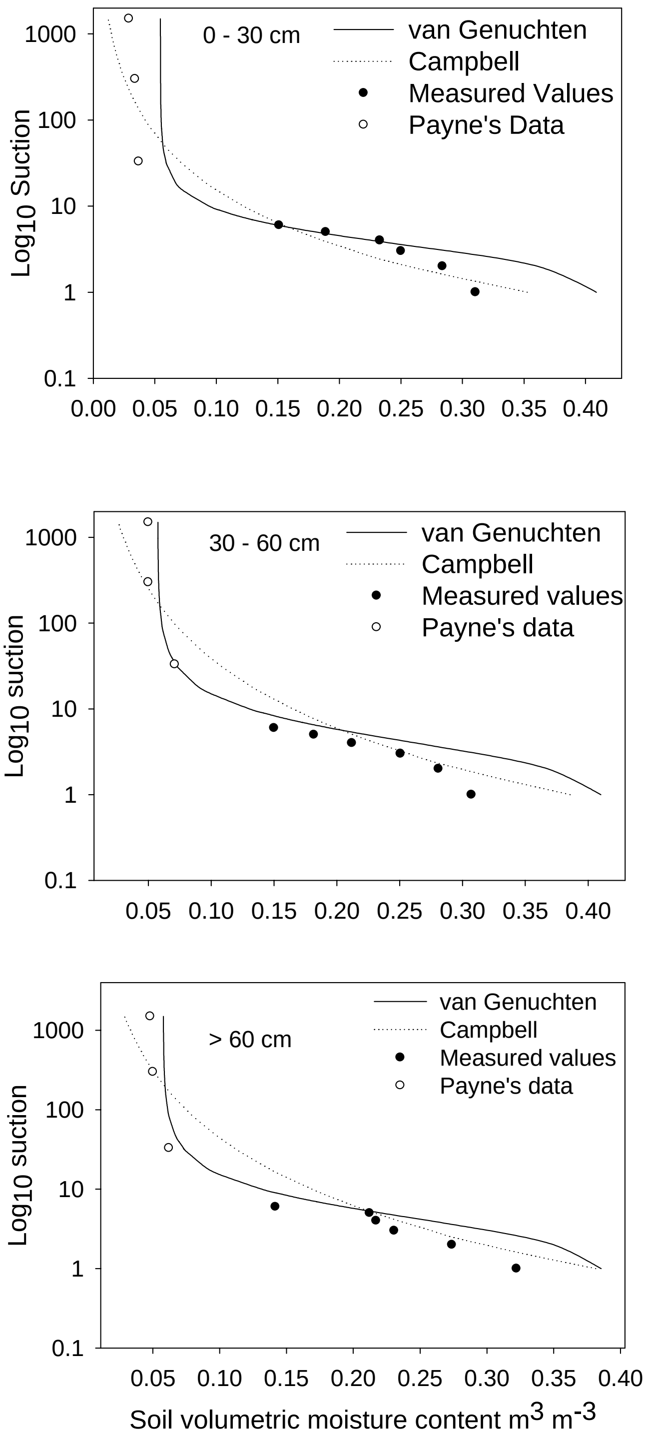


Figure 3.1. Estimation of moisture retention curves by van Genuchten and Campbell models compared with measured values of the soil profile at Banizoumbou. Suction units are kPa.

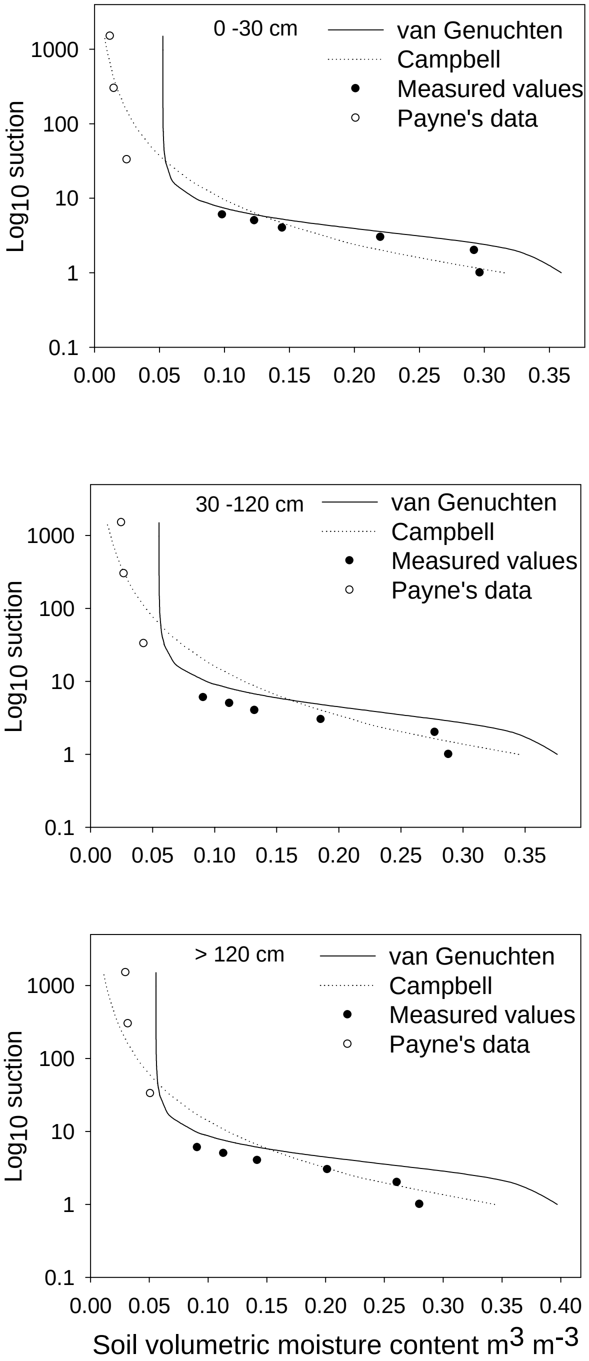


Figure 3.2. Estimation of moisture retention curves by van Genuchten and Campbell models compared with measured values of the soil profile at Bagoua. Suction units are kPa.

At Bagoua (Fig. 3.2), the Campbell model gave a good approximation of the moisture retention curve for the 0 – 30 cm soil depth interval, with an overall RMSE of 0.04 m^3 m^{-3}. The van Genuchten model also had an overall RMSE of 0.04 m^3 m^{-3} for the 0 – 30 cm depth interval. For the 30 – 120 and > 120 cm depth intervals, the Campbell model had an RMSE of 0.06 m^3 m^{-3} and overestimated h for θ between 0.05 and 0.20 m^3 m^{-3}. The van Genuchten model had an RMSE of 0.08 and 0.09 m^3 m^{-3} for the 30 – 120 and > 120 cm depth intervals respectively. As at Banizoumbou, the van Genuchten model tended to overestimate dry end θ while performing well for the wet end.

Unsaturated hydraulic conductivity

At Banizoumbou (Fig. 3.3), the van Genuchten model was in excellent agreement with Klaij and Vachaud's field method giving K values ranging from 0 to 5.3 mm d^{-1} for θ values of 0.04 to 0.10 m^3 m^{-3}. For the same θ range, the Campbell and Vauclin models estimated negligible K.

At Bagoua (Fig. 3.4), the van Genuchten model slightly overestimated K for the range of θ but was still close to Klaij and Vachaud's field method. At this site, the Klaij and Vachaud field method gave K ranging from 0.2 to 2.5 mm d^{-1} for θ values from 0.04 to 0.10 m^3 m^{-3} and the Vauclin model estimated K values from 0 to 1.3 mm d^{-1}. Hydraulic conductivity values given by the Klaij and Vachaud field method and the van Genuchten model at this site fall within the range of what has been previously reported for similar soils in the Sahel (Klaij and Vachaud, 1992; Grema and Hess, 1994). The Campbell model resulted in consistently lower K over the range of θ, compared with the Klaij and Vachaud and van Genuchten models, at Bagoua.

Discussion

Parameter estimation by SOILPAR and ROSETTA using soil particle size and bulk density data led to an acceptable estimation of the moisture retention curve by the Campbell model and hydraulic conductivity by the van Genuchten model.

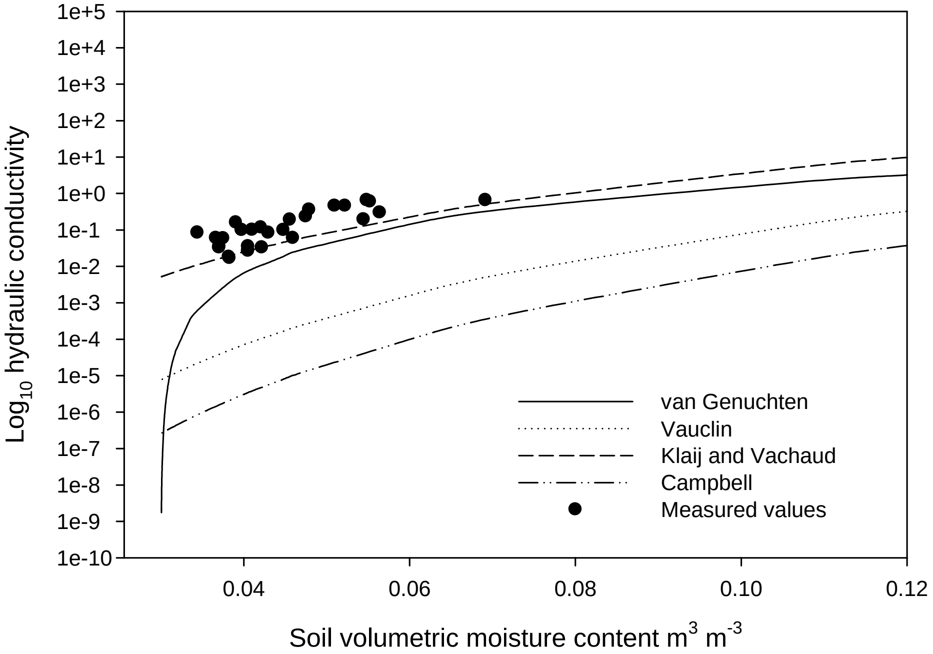


Figure 3.3. Unsaturated hydraulic conductivity curves estimated by the van Genuchten, Campbell, and Vauclin models and compared with the Klaij and Vachaud field method for the 1.4 m soil depth at Banizoumbou. Unsaturated hydraulic conductivity units are mm d^{-1}.

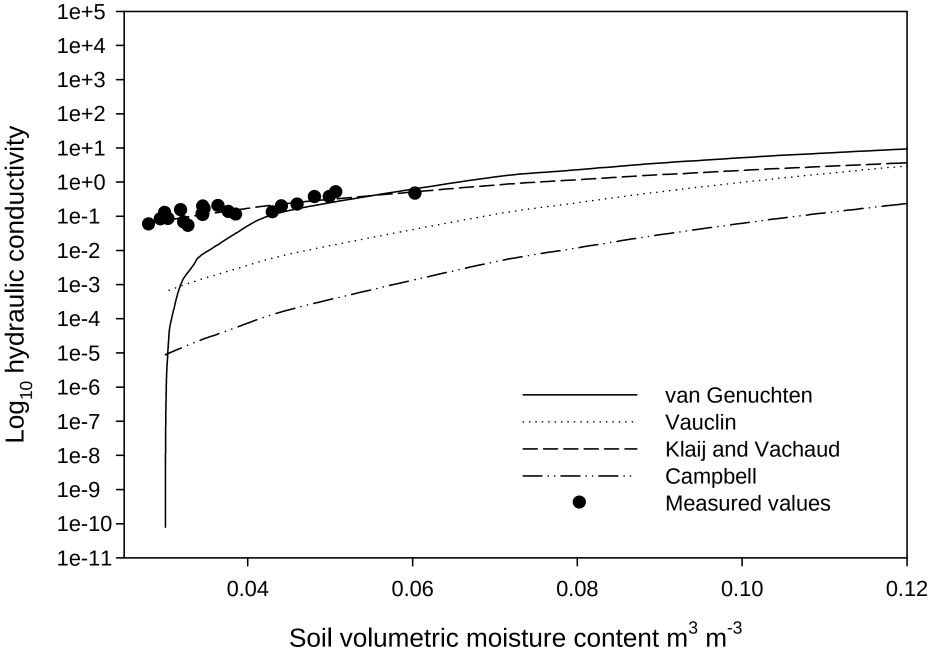


Figure 3.4. Unsaturated hydraulic conductivity curves estimated by the van Genuchten, Campbell, and Vauclin models and compared with the Klaij and Vachaud field method for the 1.4 m soil depth at Bagoua. Unsaturated hydraulic conductivity units are mm d^{-1}.

The Campbell model appeared to be better suited for estimating moisture retention for soils with high sand content as at Bagoua and the Banizoumbou topsoil. On the other hand, the van Genuchten model consistently overestimated moisture retention at the dry regime while generally performing well for the wet regime at both sites and for all depth intervals. The general disagreement between the van Genuchten and Campbell models was also reported for a Walla Walla silt loam soil under semiarid conditions (Chen and Payne, 2001). They found that the Campbell model tended to estimate higher suction as moisture content decreased below 0.30 m^3 m^{-3}. The large difference in Ks values used by the two models (e.g. 23.74 cm d^{-1} for the van Genuchten model vs. 176.23 cm d^{-1} for the Campbell model at Banizoumbou) may have caused the discrepancy in the water retention curves. Given the labor, time and cost requirements for field measurements, the Campbell model can be a faster and cheaper alternative for estimating the moisture retention and the van Genuchten model would be an alternative for determining K for the Fakara soils.

The unsaturated hydraulic conductivity curves derived from Klaij and Vachaud's direct method at both sites were similar to those derived from neutron probe readings and internal drainage experiments on similar soils in Niger (Hartmann and Gandah, 1982; Hoogmoed and Klaij, 1990; Payne et al., 1991a) and in Senegal (Vachaud et al., 1978; Vauclin et al., 1983). The van Genuchten model consistently estimated K values similar to Klaij and Vachaud's direct method for the 1.4 m soil depth at both sites. The Campbell model on the other hand, underestimated K, making it a less likely candidate for modeling K at the study sites or for similar soils. Performance of the Campbell model can be greatly improved when the particle size distribution data used in determining the Campbell parameters are as detailed as possible and not just the clay, silt and sand contents as used in this study (Wagner et al., 2001). The Vauclin model underestimated K for both soils but especially so for the Banizoumbou soil, which had higher clay content (Table 3.1). The Vauclin model gave better results for the Bagoua soil which had higher sand content (Table 3.2).

It has been generally accepted that the accuracy of PTFs tends to increase with an increase in the number of measured input parameters, but others have recently shown that this is not necessarily true (Schaap et al., 2004). In this study all the model input parameters were estimated using ROSETTA and SOILPAR but the resulting soil hydraulic properties were still of modest accuracy.

CHAPTER IV

ON-FARM MANAGEMENT EFFECTS ON PROFILE MOISTURE DISTRIBUTION AND WATER BALANCE OF SANDY SOILS GROWN TO PEARL MILLET IN NIGER

Major constraints to pearl millet [*Pennisetum glaucum* (L.) R.Br.] production under the rainfed subsistence farming systems of Niger include declining and inherently poor soil fertility (West et al., 1984; Manu et al., 1991; Casenave and Valentin, 1992; Manu et al., 1996; Rockström et al., 1998; Bielders et al., 2002), the use of unimproved pearl millet cultivars, and erratic rainfall that usually falls in high intensity storms (Sivakumar, 1989; Sivakumar, 1993; D'amato and Lebel, 1998). Average grain yields of the staple cereal, pearl millet, under subsistence farmer management are generally low, varying from 150 to 550 kg ha^{-1} (McIntire and Fussel, 1989; Krogh, 1997; Sivakumar and Salaam, 1999). The effects of organic manure and inorganic fertilizer on pearl millet yields have been extensively studied in Niger (Bationo and Mokwunye, 1991a; Bationo et al., 1992; Bationo et al., 1993; Rockström and de Rouw, 1997; Powell et al., 1998; de Rouw, 2004; de Rouw and Rajot, 2004a), but relatively few studies have been conducted on manure/fertilizer effects on the water balance of sandy soils grown to pearl millet, and fewer still under subsistence farmer conditions.

Some water balance studies have concluded that water is not always the limiting constraint to pearl millet production. Payne (1997) looked at fertilizer, cultivar, and plant population effects on the yield and water use of pearl millet at the ICRISAT Sahelian Center Experiment Station in four years (1983, 1984, 1986, and 1990) with varying rainfall amounts. Genotypic differences in evapotranspiration, ET, were shown to be only due to differences in length of growing season where the long season cultivars consistently had higher ET. Fertilizer only slightly increased ET, whereas combination of high fertilizer application and high plant populations led to ~50 mm increase in water use. His study showed that it is possible to optimize pearl millet yield and WUE for most climatic zones of the Sahel without risk of exhausting plant available water by using moderate plant populations of at least 10 000 hills ha^{-1} and moderate fertilizer applications of ~20 kg N ha^{-1} and ~9 kg P ha^{-1}. In an earlier study, Payne et al. (1990a) studied root zone water balances of three low input pearl millet fields at three sites in Niger. At their driest site (233 mm total annual rainfall), ET was equal to rainfall whilst cumulative root zone drainage and change in root zone moisture content were both zero. The authors concluded that water was the primary limiting constraint to production only under dry conditions as prevailed at this site. Their conclusion was based on De Wit's statement (De Wit, 1958) that if water is in short supply, transpiration equals the amount of available water, corrected for evaporation and losses such as drainage and runoff; and if water is not limiting, transpiration is less than the available water.

Affholder (1995) studied the effect of organic matter input on the water balance and pearl millet yield in 1990 and 1991 at Bambey and Sob, Senegal. Rainfall at Sob in 1990 and 1991 was 324 and 356 mm respectively and at Bambey it was 374 and 328 mm in 1990 and 1991 respectively. Fields used at the Bambey site were located at an experiment station and had been receiving fertilizer applications for many years before the experiment started and may not have been representative of farmers' conditions. At Bambey, the author compared a composting (3 Mg compost ha^{-1}) treatment to a reference treatment with no compost added. However both treatments had received 40 kg NPK ha^{-1} at the beginning of the experiment. On the other hand, fields used at Sob were located in the village and hence were more representative of farmers' conditions. At Sob, the author compared three fertility levels; 1) House field with 9 Mg manure ha^{-1} applied for at least three years; 2) Bush field with 3 Mg manure ha^{-1} applied in the current year; and 3) Bush field with no manure application for the previous three years. He observed that at both sites and during both seasons pearl millet grown on fields where no manure had been applied did not experience any moisture constraint at all during sensitive periods (e.g. grain filling) whereas pearl millet grown on fields which had received manure, especially at the Bambey site, experienced moisture stress during grain filling and maturation. Although at Bambey manure had a positive effect on the number of grains per square meter, it induced a decrease in individual grain mass. He also observed that the higher rate of moisture consumption in manured fields at Bambey kept the soil moisture content low and promoted storage of rainwater in the surface layers, hampering the depth penetration of the wetting front, which in turn limited the downward growth of roots. Although the author did not report root zone drainage in his study, the restriction of the depth penetration of the wetting front in high fertility treatments may also have led to a reduction in the root zone drainage as was reported for degraded sandy soils in a similar study by Cissé and Vachaud (1988).

In their study, Cissé and Vachaud (1988) investigated the effect of manure on the yield and water use of pearl millet and groundnut on sandy soils during 1983 with 210 mm total rainfall, 1984 with 279 mm total rainfall, and 1985 with 347 mm total rainfall. They observed that pearl millet grown on high fertility fields (10 Mg manure ha^{-1} and 150 kg NPK ha^{-1} + 50 kg Urea ha^{-1}) had higher ET until around tillering (30 – 40 days after sowing) and at grain filling (48 – 70 days after sowing) compared with pearl millet grown with only fertilizer application. From grain filling until the end of the season ET in the manured fields fell below ET in the fertilizer only fields, just as Affholder (1995) observed for his high vs. low fertility treatments. Cumulative root zone drainage was also reduced significantly in the high fertility fields compared with the fertilizer only fields. Although the authors did not mention grain yields, the total dry matter produced by pearl millet in the fertile fields were twice as high compared with the control treatment during both seasons.

Klaij and Vachaud (1992) also studied the seasonal water balance of a sandy soil at the ICRISAT Experiment Station in Niger during the 1986 growing season. Total rainfall received between day of sowing and harvesting was 440 mm. In their study, pearl millet grown under high fertility conditions (30 kg P_2O_5 ha^{-1} and 40 kg N ha^{-1}) used 58 mm more water compared with pearl millet grown in the low fertility treatment (no inputs, similar to farmer’s conditions). In their study, pearl millet total dry matter production in the fertile plots was almost three times higher than in the control plots, but as in Cissé and Vachaud (1988), the authors did not report grain yield. However, their findings were similar to those of Payne et al., (1997) in suggesting that pearl millet water-use efficiency can be increased by better management without reducing pearl millet total dry matter yields, and that not all plant available moisture is used under low fertility conditions which prevail under subsistence farmer management except in very dry zones.

Although the aforementioned studies looked at fertility effects on pearl millet yields and the water balance of sandy soils, in most studies other than that by Payne et al. (1990), fertilizer or manure quantities applied were higher than what most subsistence farmers in the region typically apply. Additionally, some studies did not report grain yield. The moisture stresses at tillering and grain filling observed for pearl millet grown under high fertility conditions in the two Senegalese studies (Cissé and Vachaud, 1988; Affholder, 1995) were not reported for the Niger studies, at least not to the extent of reducing grain yields (Payne et al., 1990a; Klaij and Vachaud, 1992; Payne, 1997).

Whilst studies on experiment stations, e.g. Payne (1999) have shown that water can be used more efficiently for pearl millet production by decreasing D and increasing partitioning of rainfall to transpiration through improved management, on-farm studies that use technologies appropriate to subsistence cropping systems and investigate the potential impact of such water-balance modifications are still needed. This is especially so because results from experimental stations under controlled conditions are not always representative of farmer field conditions. Because of the poor resource base of most subsistence farmers in the region, the application of very small quantities of fertilizer ("microdose") near planted seeds (NUTMEN/GEMS, 2002) has been proposed to increase pearl millet yield and is the subject of ongoing studies. However, to our knowledge none of studies on microdose have examined its effects on soil moisture or the soil water balance.

It is against this backdrop that this study was carried out with the primary objective of evaluating, on farmers' fields, the effect of corralling and microdose on the yields and water balance of pearl millet grown on sandy soils in the Fakara region. As a secondary objective, pearl millet cultivar effects on yields and the water balance were also evaluated.

Materials and methods

Site description and field experiment

Banizoumbou is a village located at coordinates 13°31'N and 2°39'E, 65 km east of Niger's capital city, Niamey and Bagoua, is located at 2°46' E and 13°29' N, 12 km south east of Banizoumbou. Farmers' fields were located on < 2 % slope with no evidence of surface crusting and runoff or runon. The climate at the study sites is hot and semi-arid with a unimodal rainfall distribution. Most of the rain falls between June and September, with an average annual rainfall of 500 mm (Le Barbe and Lebel, 1997). Soils in the study sites are classified as Psammentic Kandiustalfs (Soil Survey Staff, 1975; Heil et al., 1997) and pearl millet is the major crop grown in these villages.

A factorial experiment in a randomized complete block design was set up in farmers' fields (and managed by the farmers under the supervision of an ICRISAT technician) at both villages in 2003. The effects of five different manure treatments, three fertilizer treatments, and two cultivars on the water balance were analyzed. The five manure treatments served as blocks and were: 1) Two years since last corralling, *C2*; 2) One year since last corralling, *C1;* 3) Current corralling, *C0*; 4) Transported manure, *TM*; and finally 5) No manure, NM. The three fertilizer treatments were: 1) A control with no fertilizer application; 2) Twenty kg ha^{-1} di-ammonium phosphate (DAP) supplying 3.6 kg N ha^{-1} and 3.85 kg P ha^{-1}; and 3) Twenty kg ha^{-1} DAP + 10 kg ha^{-1} urea supplying 8.2 kg N ha^{-1} and 3.85 kg P ha^{-1}). The unusually low amounts of fertilizer were based upon the "microdose" technology (see Chapter II), which places very small amounts of fertilizer in close proximity to seeds. Finally, the two pearl millet cultivars were the local landrace, Heini Kirei, and an improved cultivar, Zatib. Individual plot size was 10 m x 10 m, and each fertilizer/cultivar treatment was replicated thrice in each block.

In 2003 sowing was done after the first major rains greater than 20 mm on day of year (DOY) 165 at both sites. For the 2004 season, sowing was done on DOY 139 and 181 at Bagoua and Banizoumbou respectively. Plants were thinned to 3 plants per hill (30 000 plants ha^{-1}) 14 days after sowing and weeding done twice during the season at both sites using the traditional hand hoe (hilaire). Plots were harvested on DOY 281 at Banizoumbou and DOY 287 at Bagoua in 2003. During the 2004 growing season, the leaf area index (LAI) of pearl millet in the different treatments was measured. At Bagoua LAI measurements were taken at 37, 69, and 87 days after sowing in the NM, C0 and C2 treatments whilst in the TM and C1 they were taken at 70, 92, and 110 days after sowing. At Banizoumbou, LAI measurements were taken at 45, 58, 89, and 109 days after sowing in all the treatments. The LAI was measured using a leaf area meter (Li-Cor model, LI-3100; Li-Cor, Inc., Lincoln, Nebraska).

On each LAI measurement date, three “representative” pearl millet hills were harvested from the two border rows in each of the three replications. The green leaves were then transported to the lab in a 60 L cooler box for LAI and dry weight measurement. The dry weight was determined after oven drying the leaves at 70°C for 24 hours and measuring the weight using a scale accurate to 1 mg. Using regression, models relating LAI to leaf dry weight were formulated. These models were used later in the season to calculate LAI when it became difficult to transport turgid leaves from the field to the lab. Harvesting was done on DOY 287 at Banizoumbou and DOY 270 at Bagoua in 2004.

Meteorological data collection

Daily weather data (relative humidity, wind speed, global irradiance, air temperature and potential evapotranspiration) were collected from an automatic weather station (Campbell CR10, Campbell Scientific Inc., Logan, Utah) located at a village 6 and 12 km from Bagoua and Banizoumbou respectively. In 2003, the weather data for May to July were lost during downloading to a personal computer.

Soil moisture measurements

Soil profile volumetric moisture content was determined to a depth, Z_m, of 1.8 m in each of the experimental plots using a field calibrated neutron probe (IH II Probe, Didcot Instrument Co., UK). A calibration curve was developed for each of the following depths; 0-15 cm; 15-30 cm and > 30 cm. Although neutron probes are known to lose resolution near the surface because of escaping neutrons (Holmes, 1956), satisfactory curves were obtained near the surface ($r^2 = 0.99$ for 15 cm; 0.98 for both the 15-30 cm and > 30 cm depth). Soil volumetric moisture content (%) was calculated by

$$\theta_v = a + b(C / C_s)\,, \qquad [4.1]$$

where θ_v is volumetric moisture content (%); a is the intercept of the calibration curve; b is the slope of the curve; C is the neutron count read by the neutron probe; and C_S is the standard count. The standard count was obtained at the beginning of each measurement date by taking a neutron probe reading in a drum full of pure water. The amount of water stored in the profile was calculated by the trapezoidal integration of the soil moisture content values over the depth of the profile.

In 2003 soil moisture measurements began 19 and 20 days after sowing at Bagoua and Banizoumbou respectively. Profile moisture measurements were terminated on DOY 251 (about 30 days and 36 days before harvesting at Banizoumbou and Bagoua respectively) due to neutron probe failure.

In 2004 profile soil moisture measurements at Banizoumbou started 1 day after sowing and at Bagoua they started 55 days after sowing in the TM and C1 treatments and 12 days after sowing in the NM, C2 and C0 treatments. Neutron probe failure at the beginning of the season led to lack of readings in the TM and C1 treatments at Bagoua and hence their exclusion from the water balance calculations for 2004.

Water balance

To calculate the water balance at each time interval, change in root zone soil moisture (ΔS) was considered equal to the difference between the input (rainfall, R) and output (evapotranspiration, ET, and drainage from the root zone, *D*) as shown in Eq. [4.2]. Rainfall was measured daily by the farmers at each site using a non-recording rain gauge; ΔS was calculated from neutron probe measurements as explained in the preceding section; and maximum rooting depth, Z_r, was assumed to be 1.4 m based on earlier work in the region (Payne et al., 1990a; Klaij and Vachaud, 1992). Runon and runoff at the study sites were both assumed to be negligible because of the absence of surface crusting and the fact that the selected farmers' fields were located on less than 2 % slope, leading to the following water balance equation:

$$\Delta S = R - (ET + D)\,. \qquad [4.2]$$

Following the method of Klaij and Vachaud (1992), the growing season was split into two stages. The first stage was applicable after the prolonged dry season (October to May) when the soil profile moisture had been depleted by evapotranspiration and drainage. During this time, the wetting front had not passed Z_m and soil moisture content at Z_m remained sufficiently low that water flux at Z_m given Darcy's equation was negligible. Therefore the calculation of root zone drainage and ET was as follows,

$$D = \Delta S_{r\,m}\,, \qquad [4.3]$$

and

$$ET = R + \Delta S_{om}\,, \qquad [4.4]$$

where D and ET are root zone drainage and evapotranspiration between two neutron probe readings; ΔS_{rm} and ΔS_{om} are the change in soil moisture content below the root zone (1.4 – 1.8 m) and in the whole soil profile (0 - 1.8 m), between two neutron probe measurements respectively.

As the season progressed and more rainfall events occurred, stage two set in and the change in moisture content at Z_m was no longer negligible. During stage two, D and ET were calculated by

$$D = -K(\theta)\nabla H\Delta t, \qquad [4.5]$$

and

$$ET = R + \Delta S - D, \qquad [4.6]$$

where K(θ) is unsaturated hydraulic conductivity at Z_r; ∇H is the hydraulic head gradient at Z_r; Δt is the time period between two consecutive neutron probe readings; and D is drainage through the Z_r plane.

Estimation of K(θ) from neutron probe readings

According to Klaij and Vachaud (1992), if during a time interval for conditions of stage one, S_{rm} increased by ΔS, then the same amount of water must have drained through that plane (Eq. [4.3]). A single K-θ value of the soil hydraulic function can be estimated using Eq. [4.7]:

$$K(\theta)_a = -D\ \nabla H\Delta t \qquad [4.7]$$

where θ_a is the arithmetic mean of the soil water content at the beginning (t = t) and end of the time interval ($t = t + \Delta t$) measured at $Z = Zr$. A ∇H of (-1) was assumed at both sites based on results from earlier work in the region (Hartmann and Gandah, 1982; Klaij and Vachaud, 1992). By using Eq. [4.7] and repeating the calculation for several time intervals per neutron probe during stage one allowed for the regression of the K vs. theta to give a drainage or K function of the form:

$$K(\theta)_a = a\theta^b , \qquad [4.8]$$

where *a* and *b* are constants.

Statistical analyses

Differences in root zone drainage, ET, and WUE due to manure, fertilizer and cultivar treatments were determined using analysis of variance (ANOVA) of the general linear model (GLM) procedures (SPSS for Windows, Release 12.0, 2004, Chicago: SPSS Inc.). Effects were considered significant at a probability level of ≤ 0.05. For ANOVA, the model used was:

$$\text{Parameter} = \text{Constant} + \text{Manure} + \text{Fertilizer} + \text{Cultivar} + \text{Fertilizer} * \text{Cultivar} + \text{Error} \qquad [4.9]$$

where parameter is root zone drainage, ET, or WUE.

Results

Banizoumbou

The total rainfall received at the sites during the two seasons is shown in Appendix B-1 and was close to the 500 mm annual average for the area (Le Barbe and Lebel, 1997).

Leaf area index

The following regression models were developed from leaf area vs. leaf dry weight data and used to derive LAI during the 2004 season:

For the local pearl millet cultivar,

$$LAI = (0.017 \times DryWeight) - 0.007; r^2 = 0.94, \qquad [4.10]$$

and for Zatib,

$$LAI = (0.02 \times DryWeight) - 0.01; r^2 = 0.98. \qquad [4.11]$$

From the beginning of the 2004 growing season until ~20 days after sowing, the difference in LAI between the manure treatments was small. Around 60 days after sowing, pearl millet grown in the higher fertility treatments (C1, C0 and TM) had higher LAI than the NM and C2 treatments, which still had LAI<0.2. The maximum LAI was reached at around 90 days after sowing with the high fertility treatments being associated with LAI around 1.1. The low fertility treatments, NM and C2 had LAI of 0.2 and 0.4 respectively (Fig. 4.1).

Even with up to 8 Mg manure ha^{-1} being applied in the corralling treatments, maximum pearl millet LAI in the high fertility treatments was still only around 1.1, as other studies in the region have shown (Payne, 2000). Such low maximum LAI especially in the NM and C2 treatments are expected to lead to large proportions of rainfall being lost as soil evaporation (Wallace et al., 1993), seriously impacting the amount of water available for crop growth.

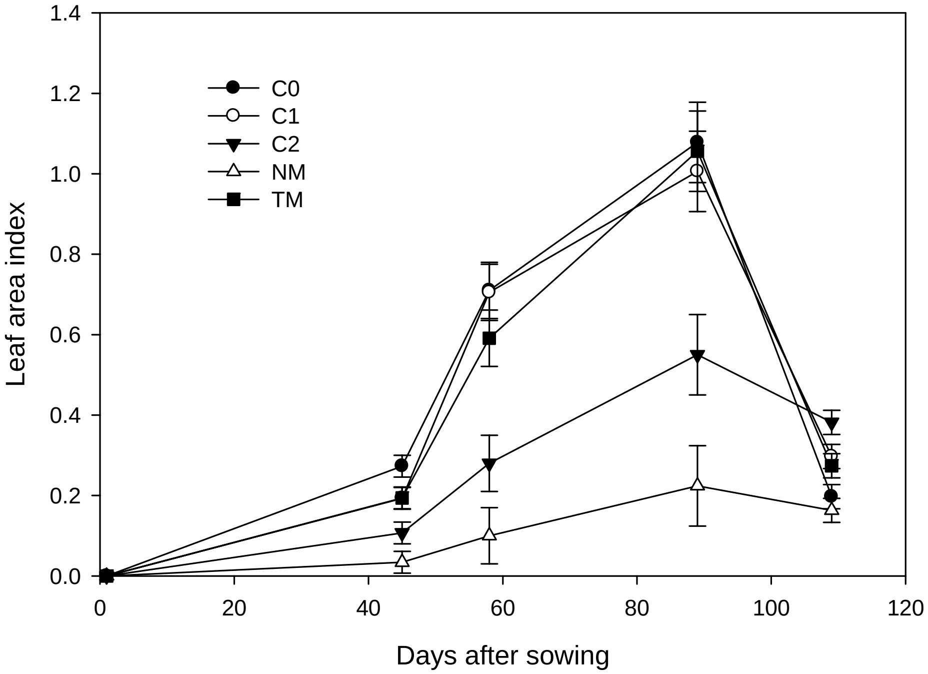


Figure 4. 1. Manure effects on leaf area index at Banizoumbou in 2004. NM is no manure; TM is transported manure; C0 is current corralling; C1 is one year since last corralling; and C2 is two years since last corralling.

Soil profile moisture distribution

Manure effects on soil profile moisture distribution at the beginning of the 2003 growing season are shown in Fig. 4.2. At 20 days after sowing, there was slightly more profile moisture content in the low fertility treatment NM and the C1 treatment, especially below the maximum rooting depth, suggesting that it would be unavailable to plants. At 34 days after sowing, the NM had the highest profile moisture content compared with the rest of the treatments. Towards the end of the season (Fig. 4.3) at 75 days after sowing, the difference in profile moisture content was small, but at 88 days after sowing there was again more profile moisture content in the NM treatment compared with the rest of the treatments. The high fertility treatment had the lowest profile moisture content at the end of the 2003 season. The maximum difference in end of season root zone moisture content was measured between the low fertility treatment, NM (103 mm) and the current corral, C0, (70 mm). High residual profile moisture content in NM may be because pearl millet grown under low fertility conditions has a less developed rooting system and hence cannot extract water from deeper soil layers (Payne et al., 1995). On the contrary, pearl millet grown under the high fertility plots used more profile moisture from the deeper soil layers. Studies in Senegal by Cissé and Vachaud (1988) and Affholder (1995) showed the restriction of the depth penetration of the wetting front in fertile fields resulting in lower residual moisture content at depth. However, the high residual profile moisture content at the end of the growing season is of no benefit to the farmer because it is almost all lost to drainage and evaporation during the long hot and dry period (October – May) following harvesting (Payne et al., 1990b)

At the beginning of the 2004 growing season (Fig. 4.4) there was slightly more residual moisture content in the NM and TM treatments, especially below the maximum rooting depth. This may well be related to the higher end of season (2003) profile moisture content in the low fertility treatments shown in Fig. 4.3.

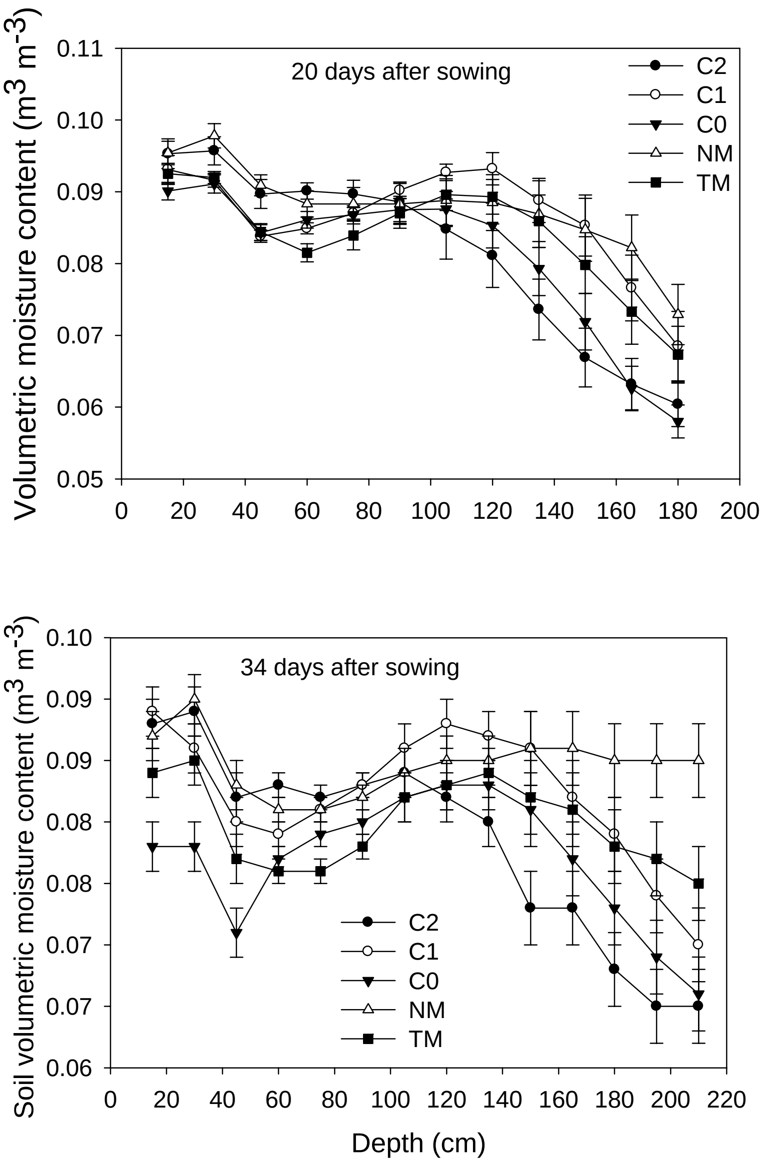


Figure 4. 2. Soil profile moisture distribution at beginning of 2003 growing season at Banizoumbou in 2003. NM is no manure; TM is transported manure; C0 is current corralling; C1 is one year since last corralling; and C2 is two years since last corralling.

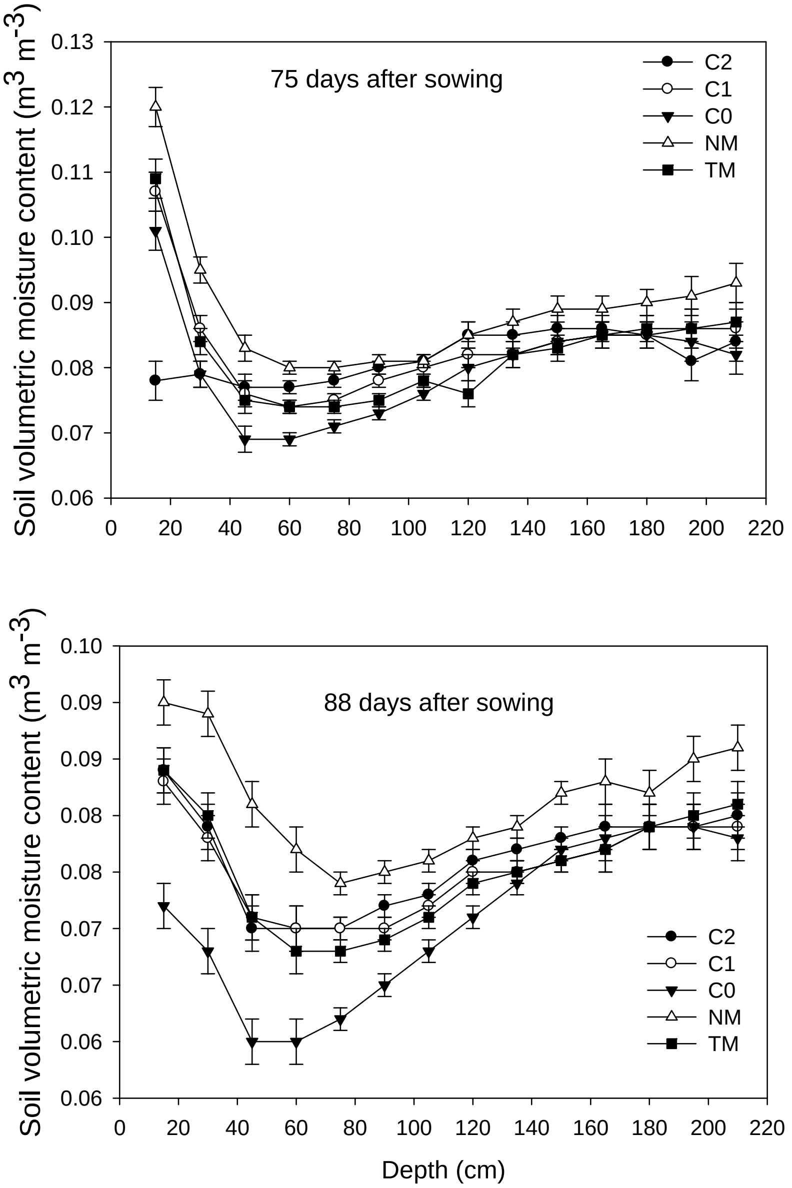


Figure 4.3. Soil profile moisture distribution at the end of the 2003 growing season at Banizoumbou. NM is no manure; TM is transported manure; C0 is current corralling; C1 is one year since last corralling; and C2 is two years since last corralling.

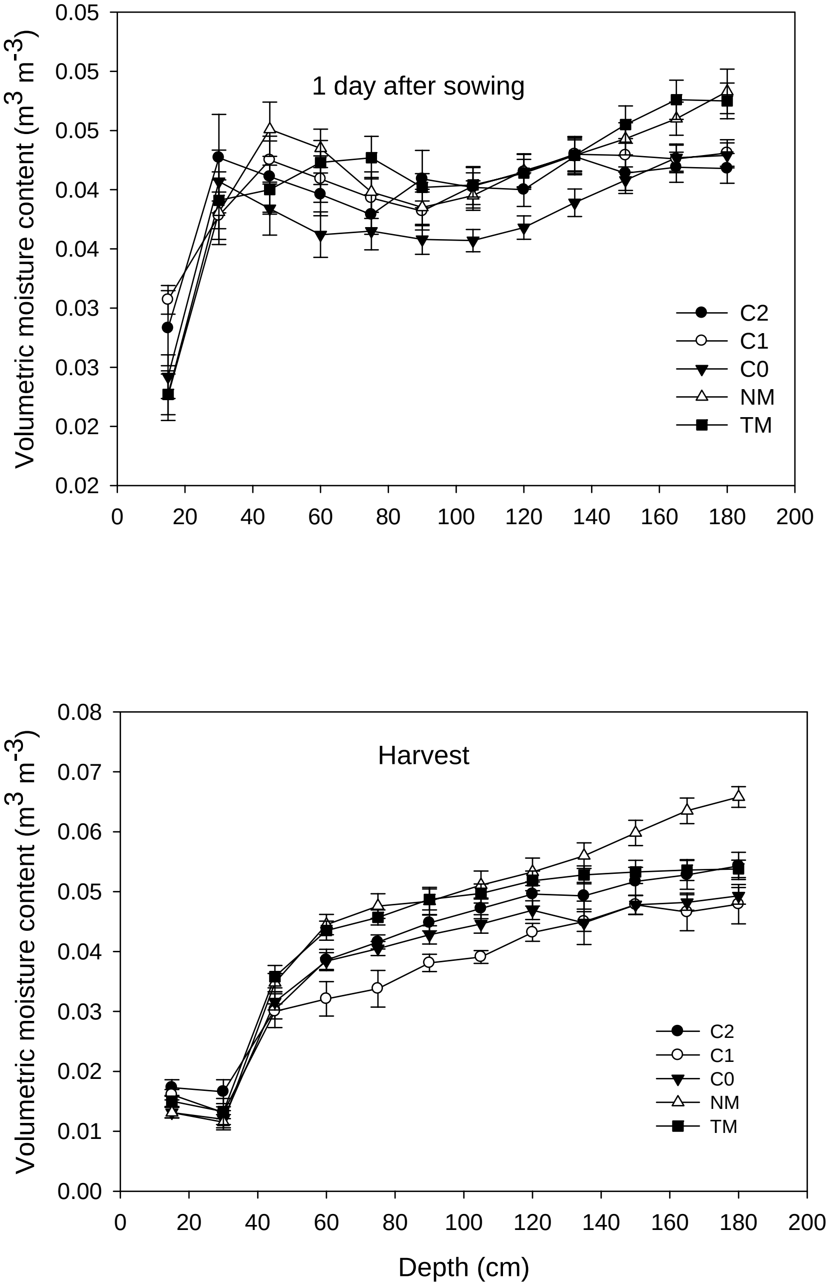


Figure 4.4. Soil profile moisture distribution at Banizoumbou in 2004. NM is no manure; TM is transported manure; C0 is current corralling; C1 is one year since last corralling; and C2 is two years since last corralling.

At the end of the 2004 growing season, the low fertility treatment (NM) had higher residual moisture content compared with the rest of the treatments, especially beyond the rooting zone.

There was higher soil moisture content at 1.8 m throughout the 2004 season in the low fertility treatment, NM (Fig. 4.5) compared with the rest of the treatments, indicating that pearl millet in the more fertile plots consumed more water during the course of the season, generally depleting the profile soil moisture content and preventing moisture movement to deeper soil layers.

Root zone drainage, ET, and ΔS

Change in root zone storage (ΔS) was negligible at Banizoumbou and ANOVA for root zone drainage and ET at Banizoumbou in 2004 (Appendix C-1 and C-2) showed significant differences due only to manure. Although fertilizer may have been expected to influence the water balance, the small quantities applied through microdose may have been insufficient to impact drainage and ET.

The hydraulic conductivity function used to compute D at Banizoumbou is shown in Fig. 4.6. Moisture content ranging from 0.04 to 0.10 $m^3 m^{-3}$ led to K ranging from 0 to 5.3 mm d^{-1}, which is very close to what Klaij and Vachaud (1992) found for similar soils in Niger and what Grema and Hess (1998) found for sandy soils in Nigeria. Manure effects on cumulative root zone drainage and ET are shown in Fig. 4.7. During the 2004 season, cumulative root zone drainage at Banizoumbou was highest in the low fertility treatments, NM and C2, and amounted to 30 % of total rainfall. The C0 and C1 treatments had the lowest root zone drainage in 2004 amounting to less than 10 % of total rainfall. The high fertility treatments, C0 and C1 had the highest water use of ~ 380 mm and the low fertility treatments, NM, C2 and TM had ~ 280 mm water use. Thus, recent corralling decreased root zone drainage and increased ET by about 100 mm. This increase in efficient water use from corralling is therefore temporary, and at least for this particular site, was not duplicated by transported manure, which is of dubious quality.

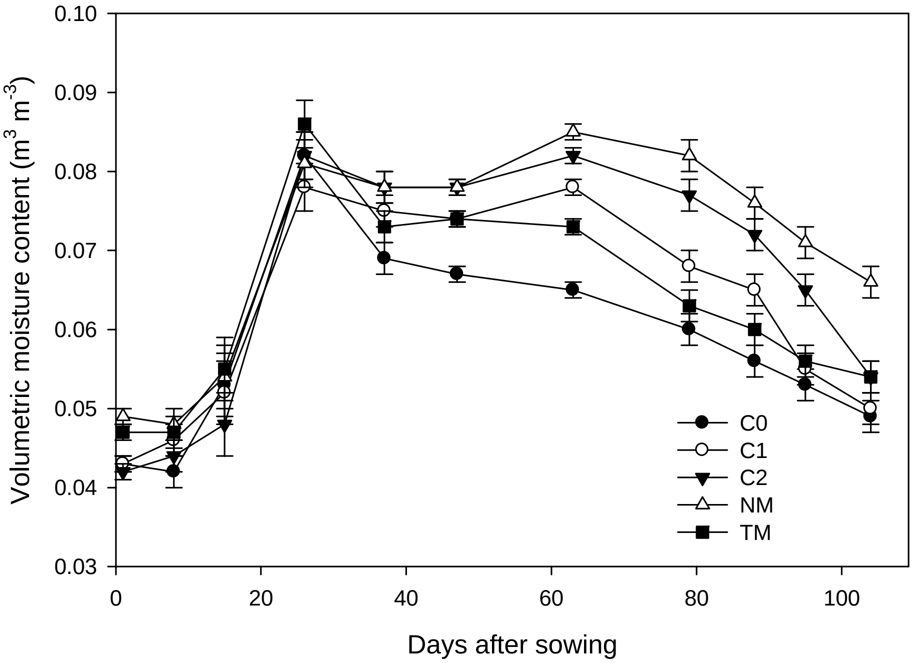


Figure 4.5. Manure effects on soil moisture content at maximum depth of measurement (1.8 m) at Banizoumbou in 2004. NM is no manure; TM is transported manure; C0 is current corralling; C1 is one year since last corralling; and C2 is two years since last corralling.

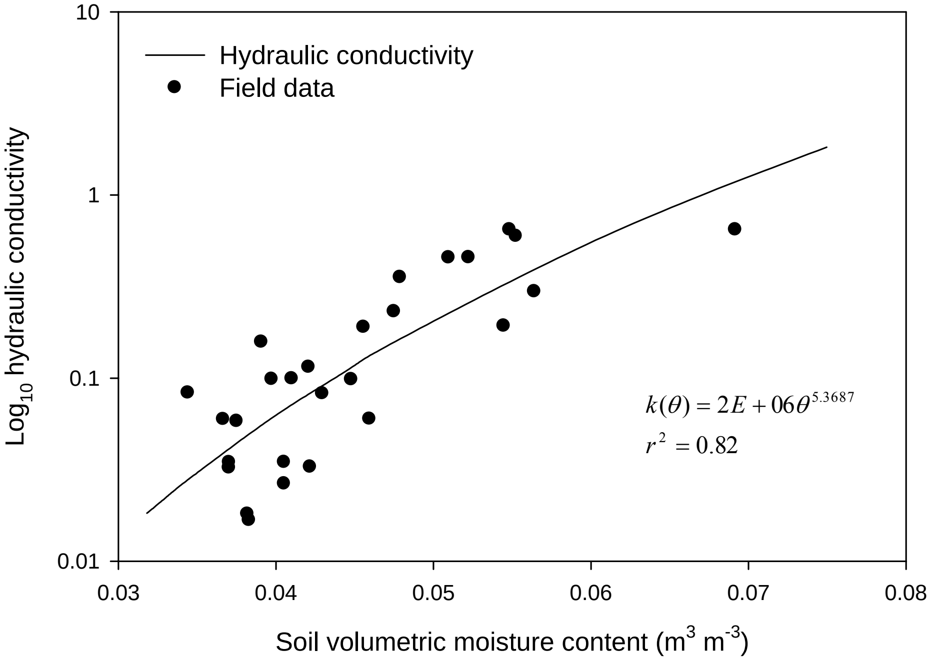
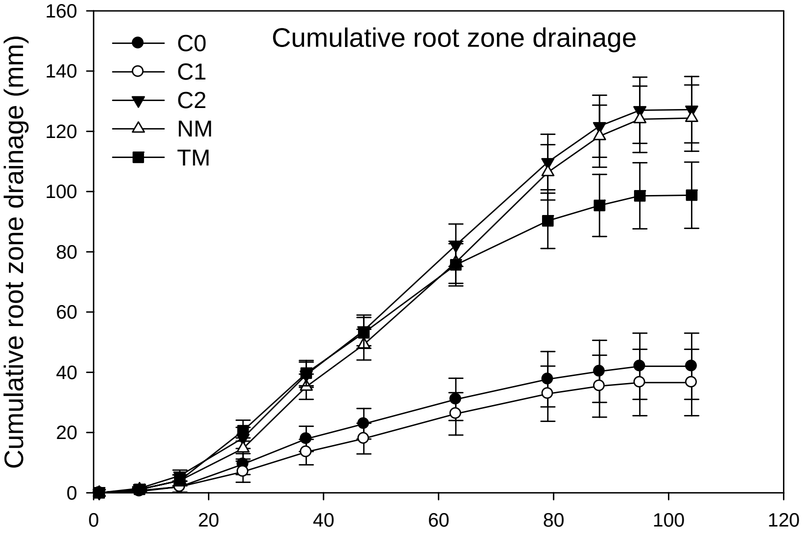


Figure 4.6. Hydraulic conductivity at maximum rooting depth (1.4 m) at Banizoumbou measured in 2004. Hydraulic conductivity units are mm d^{-1}.



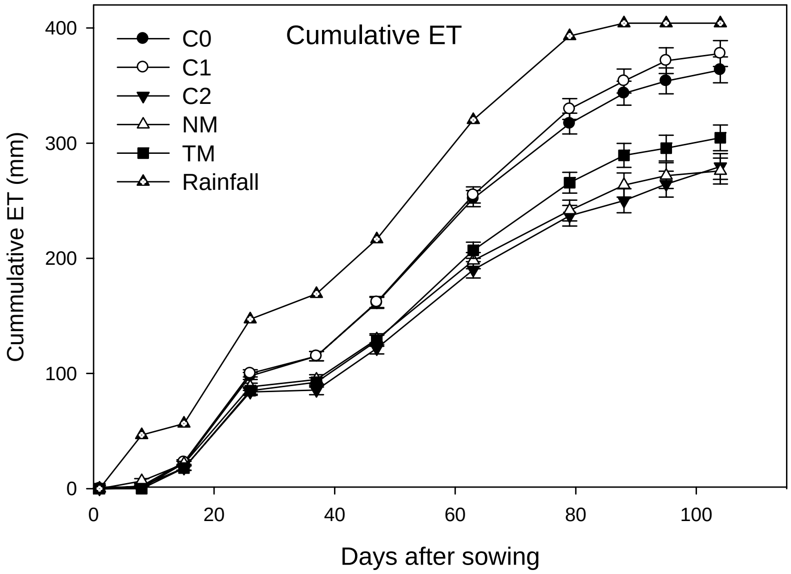


Figure 4.7. Manure effects on cumulative drainage and ET at Banizoumbou in 2004. NM is no manure; TM is transported manure; C0 is current corralling; C1 is one year since last corralling; and C2 is two years since last corralling.

Water use efficiency

ANOVA tables for treatment effects on pearl millet WUE at Banizoumbou are shown in Appendix C-3. Manure had the most significant effect ($p<0.001$) on the WUE at this site and hence results presented in Table 4.1 are only for manure effects.

Water use efficiency in 2004 was low but comparable to what has been reported in the region under Sahelian conditions (Payne, 1997; Rockström et al., 1998). In the water balance study by Payne (1997) for example, the author reported pearl millet grain WUE ranging from 1.4 to 3.5 kg ha^{-1} mm in the 1990 growing season, which apparently had similar rainfall total to Banizoumbou in 2004. However unlike the low total dry matter WUE in this study which ranged from 0.9 kg ha^{-1} mm^{-1} in the NM treatment to 6.2 kg ha^{-1} mm^{-1} in the C0 treatment, the author reported total biomass WUE ranging from 7.9 kg ha^{-1} mm^{-1} under low fertility to 19.9 kg ha^{-1} mm^{-1} under high fertility treatments. In Rockström et al., (1998) grain WUE for pearl millet ranged from 1.2 kg ha^{-1} mm^{-1} to 2.5 kg ha^{-1} mm^{-1} and total dry matter WUE ranged from 7 kg ha^{-1} mm^{-1} to 11 kg ha^{-1} mm^{-1}.

The low WUE at this site during this season resulted from the low pearl millet yields in 2004, which were caused by a shorter growing season and less total rainfall. However, currently corralled (C0) fields had WUE values more than five times higher than that in the control NM. Residual effects of corrals (C1 and C2) were effective in raising both grain and total dry matter WUE at this site to levels more than twice as high as the control.

The consistently high WUE in the corralling treatments, especially C0, shows the importance of this traditional practice in the rainfed subsistence farming system of the Fakara. Because highest WUE is achieved at the highest yields (Stewart, 1989) any management practices which improve pearl millet yields should also cause an increase in WUE.

Table 4.1. Manure effects on the water use efficiencies at Banizoumbou in 2004. NM is no manure; TM is transported manure; C0 is current corral; C1 is one year since last corralling; and C2 is two years since last corralling; TDM is total dry matter; and WUE is water use efficiency.

Manure treatment	Grain yield	TDM	WUE (Grain)	WUE (TDM)
	kg ha^{-1}	kg ha^{-1}	kg ha^{-1} mm^{-1}	kg ha^{-1} mm^{-1}
NM	95 a	354 a	0.3 a	0.9 a
TM	703 b	1976 bc	1.9 bc	5.4 bc
C0	851 c	2307 c	2.3 c	6.2 c
C1	635 b	1816 b	1.7 b	4.7 b
C2	321 d	910 d	0.9 d	2.4 d

†Means followed by the same letter and in the same column are not significantly different with LSD test at 5 % confidence level.

‡WUE=Yield/ET

Bagoua

Leaf area index

The LAI at Bagoua was measured using a leaf area meter at the beginning of the season and later calculated by relating leaf area to leaf dry weight as at Banizoumbou. The regression equation used to calculate LAI for the local cultivar was,

$$LAI = (0.022 \times DryWeight) - (0.0004 \times DryWeight^{2}) - 0.05; r^{2} = 0.98 , \qquad [4.11]$$

and for Zatib it was,

$$LAI = (0.024 \times DryWeight) - (0.00005 \times DryWeight^{2}) - 0.035; r^{2} = 0.98 . \qquad [4.12]$$

Fig. 4.8 shows the manure treatment effects on pearl millet LAI at Bagoua in 2004. The TM and C1 treatments which were planted 33 days earlier than the C0, C2 and NM treatments had their LAI measurements taken beginning at 70 days after sowing. The TM treatment was associated with the highest maximum LAI which was measured at around 70 days after sowing. The lowest maximum LAI was recorded in the low fertility treatments, C2 and NM. As at Banizoumbou, manure had a positive effect on pearl millet LAI on farmers' fields at the two sites.

The Bagoua site was associated with higher LAI in the TM treatment compared with the Banizoumbou site, possibly because of differences in the manure quality at the two sites. Manure transported to farmers' fields at Banizoumbou was composed mainly of straw (~ 90 %) and little fecal matter, whereas at Bagoua the manure was mainly composed of dung. However, as at Banizoumbou, manure quantities used at Bagoua reached ~ 8 Mg ha^{-1}, which most farmers may not be able to consistently apply every year on their fields especially to fields located far from the homestead.

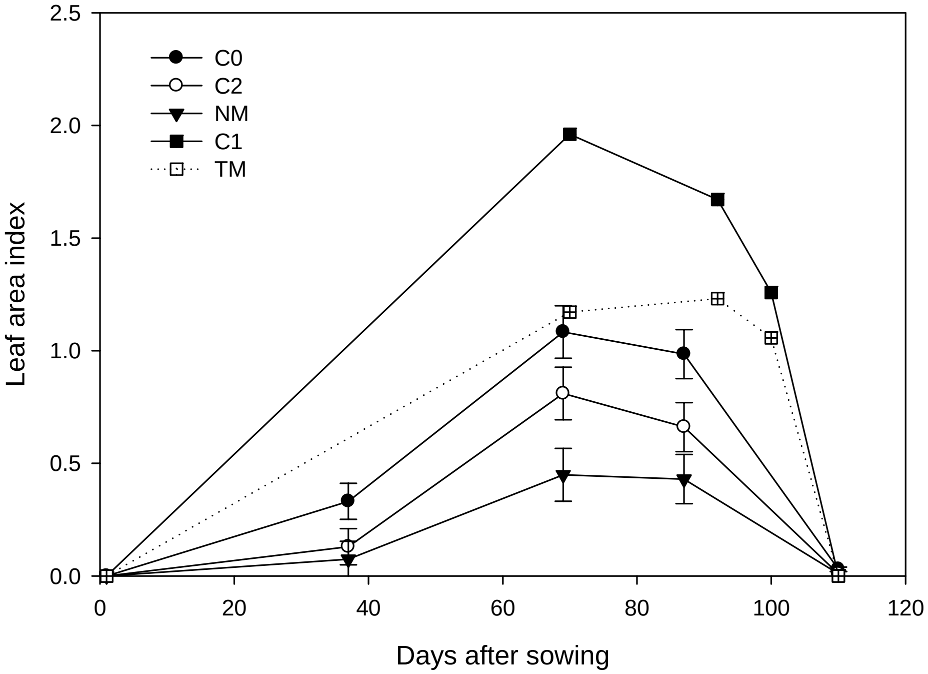


Figure 4.8. Manure effects on leaf area index at Bagoua. NM is no manure; TM is transported manure; C0 is current corralling; C2 is two years since last corralling; and C1 is one year since last corralling.

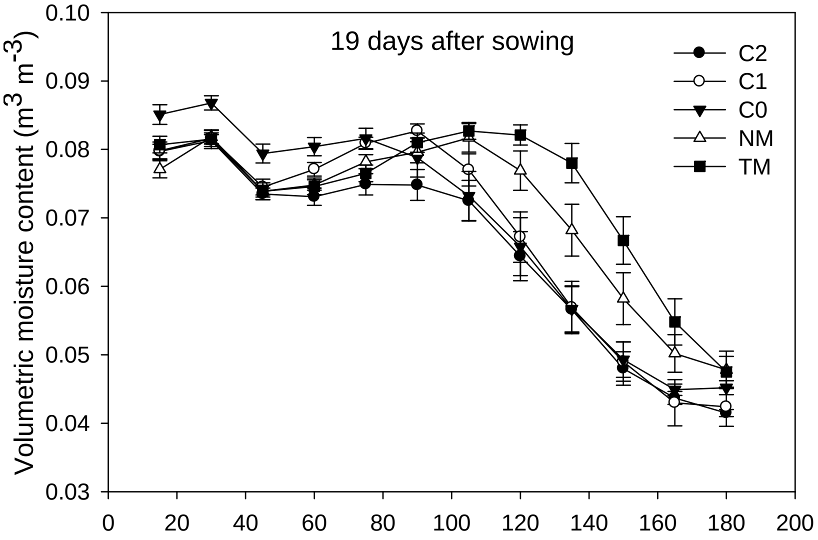
Soil profile moisture distribution

At the beginning of the 2003 growing season (Fig. 4.9), at 19 days after sowing the NM and TM treatments had the highest soil profile moisture. The difference in root zone moisture content was small and ranged from 107 mm in the C0 treatment to 117 mm in the TM treatment. At 34 days after sowing the NM and TM treatments continued to have higher profile moisture content especially below the 1.2 m. Towards the end of the season at 76 days after sowing (Fig. 4.10) the difference in profile moisture content among the treatments was small. At 86 days after sowing, the low fertility treatment, NM, had 14 mm more root zone moisture content than the current corralling treatment, C0. The higher residual root zone moisture content in the low fertility treatment is presumably the result of sparse root and canopy systems caused by low soil fertility.

In 2004 (Fig. 4.11) at 15 days after sowing the low fertility treatment, NM, had slightly higher residual profile moisture content compared with the other treatments. For example, NM had 75 mm within the root zone whereas the high fertility treatment, C0 had 62 mm soil moisture content. Towards the end of the season the low fertility treatments (NM and C2) had slightly higher residual root zone soil moisture content and moisture content ranged from 69 mm in the NM treatment to 88 mm in the C0 treatment. At the end of the 2004 growing season, the soil profile moisture content at 1.8 m was the same in all treatments (Fig. 4.12). However, during the course of the season, the low fertility treatments (NM and C2) had slightly higher soil profile moisture content compared with the C0 and TM treatments implying less water extraction in the lower fertility treatments compared with the high fertility ones.

Root zone drainage, ET and ΔS

ANOVA for root zone drainage and ET at Bagoua showed significant differences due to manure treatment but not to microdose (Appendix C-4 and C-5). As at Banizoumbou, the lack of response to microdose fertilizer was probably due to the low fertilizer quantities applied.



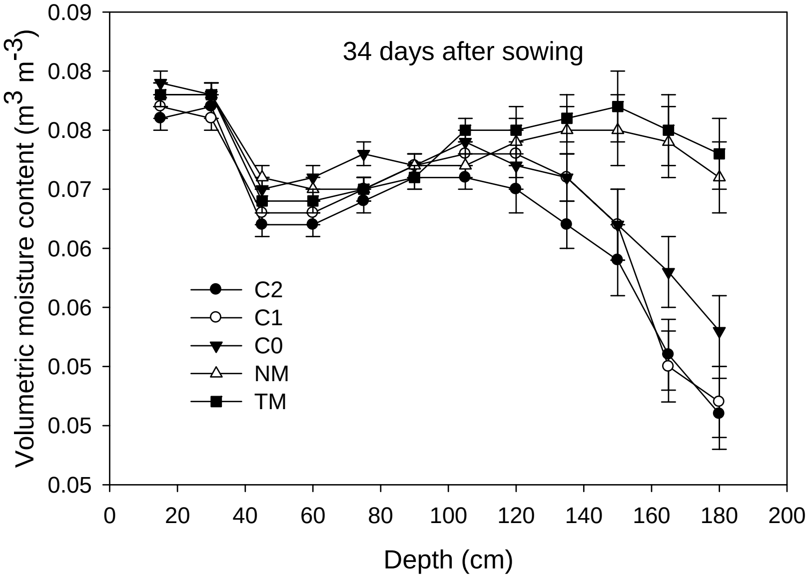


Figure 4.9. Soil profile moisture distribution at Bagoua in 2003. NM is no manure; TM is transported manure; C0 is current corralling; C1 is one year since last corralling; and C2 is two years since last corralling.

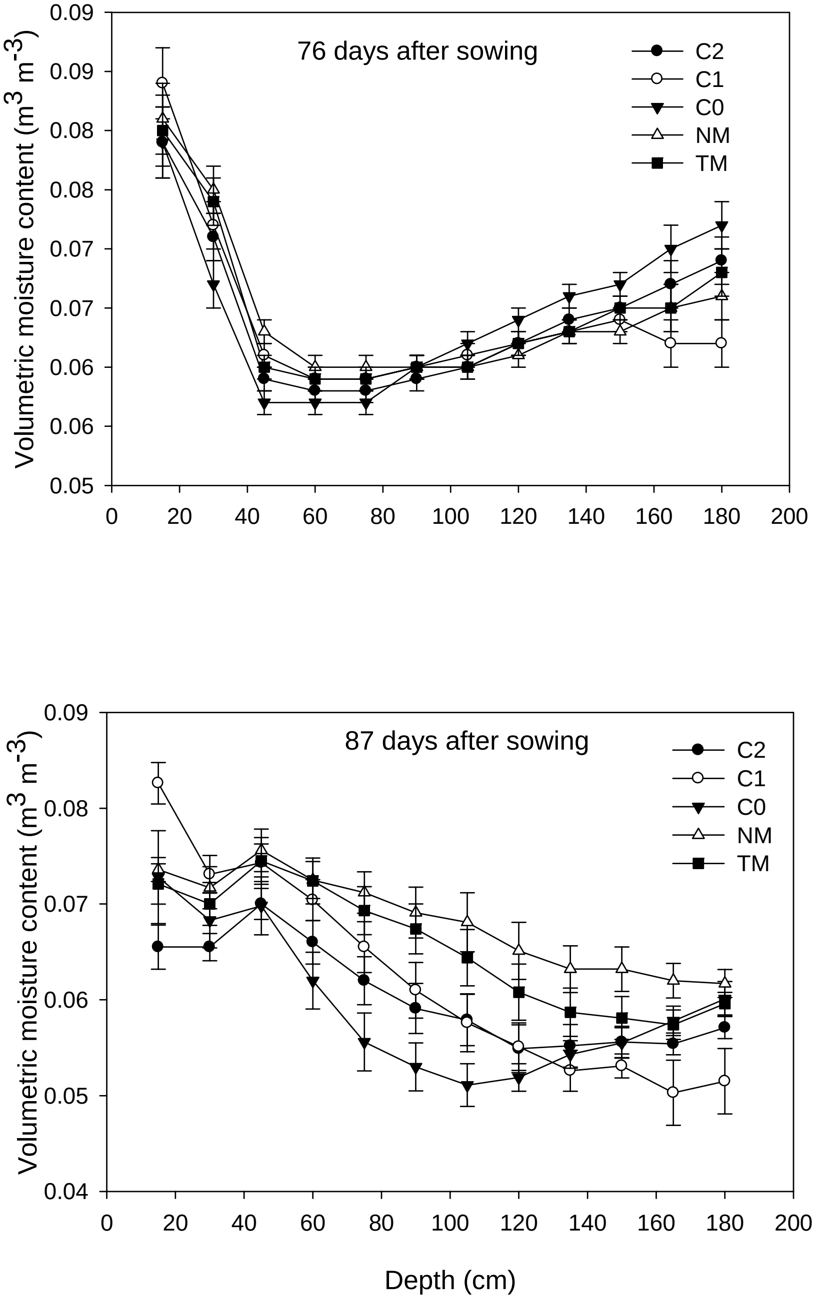


Figure 4.10. Soil profile moisture distribution at the end of the 2003 growing season at Bagoua. NM is no manure; TM is transported manure; C0 is current corralling; C1 is one year since last corralling; and C2 is two years since last corralling.

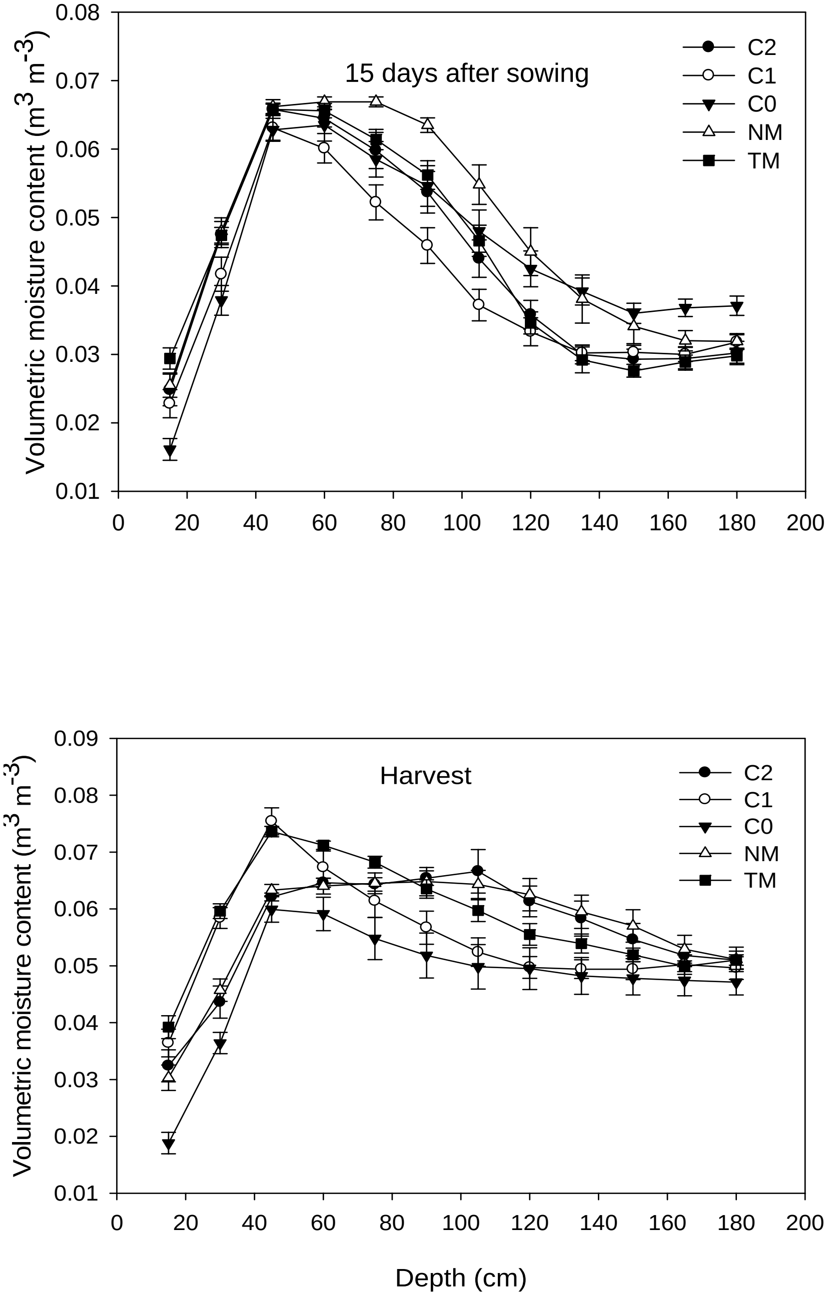


Figure 4.11. Soil profile moisture distribution at Bagoua in 2004. NM is no manure; TM is transported manure; C0 is current corralling; C1 is one year since last corralling; and C2 is two years since last corralling.

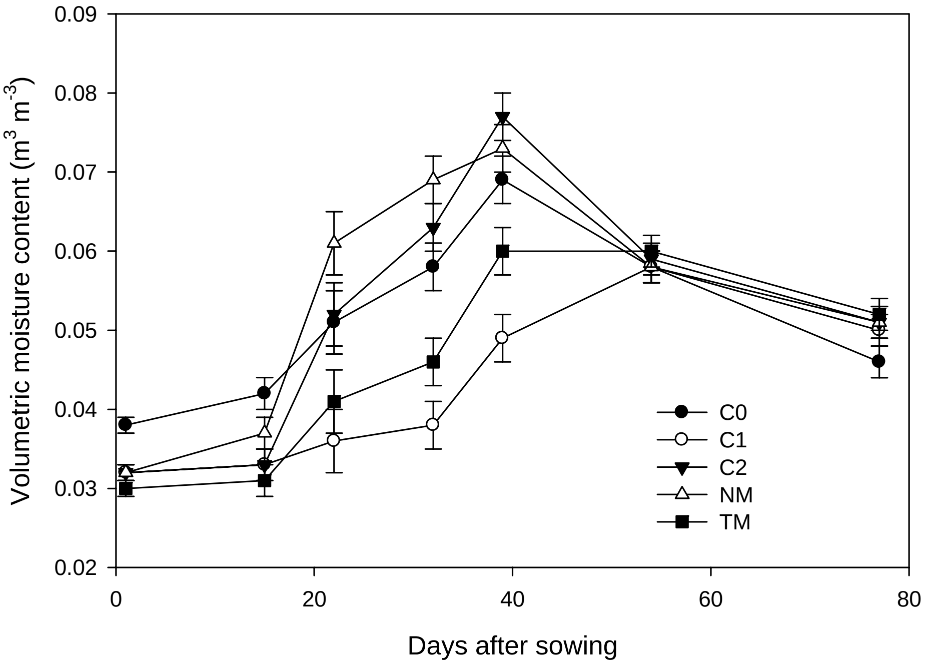


Figure 4.12. Manure effects on soil moisture content at the maximum depth of measurement (1.8 m) at Bagoua in 2004. NM is no manure; TM is transported manure; C0 is current corralling; C1 is one year since last corralling; and C2 is two years since last corralling.

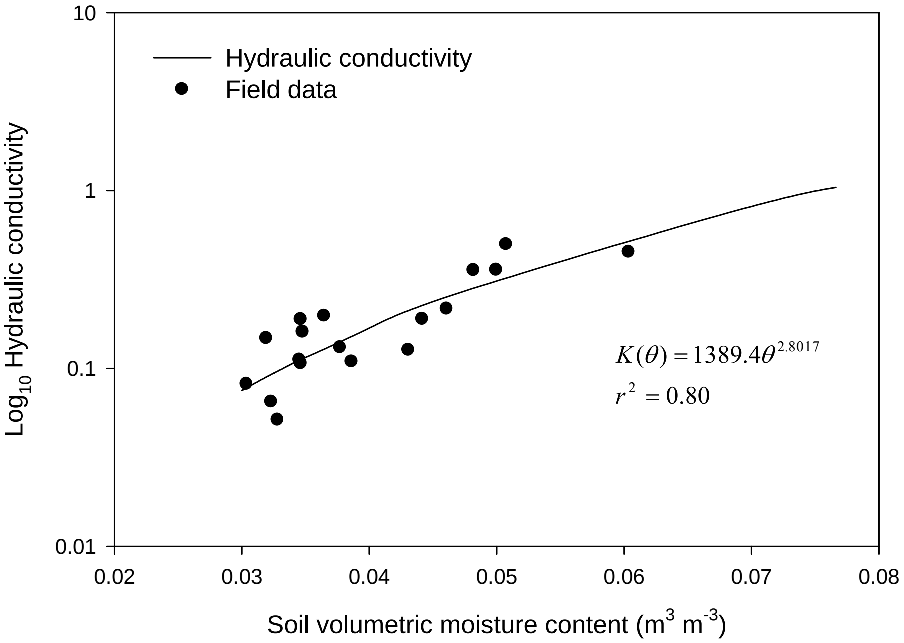


Figure 4.13. Hydraulic conductivity at maximum rooting depth (1.4 m) measured at Bagoua in 2004.

Change in root zone moisture storage at Bagoua was highest (20 mm) in the one year after corralling (C1) treatment and negligible in the current corralling (C0) treatment. Soil hydraulic conductivity at Bagoua is shown in Fig. 4.13 and manure effects on cumulative root zone drainage and ET are shown in Fig. 4.14. The response of drainage to manure treatment was pronounced at this site. The low fertility treatments, C2 and NM were associated with the highest drainage losses (~ 48 mm) associated with high water content at 1.8 m (Fig. 4.12). Such high root zone drainage under low fertility conditions have been reported in other studies on similar soils in Niger (Payne et al., 1990a; Klaij and Vachaud, 1992; Rockström et al., 1998). The lowest amount of root zone drainage, 15 mm, was in C1, which had been corralled the previous year. Pearl millet grown in the C1 and TM treatments had total ET values ~ 50 mm greater than the control NM treatment. There was no difference ET among the different manure treatments for most of the growing season.

Water use efficiency

The ANOVA table for manure effects on the WUE at Bagoua is presented in Appendix C-6. As at Banizoumbou, manure explained most of the differences in WUE and hence results presented in this section are for manure effects only. Generally the response of pearl millet WUE to manure treatments at Bagoua was not as high as at Banizoumbou.

The application of manure through corralling led to the doubling of the grain WUE from 1.7 kg ha^{-1} mm^{-1} in the NM treatment to 3.8 kg ha^{-1} mm^{-1} in the C0 treatment (Table 4.2). Residual effects of corralling on grain WUE apparently lasted only one year, similar to the Banizoumbou site, had disappeared two years after corralling (C2 treatment). In contrast to the Banizoumbou site, however, where transported manure TM did not increase grain WUE, the higher quality transported manure at Bagoua did increase WUE. For total dry matter production during this season, WUE increased from 6.1 kg ha^{-1} mm^{-1} in the NM treatment to 11.7 kg ha^{-1} mm^{-1} in the C0 treatment.

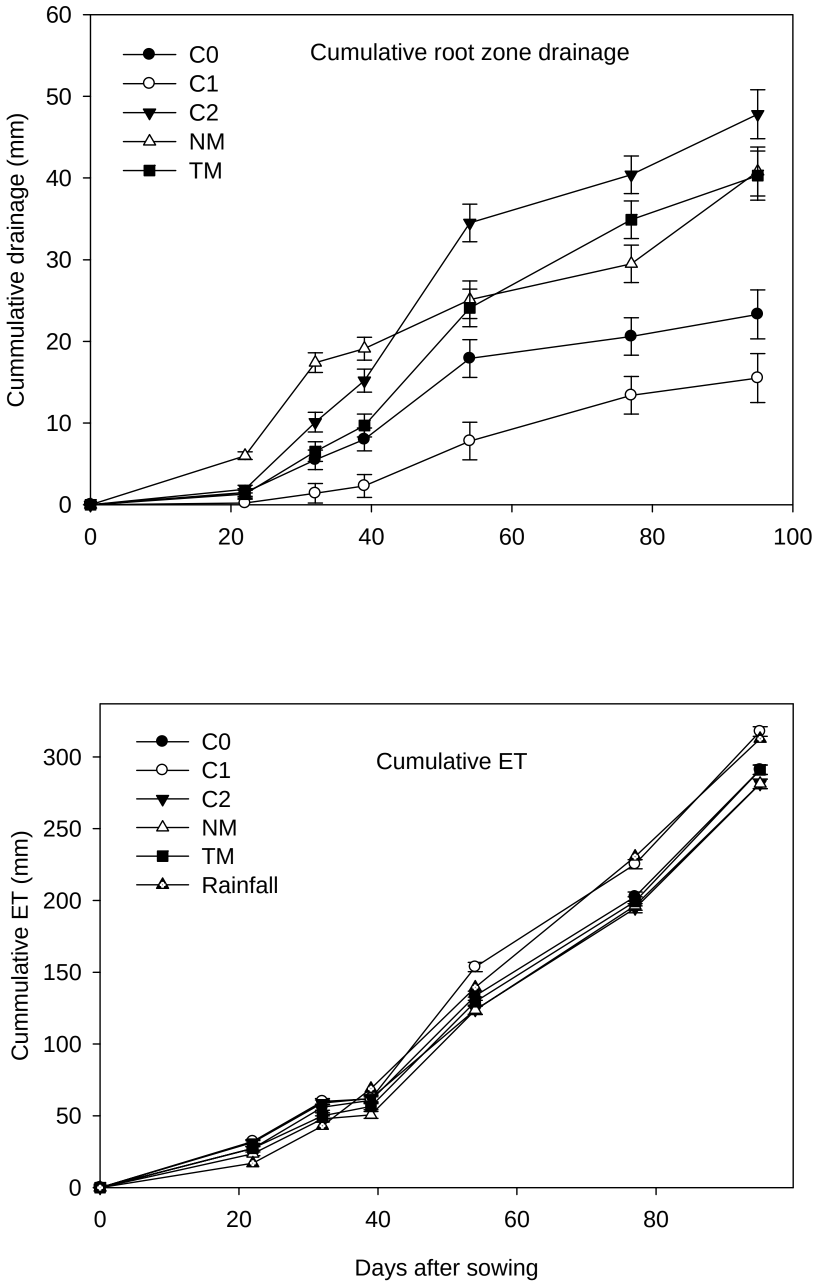


Figure 4.14. Manure effects on cumulative drainage and ET at Bagoua in 2004. NM is no manure; TM is transported manure; C0 is current corralling; C1 is one year since last corralling; and C2 is two years since last corralling.

Table 4.2. Manure effects on the water use efficiencies at Bagoua in 2004. NM is no manure; TM is transported manure; and C1 is one year since last corralling; TDM is total dry matter; and WUE is water use efficiency.

Manure treatment	**Grain yield**	**TDM**	**WUE (Grain)**	**WUE (TDM)**
	kg ha^{-1}	**kg ha^{-1}**	**kg ha^{-1} mm^{-1}**	**kg ha^{-1} mm^{-1}**
NM	**482 ab**	**1715 ab**	**1.7 a**	**6.1 ac**
TM	**721 bc**	**2910 cd**	**2.5 b**	**9.9 bc**
C0	**1108 d**	**3400 e**	**3.8 c**	**11.7 d**
C1	**847 c**	**2996 de**	**2.7 b**	**9.4 bc**
C2	**610 b**	**1875 b**	**2.2 a**	**6.7 c**

†Means followed by the same letter and in the same column are not significantly different with LSD test at 5 % confidence level.

‡WUE=Yield/ET

Response of WUE to manure at Bagoua was not as high as it was at Banizoumbou, presumably because fields used at Bagoua were closer to the farmers' homestead and are generally better managed during the growing season (Prudencio, 1983). The Bagoua site also had slightly higher available P before the experiment started.

Discussion

Water balance data from this study have shown that it is possible to manipulate the water balance components (ET, ΔS, and D) by corralling.

The high fertility treatments (C1 and C0) consistently resulted in the lowest D at both sites. The NM treatment at Bagoua resulted in D up to 12.5 % of total rainfall and at Banizoumbou D in the NM treatment was ~30 % of total rainfall. Such high D in the low input system especially at Banizoumbou emphasizes the low efficiency of water use under subsistence farmer management. By reducing D with manure application in the high fertility treatments (C1 and C0), ET was increased by up to 100 mm at Banizoumbou and 50 mm at Bagoua without causing moisture stress during the growing season as evidenced by consistently high pearl millet yields. Although this study did not measure transpiration and evaporation separately, the fact that corralled fields were associated with the highest maximum LAI, higher WUE and total dry matter implies that corralling led to an increase in transpiration at the expense of soil evaporation.

The cumulative change in root zone moisture storage at the end of the season, ΔS, at Banizoumbou was negligible. At Bagoua cumulative ΔS was negligible only in the current corral (C0) and highest (20 mm) one year after corralling (C0). Pearl millet grown under corralling extracted more moisture from the root zone at both sites as evidenced by the consistently lower end of season root zone storage under corralling vs. the low fertility treatments (NM and C2). The presence of moisture in the root zone at the end of the season especially in the low fertility treatments, has been previously reported in other studies in the region (Payne et al., 1990a; Payne et al., 1991b; Payne et al., 1991a; Klaij and Vachaud, 1992; Rockström et al., 1998) and was the reason for higher residual moisture content measured in the low fertility treatments at the beginning of the 2004 season. Presence of moisture within the root zone at the end of the season accentuates the fact that water may not always be the limiting factor under low input pearl millet in the Sahel.

Residual effects of corralling on yields at both sites were still significant in the second year but for D, ET, and WUE residual effects only lasted one year and disappeared in the second year suggesting that corralling may have to be done once every two years to increase pearl millet water use on farmers' fields. Generally, pearl millet WUE at the two sites was low but comparable to previous reports for the region and similar soils (Payne, 1997; Rockström et al., 1998; Oluwasemire et al., 2002). The low WUE especially at Banizoumbou can be attributed to low pearl millet LAI in farmers' fields which may have resulted in a larger proportion of rainfall being lost as soil evaporation. On the other hand, the quantities of manure required to raise pearl millet LAI high enough to reduce soil evaporation (e.g. 8 Mg manure ha^{-1} in current corralling) are out of the reach of most subsistence farmers in the region (Wezel and Haigis, 2002; Schlecht and Buerkert, 2004; Schlecht et al., 2004). In addition to the low quantity of manure, manure quality also plays an important role as evidenced by the failure of transported manure to raise WUE significantly at Banizoumbou compared with transported manure at Bagoua.

No pearl millet cultivar effects were observed for the water balance at the two sites and the microdose technology did not decrease D, increase ET or pearl millet WUE at the two sites. It may be appropriate to combine the microdose with modest manure applications (< 8 Mg ha^{-1}) to cause an increase in pearl millet water use and raise pearl millet yields under subsistence farmer management in the Fakara. Such an approach may be even more appropriate for the subsistence farmers in the Fakara who cannot afford high fertilizer costs and cannot consistently apply manure to all their fields.

CHAPTER V

OVERALL CONCLUSIONS AND RECOMMENDATIONS

Based on the yield and water balance data from this study, the following conclusions can be made:

1. Manure application through corralling cattle on fields remains a very important practice for maintaining soil fertility and sustaining millet yields under subsistence farmer management in the Fakara region especially in the face of shortening fallows and unaffordable fertilizer prices.
2. Corralling reduces root zone drainage and increases evapotranspiration on pearl millet fields without posing a risk of water constraint during the growing season.
3. The microdose technology is effective in raising pearl millet yields only under very low soil fertility conditions but has no significant effect on the water balance (D, S and ET) of the sandy soils grown to pearl millet in the Fakara. The fact that there was usually no difference in the yield response to either DAP or DAP + U, seems to suggest that P may have been more limiting since the additional N supplied by urea in the latter treatment did not increase yields.
4. The improved pearl millet cultivars generally outperformed the local landrace for grain yields but not for straw yields.

The following recommendations can thus be made:

1. Because the residual effects of manure were effective in raising pearl millet yields even two years after last corralling, farmers can be encouraged to corral cattle on their fields at least once every three years. In addition, farmers can also be encouraged to ensure that manure is not concentrated only on smaller areas of the fields, but spread out more evenly to reduce spatial variability of millet growth and yields whilst curbing wasteful losses like leaching.

2. For microdose to be more effective in raising millet yields and positively impact the water balance on farmers' fields, the technology's current fertilizer rates must be raised to supply at least the critical P level so that millet response to N can be realized. Alternatively, the microdose technology may be combined with modest manure applications (e.g. < 8 Mg ha^{-1}) to raise millet water use and yields.

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APPENDIX A

ANOVA TABLES FOR PEARL MILLET YIELDS AT BANIZOUMBOU AND BAGOUA

A-1. ANOVA for within block treatment effects on pearl millet grain yields at Banizoumbou in 2003 and 2004.

Year	Source of variation		Manure treatment				
			NM	TM	C2	C1	C0
2003	**Fertilizer**	**SS**	**334446**	**3973**	**60129**	**427935**	**726817**
		df	**2**	**2**	**2**	**2**	**2**
		P value	**0.001**	**0.943**	**0.624**	**0.111**	**0.361**
	Cultivar	**SS**	**103107**	**127226**	**84100**	**101655**	**466235**
		df	**2**	**2**	**2**	**2**	**2**
		P value	**0.073**	**0.180**	**0.521**	**0.563**	**0.513**
	Fertilizer * Cultivar	**SS**	**59395**	**184348**	**253601**	**52564**	**2015737**
		df	**4**	**4**	**4**	**4**	**4**
		P value	**0.497**	**0.284**	**0.424**	**0.959**	**0.245**
2004	**Fertilizer**	**SS**	**194859**	**913234**	**679418**	**87765**	**470902**
		df	**2**	**2**	**2**	**2**	**2**
		P value	**0.007**	**0.004**	**0.000**	**0.745**	**0.072**
	Cultivar	**SS**	**49123**	**507177**	**126520**	**14044**	**1029258**
		df	**2**	**2**	**2**	**2**	**2**
		P value	**0.216**	**0.030**	**0.133**	**0.953**	**0.007**
	Fertilizer * Cultivar	**SS**	**27635**	**200626**	**15126**	**198677**	**443960**
		df	**4**	**4**	**4**	**4**	**4**
		P value	**0.758**	**0.513**	**0.967**	**0.848**	**0.262**

A-2. ANOVA for within block treatment effects on pearl millet straw yields at Banizoumbou in 2003 and 2004.

			Manure treatment				
Year	**Source of variation**		**NM**	**TM**	**C2**	**C1**	**C0**
2003	**Fertilizer**	**SS**	**2078782**	**7306**	**699342**	**5161439**	**2196187**
		df	**2**	**2**	**2**	**2**	**2**
		P value	**0.001**	**0.991**	**0.678**	**0.125**	**0.824**
	Cultivar	**SS**	**1266089**	**820305**	**335813**	**1002727**	**10613563**
		df	**2**	**2**	**2**	**2**	**2**
		P value	**0.008**	**0.156**	**0.828**	**0.642**	**0.406**
	Fertilizer * Cultivar	**SS**	**162661**	**335777**	**4817773**	**611245**	**39349793**
		df	**4**	**4**	**4**	**4**	**4**
		P value	**0.798**	**0.514**	**0.284**	**0.966**	**0.182**
2004	**Fertilizer**	**SS**	**507853**	**859680**	**954668**	**87997**	**852939**
		df	**2**	**2**	**2**	**2**	**2**
		P value	**0.002**	**0.045**	**0.000**	**0.833**	**0.010**
	Cultivar	**SS**	**56989**	**105900**	**69545**	**142555**	**187497**
		df	**2**	**2**	**2**	**2**	**2**
		P value	**0.372**	**0.641**	**0.427**	**0.745**	**0.290**
	Fertilizer * Cultivar	**SS**	**60176**	**563445**	**19020**	**1044702**	**618158**
		df	**4**	**4**	**4**	**4**	**4**
		P value	**0.700**	**0.340**	**0.973**	**0.389**	**0.111**

A-3. ANOVA for within block treatment effects on grain yields at Bagoua in 2003 and 2004.

Year	Source of variation		Manure treatment				
			NM	TM	C2	C1	C0
2003	Fertilizer	SS	4850	33419	109412	166431	18515
		Df	2	2	2	2	2
		P value	0.869	0.678	0.182	0.029	0.850
	Cultivar	SS	6607	169832	294890	242563	80531
		Df	2	2	2	2	2
		P value	0.827	0.161	0.018	0.008	0.510
	Fertilizer * Cultivar	SS	95060	210901	221705	28050	125085
		Df	4	4	4	4	4
		P value	0.279	0.324	0.155	0.831	0.699
2004	Fertilizer	SS	285382	155434	922843	5529	78408
		Df	2	2	2	2	2
		P value	0.027	0.034	0.000	0.971	0.499
	Cultivar	SS	37716	69003	131021	60492	546450
		Df	2	2	2	2	2
		P value	0.565	0.191	0.047	0.730	0.018
	Fertilizer * Cultivar	SS	380825	124325	9518	106345	439972
		df	4	4	4	4	4
		P value	0.047	0.208	0.969	0.886	0.133

A-4. ANOVA for within block treatment effects on straw yields at Bagoua in 2003 and 2004.

			Manure treatment				
Year	**Source of variation**		**NM**	**TM**	**C2**	**C1**	**C0**
2003	**Fertilizer**	**SS**	**48140**	**454878**	**114491**	**3070914**	**868924**
		Df	**2**	**2**	**2**	**2**	**2**
		P value	**0.888**	**0.759**	**0.860**	**0.049**	**0.504**
	Cultivar	**SS**	**408214**	**4631581**	**5248245**	**1020899**	**3220949**
		Df	**2**	**2**	**2**	**2**	**2**
		P value	**0.382**	**0.084**	**0.006**	**0.327**	**0.111**
	Fertilizer * Cultivar	**SS**	**596047**	**3208307**	**5157104**	**341440**	**124176**
		Df	**4**	**4**	**4**	**4**	**4**
		P value	**0.576**	**0.440**	**0.030**	**0.936**	**0.722**
2004	**Fertilizer**	**SS**	**1745925**	**532512**	**2296588**	**1569958**	**457659**
		Df	**2**	**2**	**2**	**2**	**2**
		P value	**0.002**	**0.498**	**0.000**	**0.166**	**0.385**
	Cultivar	**SS**	**53006**	**1424470**	**610129**	**1689658**	**1526686**
		Df	**2**	**2**	**2**	**2**	**2**
		P value	**0.770**	**0.173**	**0.021**	**0.146**	**0.057**
	Fertilizer * Cultivar	**SS**	**772070**	**631683**	**164149**	**649011**	**292795**
		df	**4**	**4**	**4**	**4**	**4**
		P value	**0.149**	**0.785**	**0.633**	**0.798**	**0.859**

A-5. Combined ANOVA for grain yields at Bagoua and Banizoumbou in 2003 and 2004.

Year	Source of variation	SS	df	MS	F	Sig.
2003	Site	601890	1	601890	7.5	0.007
	Manure	19929256	4	4982314	62.1	0.000
	Fertilizer	88037	2	44019	0.55	0.578
	Cultivar	963607	2	481803	6	0.003
	Cultivar * Fertilizer	629451	4	157363	2	0.101
	Site * Cultivar	10513	2	5256	0.07	0.937
	Site * Fertilizer	92518	2	46259	0.6	0.562
	Error	19648595	245	80198		
2004	Site	3244156	1	3244156	54.9	0.000
	Manure	17145704	4	4286426	72.5	0.000
	Fertilizer	2334299	2	1167150	19.8	0.000
	Cultivar	1521180	2	760590	12.9	0.000
	Cultivar * Fertilizer	144919	4	36230	0.6	0.654
	Site * Cultivar	285514	2	142757	2.4	0.091
	Site * Fertilizer	70434	2	35217	0.6	0.552
	Error	14891409	252	59093		

A-6. Combined ANOVA for straw yields at Bagoua and Banizoumbou in 2003 and 2004.

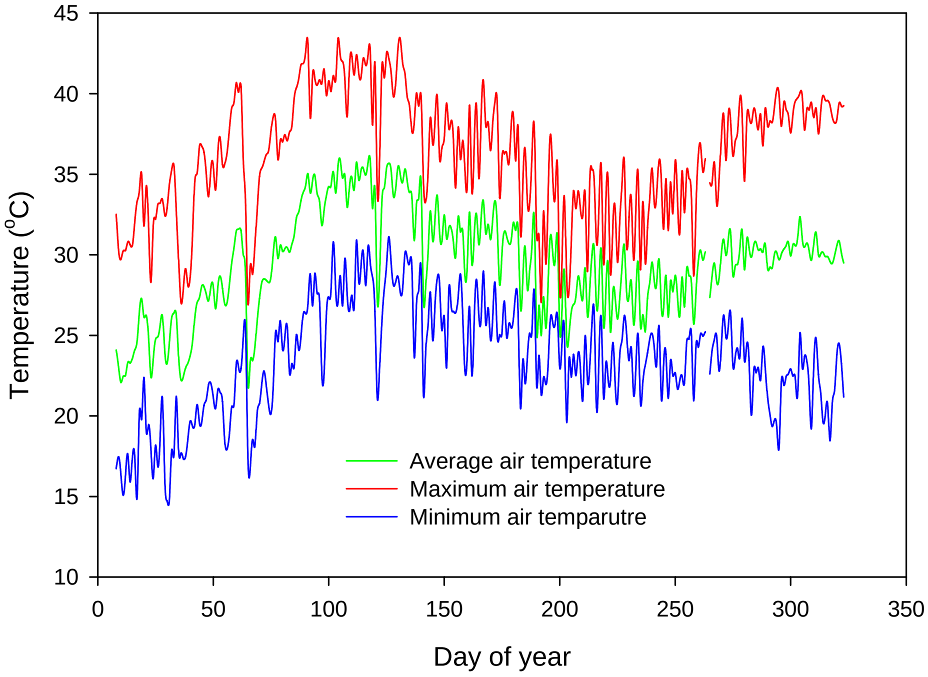
Year	Source of variation	SS	df	MS	F	Sig.
2003	**Site**	**27166216**	**1**	**27166216**	**21.2**	**0.000**
	Manure	**294052172**	**4**	**73513043**	**57.3**	**0.000**
	Fertilizer	**2418360**	**2**	**1209180**	**0.9**	**0.391**
	Cultivar	**19448084**	**2**	**9724042**	**7.6**	**0.001**
	Cultivar * Fertilizer	**8532676**	**4**	**2133169**	**1.7**	**0.159**
	Site * Fertilizer	**865985**	**2**	**432993**	**0.3**	**0.714**
	Site * Cultivar	**352964**	**2**	**176482**	**0.1**	**0.871**
	Error	**323165742**	**252**	**1282404**		
2004	**Site**	**38799418**	**1**	**38799418**	**240.9**	**0.000**
	Manure	**35322086**	**4**	**8830521**	**54.8**	**0.000**
	Fertilizer	**5972262**	**2**	**2986131**	**18.5**	**0.000**
	Cultivar	**1732597**	**2**	**866299**	**5.4**	**0.005**
	Cultivar * Fertilizer	**333078**	**4**	**83270**	**0.5**	**0.723**
	Site * Fertilizer	**409902**	**2**	**204951**	**1.3**	**0.282**
	Site * Cultivar	**2395691**	**2**	**1197845**	**7.4**	**0.001**
	Error	**40582352**	**252**	**161041**		

APPENDIX B

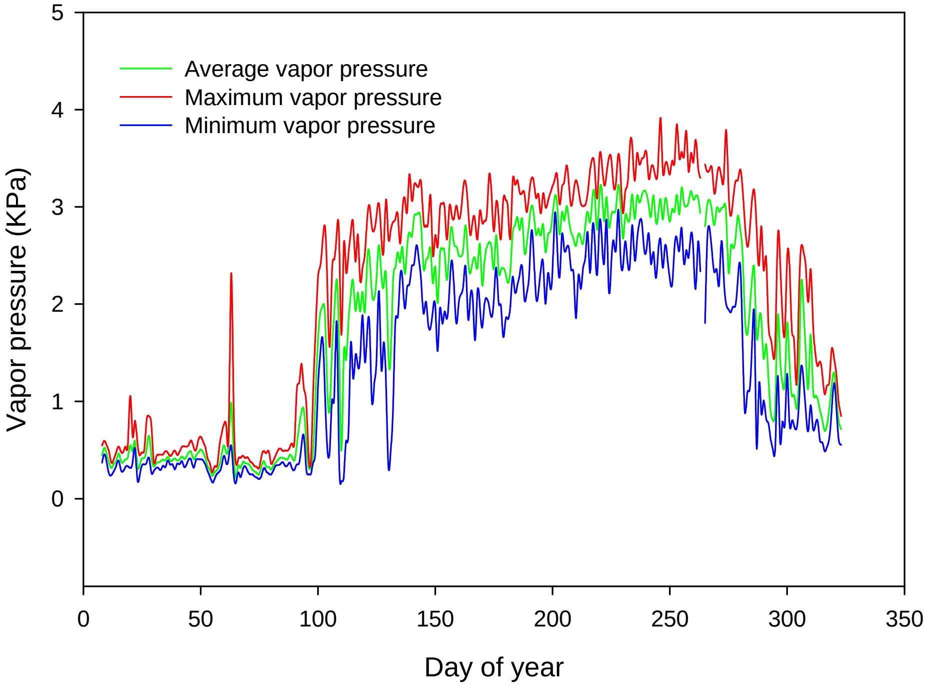
METEOROLOGICAL DATA FOR STUDY SITES

B-1. Total rainfall measured at the study sites.

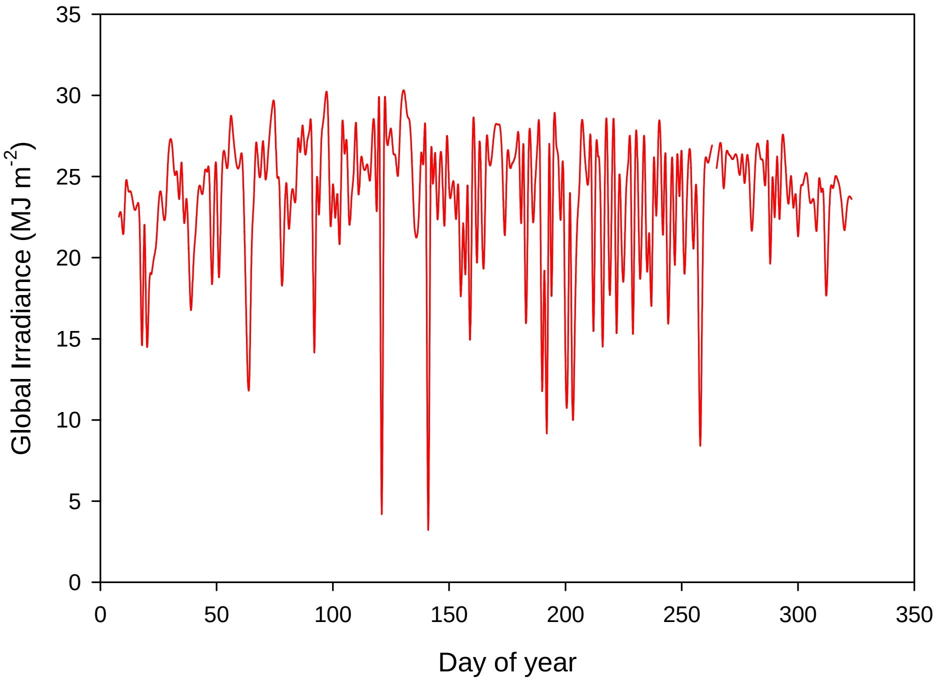
Month	2003		2004	
	Banizoumbou	Bagoua	Banizoumbou	Bagoua
	mm			
May	0	0	45	40
June	119	138	50	55
July	103	49	121	94
August	187	166	173	116
September	65	100	84	83
Total	474	452	472	432



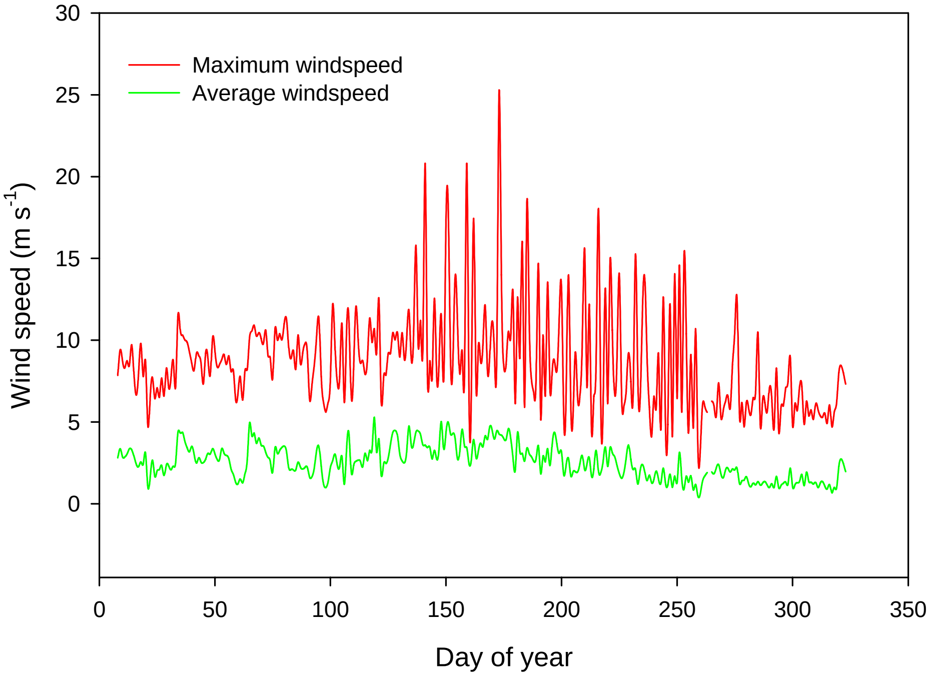
B-2. Daily air temperature at Katanga village in 2004



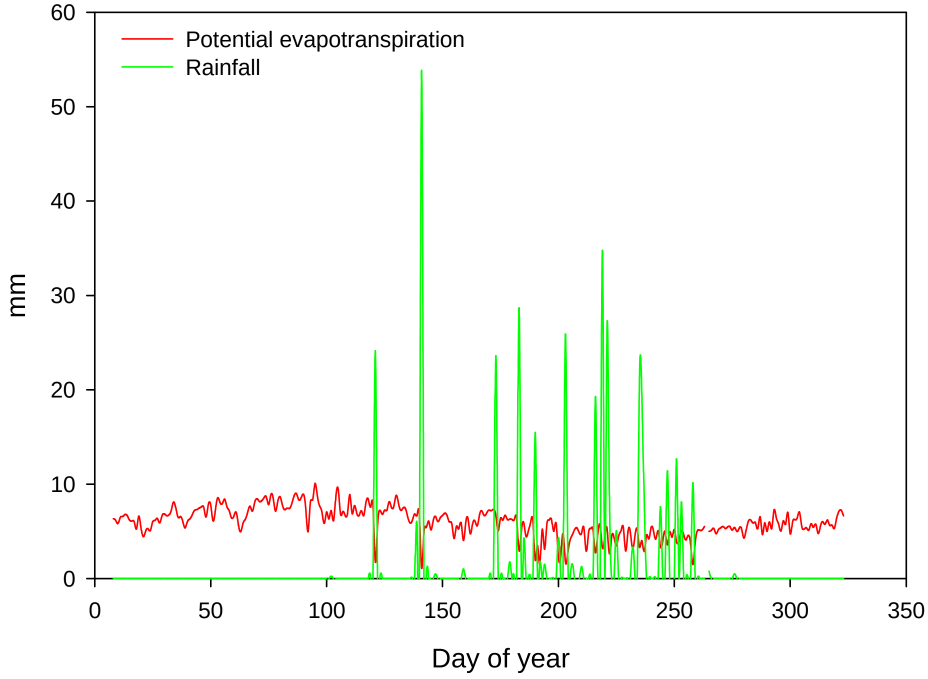
B-3. Daily vapor pressure at Katanga village in 2004



B-4. Daily total radiation at Katanga village in 2004.



B-5. Daily wind speed at Katanga village in 2004



B-6. Daily rainfall and potential evapotranspiration at Katanga village in 2004.

APPENDIX C

ANOVA TABLES FOR WATER BALANCE TERMS IN 2003 AND 2004

C-1. ANOVA for treatment effects on drainage and evapotranspiration at Banizoumbou in 2003.

Water balance term	Source of variation	SS	df	MS	F	Sig.
Drainage	Manure	1528	4	382	14.8	0.000
	Fertilizer	22	2	11	0.4	0.652
	Cultivar	7	1	7	0.3	0.607
	Fertilizer * Cultivar	2.5	2	1.2	0.01	0.953
	Error	2076	80	26		
Evapotranspiration	Manure	7884	4	1971	16.5	0.000
	Fertilizer	190	2	95	0.8	0.454
	Cultivar	379	1	379	3.2	0.078
	Fertilizer * Cultivar	613	2	307	2.6	0.083
	Error	9550	80	119		

C-2. ANOVA for treatment effects on drainage and evapotranspiration at Banizoumbou in 2004.

Water balance term	Source of variation	SS	df	MS	F	Sig.
Drainage	Manure	235	4	59	3.3	0.016
	Fertilizer	28	2	14	0.8	0.460
	Cultivar	0.01	1	0.01	0	0.976
	Fertilizer * Cultivar	32	2	16.1	0.9	0.414
	Error	1444	80	18.1		
Evapotranspiration	Manure	2072	4	518	5.5	0.001
	Fertilizer	206	2	103	1.1	0.339
	Cultivar	22	1	21.8	0.2	0.632
	Fertilizer * Cultivar	22	2	11	0.1	0.890
	Error	7531	80	94		

C-3. ANOVA for treatment effects on water use efficiency at Banizoumbou in 2003 and 2004.

Year	Source of variation	SS	df	MS	F	Sig.
2003	Manure	195.8	4	48.9	36.9	0.000
	Fertilizer	11.2	2	5.6	4.2	0.018
	Cultivar	6.0	1	6.0	4.5	0.037
	Fertilizer * Cultivar	1.5	2	0.7	0.6	0.578
	Error	106.1	80	1.3		
2004	Manure	49.4	4	12.3	35.1	0.000
	Fertilizer	10.8	2	5.4	15.3	0.000
	Cultivar	3.2	1	3.2	9.1	0.003
	Fertilizer * Cultivar	0.03	2	0.02	0.05	0.954
	Error	28.2	80	0.4		

C-4. ANOVA for treatment effects on drainage and evapotranspiration at Bagoua in 2003.

Water balance term	Source of variation	SS	df	MS	F	Sig.
Drainage	**Manure**	**24485**	**4**	**12243**	**37.2**	**0.000**
	Fertilizer	**882**	**2**	**441**	**1.3**	**0.272**
	Cultivar	**22**	**1**	**22**	**0.1**	**0.798**
	Fertilizer * Cultivar	**299**	**2**	**150**	**0.5**	**0.638**
	Error	**13810**	**80**	**329**		
Evapotranspiration	**Manure**	**24043**	**4**	**12021**	**30.8**	**0.000**
	Fertilizer	**447**	**2**	**223**	**0.6**	**0.568**
	Cultivar	**101**	**1**	**101**	**0.3**	**0.614**
	Fertilizer * Cultivar	**545**	**2**	**272**	**0.7**	**0.503**
	Error	**16352**	**80**	**389**		

C-5. ANOVA for treatment effects on drainage and evapotranspiration at Bagoua in 2004.

Water balance term	Source of variation	SS	df	MS	F	Sig.
Drainage	**Manure**	**13183**	**4**	**3296**	**20.4**	**0.000**
	Fertilizer	**188**	**2**	**94**	**0.6**	**0.561**
	Cultivar	**338**	**1**	**338**	**2.1**	**0.152**
	Fertilizer * Cultivar	**121**	**2**	**61**	**0.4**	**0.689**
	Error	**12929**	**80**	**162**		
Evapotranspiration	**Manure**	**16081**	**4**	**4020**	**20.0**	**0.000**
	Fertilizer	**274**	**2**	**137**	**0.7**	**0.508**
	Cultivar	**315**	**1**	**315**	**1.6**	**0.214**
	Fertilizer * Cultivar	**170**	**2**	**85**	**0.4**	**0.656**
	Error	**16043**	**80**	**201**		

C-6. ANOVA for treatment effects on water use efficiency at Bagoua in 2003 and 2004.

Year	Source of variation	SS	df	MS	F	Sig.
2003	**Manure**	**5.7**	**2**	**2.8**	**7.1**	**0.002**
	Fertilizer	**0.2**	**2**	**0.1**	**0.2**	**0.786**
	Cultivar	**1.0**	**1**	**1.0**	**2.6**	**0.114**
	Fertilizer * Cultivar	**0.2**	**2**	**0.1**	**0.2**	**0.825**
	Error	**18.5**	**46**	**0.4**		
2004	**Manure**	**386.8**	**4**	**96.7**	**18.9**	**0.000**
	Fertilizer	**75.2**	**2**	**37.6**	**7.3**	**0.001**
	Cultivar	**25.3**	**1**	**25.3**	**4.9**	**0.029**
	Fertilizer * Cultivar	**9.6**	**2**	**4.8**	**0.9**	**0.395**
	Error	**410.1**	**80**	**5.1**		

APPENDIX D

REGIONAL FOOD ESTIMATES

Predicting pearl millet grain yields from ET in the west African Sahel is difficult (Klaij and Vachaud, 1992) mainly because grain yield of low LAI pearl millet is largely independent of ET (Payne, 1997). This poor correlation is a result of the relative insensitivity of ET to management (see Chapter IV) for crops with low LAI. However for predictive purposes, others have used empirical linear equations relating pearl millet yield to ET as a function of management intensity and after making appropriate corrections for mean daily vapor pressure deficit during the growing season (Payne, 1997). This chapter will focus on predicting millet grain yields for various soil fertility and rainfall regimes in the Fakara region based on WUE estimates previously calculated in Chapter IV. For simplification, all the rainfall is assumed to be used for ET. The main objective is to forecast grain yields based on seasonal rainfall and present an opportunity to mitigate the effects of drought-induced food shortages in the ten villages in the Fakara region (Appendix D-1).

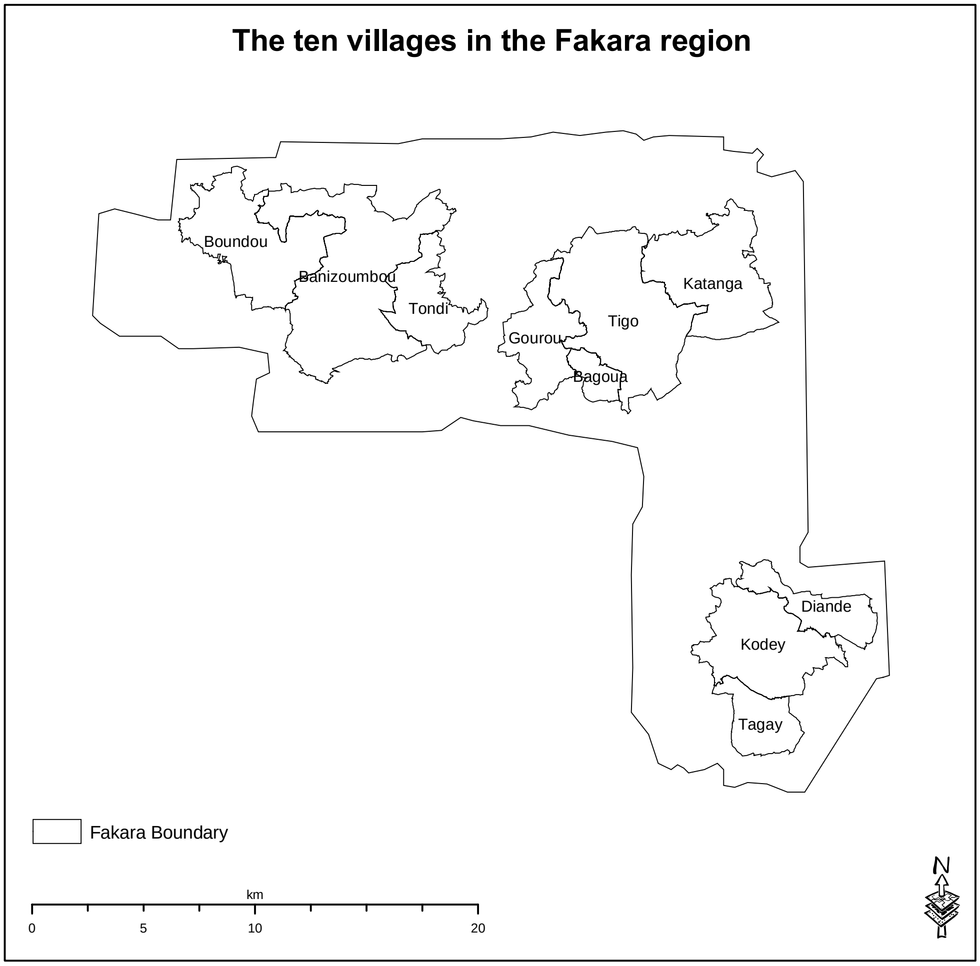
Materials and methods

Millet grain yields were predicted for the following scenarios: NM and C0 with 300, 400, 500, and 600 mm rainfall at Banizoumbou and Bagoua and then later for the area covered by the ten villages in the Fakara. A soil map for the Fakara region was converted to raster format (Appendix D-2) and from it a soil agronomic aptitude map was produced (Appendix D-3) in ArcView 8.3 using the Spatial Analyst. The soil agronomic aptitude map was then reclassified to yield a Boolean map where a 1 was arable soil and a 0 was non-arable soil (Appendix D-4). The agronomic aptitude was determined by soil type and topographic position (ILRI, unpublished). A digital elevation model of the area was processed in spatial analyst to produce a slope map (Appendix D-5) which in turn was reclassified according to slope % (Appendix D-6). All slopes less than 3 % were classified as a 1 and all others as a 0. The two Boolean images (Soil X Slope) were then multiplied using Raster Calculator to produce a final map showing arable areas (1s) and non-arable areas (0s) based on soil and slope (Appendix D-7). The grid cell size for this raster was set at 10 m.

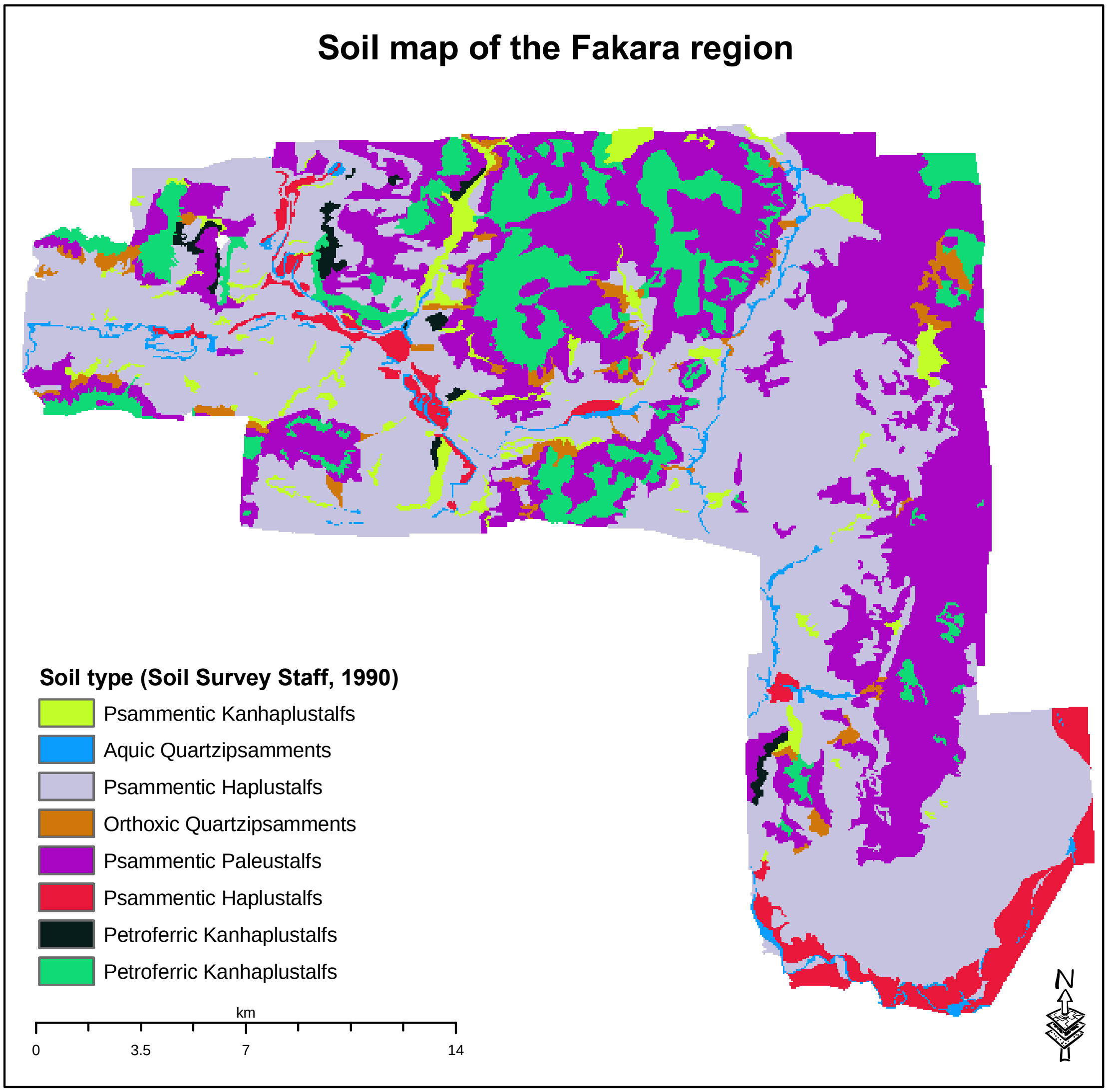
If we assume that all the seasonal rainfall is used for evapotranspiration, we can calculate the total grain yield for each of the rainfall regimes (300, 400, 500 and 600 mm) by multiplying the rainfall and the WUE of each of the manure management practice and at each site (e.g. WUE for the NM and C0 treatments at Banizoumbou and Bagoua). The product of this operation is then multiplied by the total area (ha) of each of the village sites, Banizoumbou (3 878 ha) or Bagoua (363 ha) to get the production in each of them. This process is also done for the total area covered by the ten villages in the Fakara (44 962 ha) to get the regional production.

Results and discussion

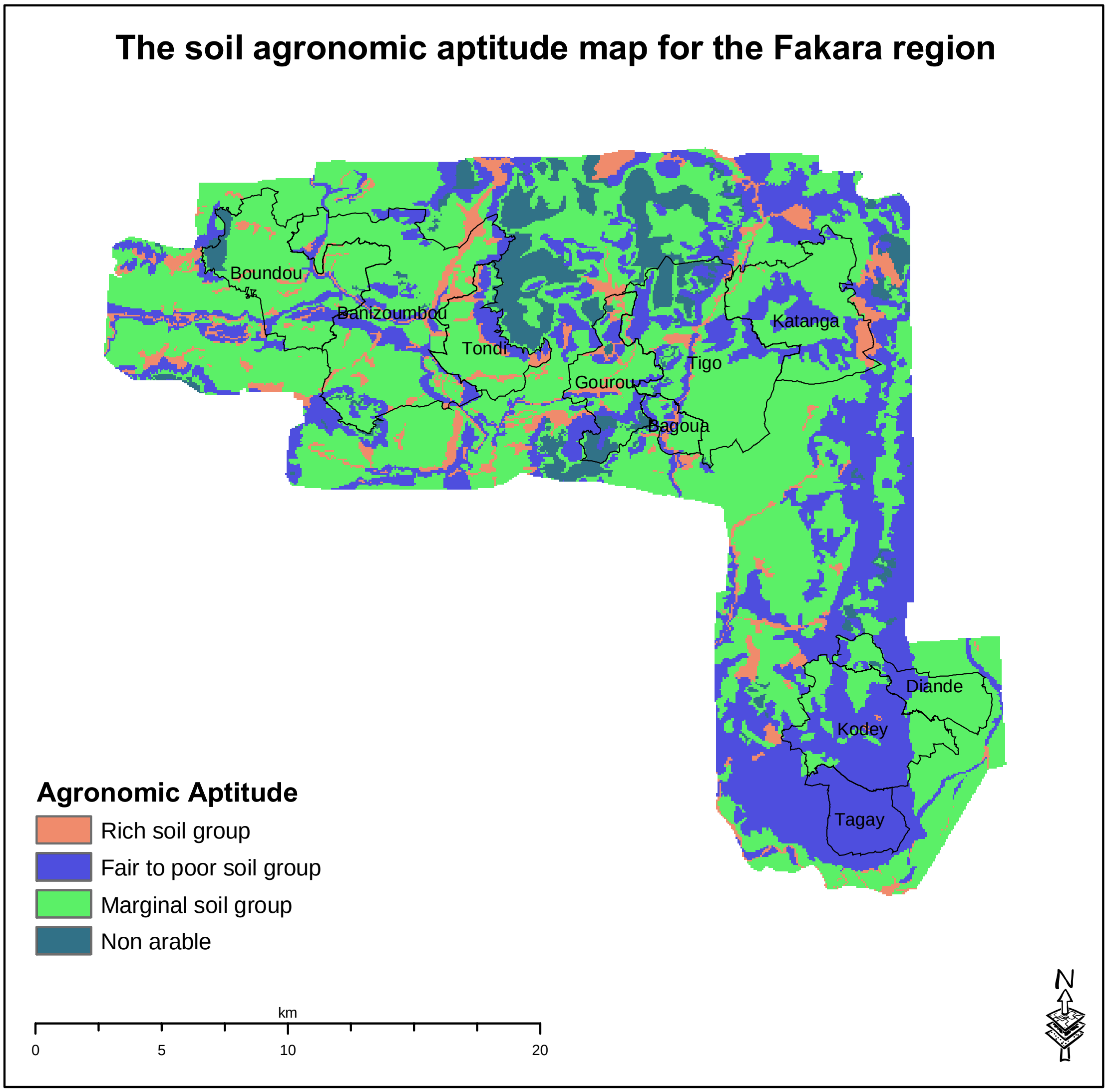
Appendix D-8 summarizes the various possible millet grain yields which can be obtained under the different soil fertility management and rainfall regimes for the ten villages in the Fakara. There is a possibility of raising the village and regional level average millet grain yields threefold when manure is applied through corralling. The practice where no manure is applied (NM) has the lowest total yields for the region under all rainfall regimes. At Bagoua, this increase is only twofold for each of the rainfall regimes probably because of higher WUE even in the NM treatment leading to a smaller difference between the low and high fertility scenarios. In a growing season with the lowest rainfall amount (scenario A with 300 mm rainfall), the average grain yields in the Fakara are about 1.3 times less than they would be if the rainfall had been 400 mm (scenario B) and 1.6 times less than they would have been in scenario C with 500 mm and lastly 2 times less than they would have been with 600 mm rainfall in scenario D. Of course these are rough estimates which may not be accurate mainly because of the underlying assumptions (no drainage and runoff losses, same WUE across sites under the same soil fertility management) but they however give an idea of the effect that rainfall and proper soil management may have on the grain yields of pearl millet in the Fakara region. If more data are available then these predictions may be improved when site differences in soil hydraulic properties and water balance are accounted for.



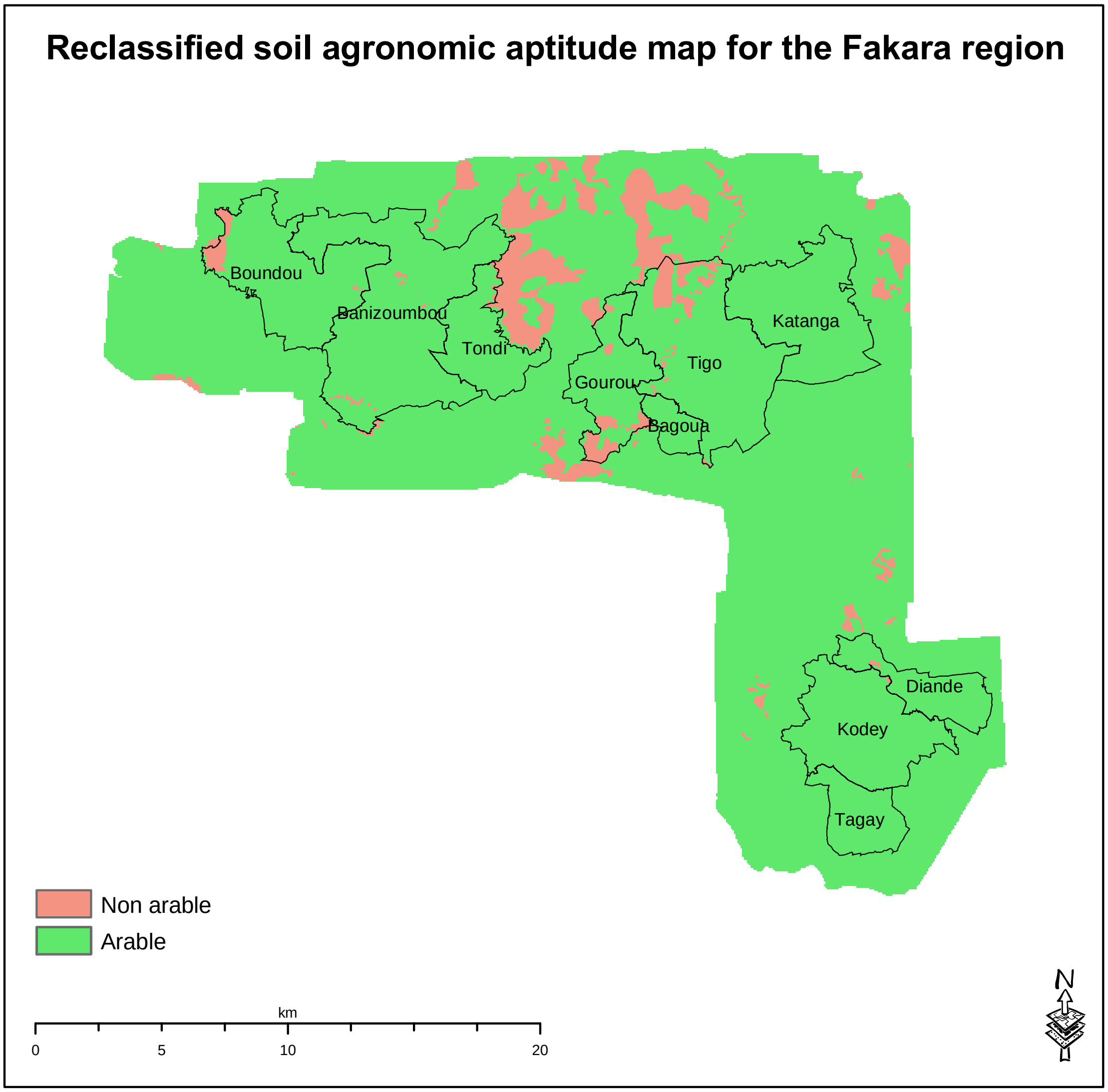
D-1. Map of the ten villages in the Fakara region



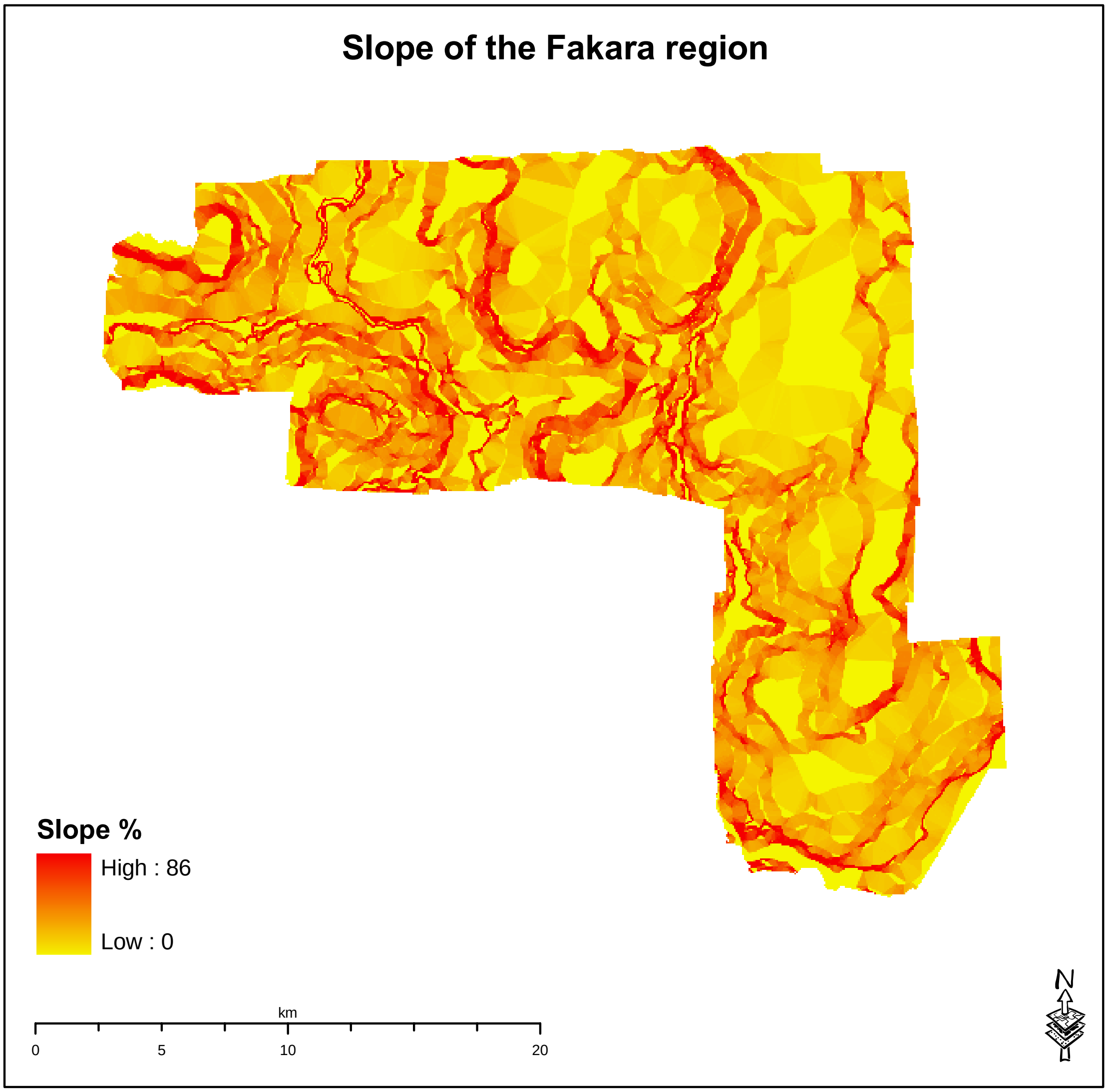
D-2. Soil map of the Fakara region.



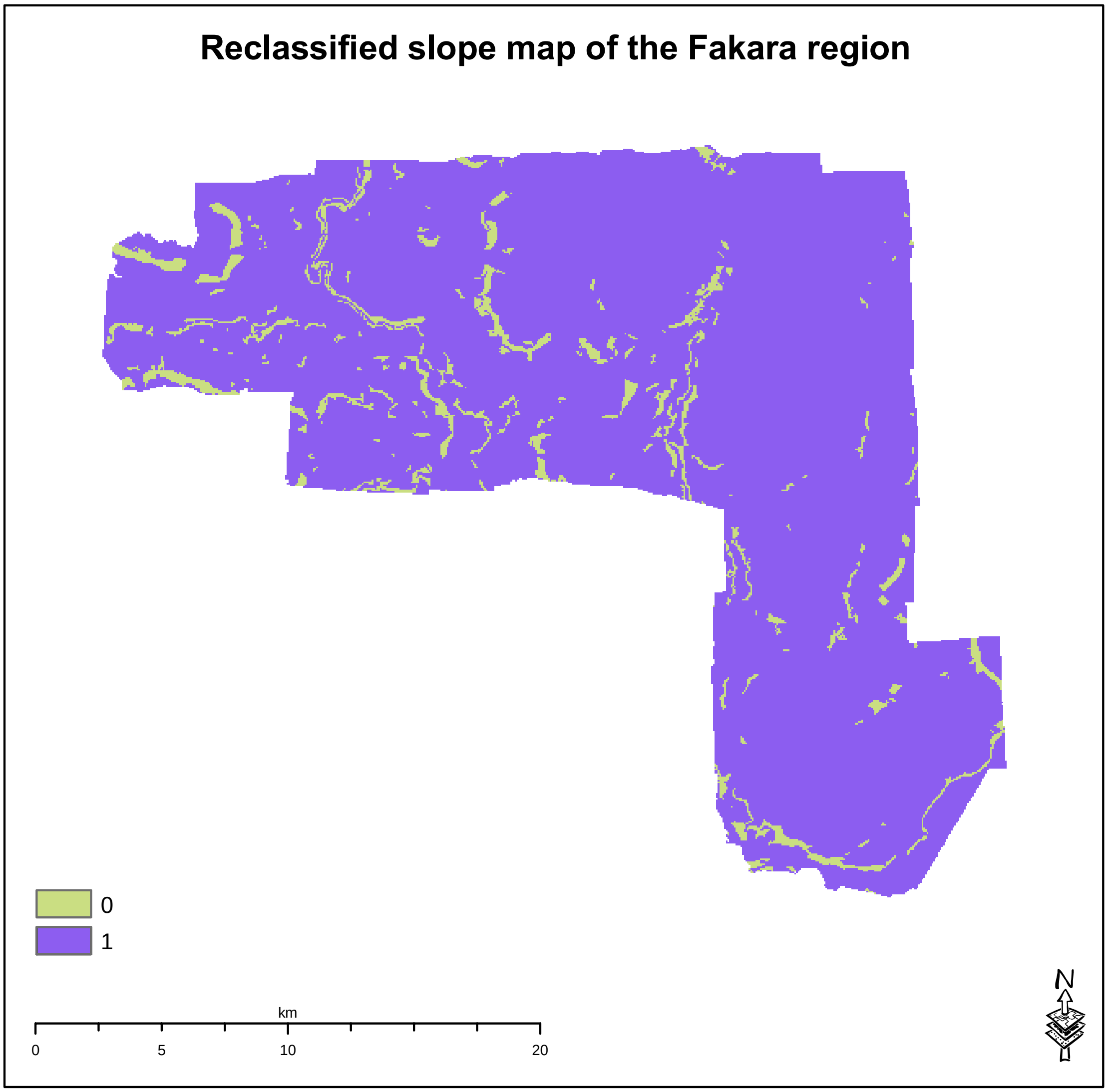
D-3. Soil agronomic aptitude of the Fakara region.



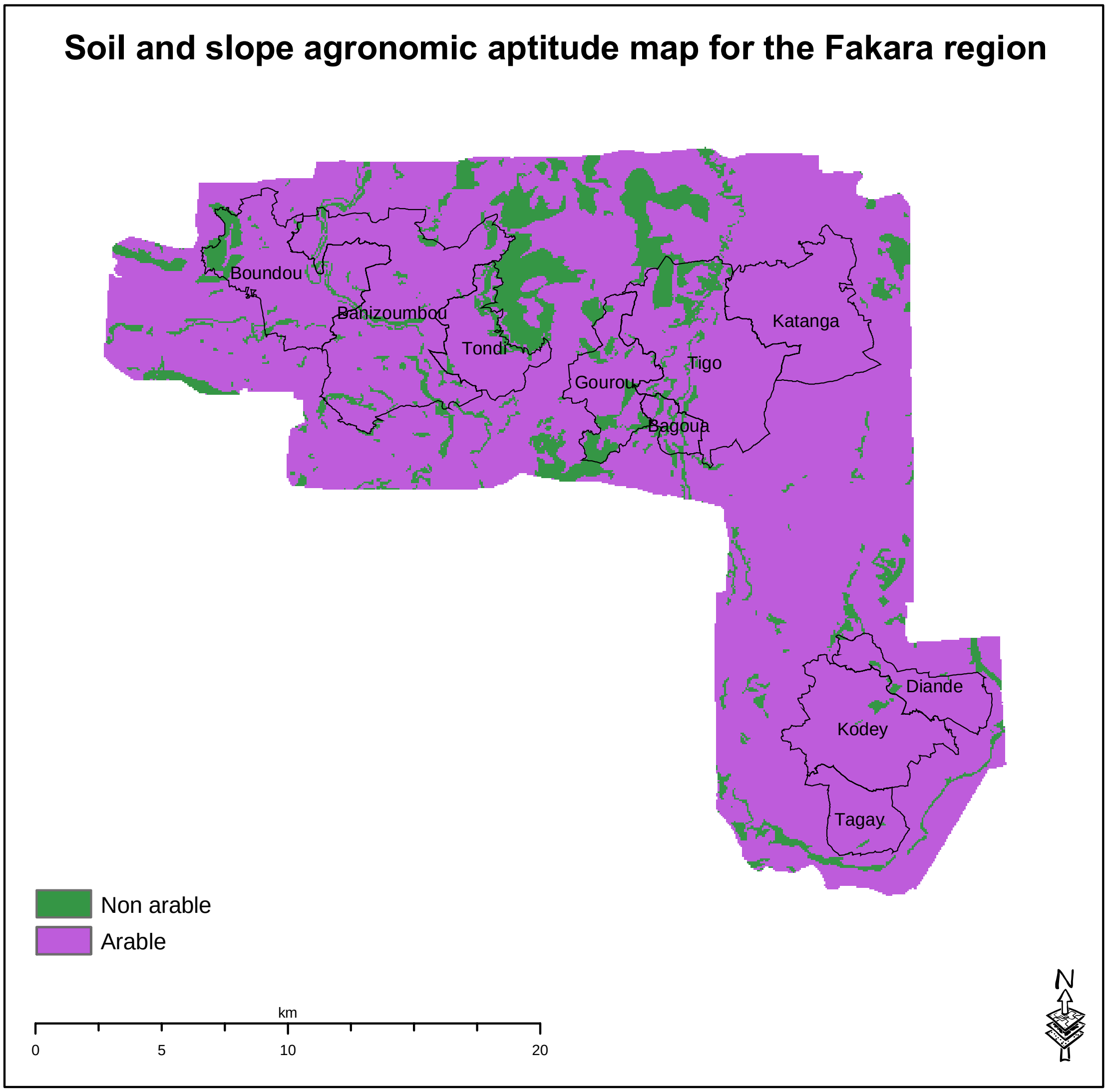
D-4. Reclassified agronomic aptitude grid based on soils.



D-5. Slope map of the Fakara region generated from a digital elevation model.



D-6. Reclassified slope map for the Fakara region.



D-7. Final agronomic aptitude map based on soil and slope maps.

D-8. Average grain production in Banizoumbou, Bagoua, and the whole Fakara region. NM is no manure and C0 is current corral.

			Rainfall regime			
Site	**Manure**	**WUE**	**A†**	**B‡**	**C§**	**D¶**
		kg mm^{-1}		**Mg**		
Banizoumbou	**NM**	**0.5**	**582**	**776**	**970**	**1163**
	C0	**2.9**	**3374**	**4499**	**5623**	**6748**
Bagoua	**NM**	**1.8**	**196**	**261**	**327**	**392**
	C0	**3.6**	**392**	**523**	**654**	**784**
Fakara average	**NM**	**1.2**	**16186**	**21582**	**26977**	**32373**
	C0	**3.3**	**44512**	**59350**	**74187**	**89025**

†300 mm rainfall

‡400 mm rainfall

§500 mm rainfall

¶600 mm rainfall

VITA

Comfort Manyame was born to Julia and Naphtali Manyame in 1975 in Harare, Zimbabwe. He completed secondary school in 1992 at Sandringham High School in Norton, Zimbabwe, and went on to attend Ellis Robins Boys' High School in Harare for his "A" Level education majoring in biology, mathematics, and chemistry. He attended the University of Zimbabwe between 1996 and 2002 where he obtained a BSc honors degree in soil science and later a Master of Philosophy degree in soil science. He attended Lund University in Sweden for a GIS and remote sensing graduate course in the summer of 2001. He taught GIS and remote sensing at Bindura University of Science Education, Zimbabwe between January and July 2002. In January 2003, he was awarded an assistantship by the Soil & Crop Sciences Department of Texas A&M University to study for a PhD degree in soil science, which he was granted in December 2006. Comfort is married to Nyasha, and together they have two children, Comfort Jr., and Julia Mufaro.

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