Integrated biophysical and socio-economic evaluation of water and soil conservation techniques: a case study from Niger

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Thesis submitted in fulfillment of the
requirements for the degree of Doctor (PhD) in
Applied Biological Sciences: Land and Water Management

For Baudewijn Wildemeersch,
my uncle

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Dutch translation of the title: Geïntegreerde biofysische en socio-economische evaluatie van water- en bodemconserveringstechnieken: een casestudy uit Niger

Cover illustration Two farmers at Torodi, Niger, inspecting their millet plants. Taken on 15 September 2013.

Cite as: Wildemeersch J. (2014) Integrated biophysical and socio-economic evaluation of water and soil conservation techniques: a case study from Niger. PhD thesis, Ghent University, Belgium

ISBN number: 978-90-5989-811-0

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Acknowledgements

I only survived the lonely hours writing this dissertation because there were many people who backed me when I left my desk.

Wim, my promoter deserves a special thanks. When I walked into his office, my questions were always answered by handing me exactly the right literature or by returning them with more questions. This stirred me to continue independently, at home or abroad. I am very grateful for the opportunity he gave me to start my doctoral research in the fascinating field of water and soil conservation, for his positive way of being and for the respect he treats his students with.

I would also like to thank the members of the examination board prof. Ann Verdoodt, prof. Filip Tack, prof. Patrick Van Damme and Dr. Visser for their time and effort to review my dissertation. Also many thanks to Demie Moore for her editorial advice and to my own editorial team Bastiaan, Céline, Hannie, Jonas, Katrien, Marc, Tessa and Rob.

Working on this PhD always felt best when I was in Niger. The field work was very challenging but so enlightening. Often, when I think about my field in Sadoré, I feel unwell because I miss it that much. I am so very grateful to Dr. Sabiou for giving me the opportunity to collaborate with INRAN (Institut National de la Recherche Agronomique du Niger). Without his guidance in how things were done ‘a la Nigerienne’, there would have been no data at all to process. I would probably still sit around in front of some office in Niamey waiting for doors to open. When long days of exhaustive fieldwork started, his office was the ideal refuge to just sit and cool down while joking. Thank you for this.

At INRAN, there are many other people I want to thank. First and foremost, Maman Garba, who helped me with so much expertise for everything, from field work to Nigerien administration. Also thank you to Ali Boubé, Germaine Ibro, Amadou Oumarou and

Ousseini for their scientific assistance and to Saadou for his jokes and wisdom during driving. A special thanks goes to Dr. Gandah for being so kind to welcome me to ICRISAT (International Crop Research Institute for Semi-Arid Tropics) and to let me use the institute's accommodation at Sadoré. Without this and the help of Dr. Fatondji, Mustafa, Souleymane, Tondji, Laoli Leopold and many other people at ICRISAT, field work would have been impossible.

I hope these acknowledgements will reach Moutari, Hama, Hassoumi, Soumana and Boubé, the farmers who helped me in the field at Sadoré and the farmers who participated in the socio-economic survey. I am very grateful to them, for in the end, it is because of them that I did not feel all too ridiculous sitting around papers all day, just to write another one.

At home, at the Soil Management department I would like to thank all members of our research unit: Bashar, Geofrey, Jan D.P., Jan V., Koen, Maarten, Mansonia , Meisam, Mojtaba, Muhammed, Linda, Linh, Nele, Nick, Phoung, Tesfay, Thadeo and Yves Dady and all colleagues from other research units at our department. For those who I shared our international office with, I am truly sorry I always put the heater down, I know Belgium is ridiculously cold for you. Thank you Annemie, Luc, Maarten, Matthieu, Sofie, Tina, Thérese and Trees for assisting me in the lab and thank you Patric for your help with the administrative burden. I am also very grateful for the work the people of the cleaning unit are doing. I enjoyed working with Bashar for the modeling part of my research, a very interesting topic which I hope will be further explored at the department. Many thanks to Steven Sleutel for his enthusiasm to collaborate for the soil quality paper and the interesting discussions we had on this topic. Last but not least, I want to thank Emma heartily for her hard work on the socio-economic study and for our shared time in Niger.

Of course, I am so very grateful to my mum and dad for showing me so much warmth, I continue to thrive on it. Between really right and really wrong, there was always so much space in which we could move freely to learn everything there was to learn and I benefit from this every day. My brothers Bastiaan, Briek and Korneel, my godchildren Mauro and Ellis and the brilliant little Mila deserve a special thanks, just because they are so sweet. I am dedicating this thesis to Baudewijn Wildemeersch, who I fondly called nonkel Beute. Thank you for giving me a roof and (much!) food when I was writing my

PhD proposal, I was very much looking forward to give you this booklet.

Finally, les amis, my friends. The ones who are here, the ones abroad and the ones who are no longer here. All of you, thank you so much for taking things seriously without ever taking yourselves too seriously and for staying lighthearted even when you are learning lessons you should not learn. Not joining you to write this dissertation was by far the hardest part of obtaining a PhD. An honourable mention goes to Rob for hiding his disappointment so well the last months every time I bailed, thank you. I am also very grateful to all the friends I have lived with during this period, both in Niger and Belgium, and unlike me, never complained about this thesis: Allena, An, Emma, Heleen, Jan, Jhonel, Karlien, Louise, Mocktar, Rob, Sofie, Steph, Thomas, Valerio and of course wonderboy Jonas. Sometimes I think that I struggled the final year, simply because Jonas already finished his PhD and we were no longer doing this together. Together with him it was just so much more fun, luckily he was always around to exactly know how I feel and cheer me up. For this, he made a fabulous team with wondergirl. She might be shy, but never for a joke, Céline. She outperformed every other model. Let's get this sillyness going.

Jasmien Wildemeersch
June 30th 2015

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List of abbreviations

AC	Air Capacity
ACTN	African Conservation Tillage Network
AGRA	Alliance for a Green Revolution in Africa
ANOVA	ANalysis Of VAariance
APGMV	Agence Panafrique de la Grande Muraille Verte
C	Control
CA	Conservation Agriculture
CEC	Cation Exchange Capacity
CERRA	Centres Régionaux de Recherche Agronomique
CF	Control Fumier
CFA	Communauté Financière Africaine
CPN-503DR	Campbell Pacific Nuclear-503 Direct Reading
CRIT	CRITical soil moisture level in the rootzone
CSA	Climate Smart Agriculture
D	Drainage
DGRN	Département de Gestion des Ressources Naturelles
DL	Demi-Lunes
DOY	Day Of the Year
E	Evaporation
EDF	Evaporation Distribution Function
ET	EvapoTranspiration
FAO	Food and Agriculture Organization of the United Nations
FC	Field Capacity
FMNR	Farmer-Managed Natural Regeneration project
HGS	HydroGeoSphere
ICP-AES	Inductively Coupled Plasma-Atomic Emission Spectroscopy
ICRISAT	International Crop Research Institute for Semi-Arid Tropics
IGNRM	Integrated Genetic and Natural Resource Management
INERA	Institut de l'Environnement et des Recherches Agricoles
INRAN	Institut National de la Recherche Agronomique du Niger
INRI	Institut National pour les Radio-Isotopes
IPCC	Intergovernmental Panel on Climate Change
IRD	Institut de Recherche pour le Développement
IRHA	International Rainwater Harvesting Alliance
ISFM	Integrated Soil Fertility Mangagement
ITCZ	InterTropical Convergence Zone
LAI	Leaf Area Index

LSD	Least Significant Difference
MDG	Millenium Development Goals
NEWS	Native Evergreen Multipurpose Woody Shrubs
NGO	Non-Governmental Organization
P	Precipitation
PAWC	Plant Available Water Capacity
PDSI	Palmer Drought Severity Index
PWP	Permanent Wilting Point
R	Runoff
RDF	Root Distribution Function
RETC	RETention Curve
RGB	Red Green Blue
RH	Relative Humidity
RMSE	Root Mean Squared Error
RWC	Relative Water Capacity
S	Soil-water storage
SCAR	SCARification
SD	Standard Deviation
SLM	Sustainable Land Management
SOC	Soil Organic Content
SPI	Standardized Precipitation Index
SPSS	Statistical Package for Social Sciences
SSA	Sub Saharan Africa
SWATRE	Soil Water and Actual Transpiration Rate Extended
SWC	Soil and Water Conservation
SWRC	Soil Water Retention Curve
T	Transpiration
TAW	Total Available Water
UN	United Nations
UNCCD	United Nations Convention to Combat Desertification
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
WH	Water Harvesting
WOCAT	World Overview of Conservation Approaches and Technologies
WRB	World Reference Base
WSC	Water and Soil Conservation
Z	Zaï

1

Problem statement and research outline

One of the greatest challenges facing our society is achieving global food security for an ever increasing population (Pretty et al., 2010). Meanwhile, global soil and water resources are becoming degraded, putting tremendous pressure on the productivity potential of many countries. One of the places experiencing these challenges in a severe way is Niger in Western Africa, where food is limited and crop yields are far below potential. This dissertation explores the potential of water and soil conservation (WSC) techniques to address water and nutrient shortages that inhibit Niger's ability to move toward greater food security for its people.

Currently, 2 million people are chronically food insecure in Niger, a number that rises (e.g. to 5.5 million in 2011) when cereal production fails due to drought (FAO, 2006; UN, 2012). After the last food crisis in 2011, the Nigerien government therefore started the '3N'-initiative (Nigeriens Nourishing Nigeriens) (HC3N, 2012), a program aiming at achieving food sovereignty by strengthening the national capacities for food production.

In Niger, the majority of food is produced by small-holder farmers. They are largely dependent on rainfed agriculture and are mainly located in the Tillaberí region, the southern, wettest part of the country (Gandah et al., 2003). Yields are often extremely low, averaging only 350 kg ha^{-1} for millet (*Pennisetum glaucum* (L.) R. Br.), while the yield potential is close to 1000 kg ha^{-1} (FAO, 2014b).

The two major limiting factors for crop production in the Tillaberí region of Niger are insufficient water availability in the rootzone and very poor soil quality, which under conventional practice lead to water and nutrient shortages for adequate crop growth (Gandah et al., 2003). Conventionally, farmers do not cultivate their fields before seeding and add no or only little manure through livestock corralling.

The insufficient availability of water in the rootzone water is related to a number of factors. The atmospheric evaporative demand is very high (potential evapotranspiration varies from 2000 to 4000 mm year^{-1}), whereas rainfall distribution during the growing season is highly unpredictable (Sivakumar, 1989). Starting and ending dates of the rainy season are uncertain and frequent dry spells often lead to crop failure. Furthermore, according to estimates by Rockström and Valentin (1997), up to 30% of the rainfall is lost as run-off and cannot be used by crops for biomass production.

Moreover, continuous cropping of cereals with little use of legumes and/or cattle manure to maintain soil organic carbon levels has greatly impoverished soil resources. Soil nutrient content (especially in terms of phosphorus and nitrogen), pH (≤ 5) and organic matter content (≤ 10 g kg^{-1}) are low for all soil types and indicate a high level of degradation (Gandah et al., 2003). As a result, nutrient availability is too low for adequate crop production.

However, according to Falkenmark et al. (2001) there is enough rainwater available in the Sahel to attain yields that are 5 to 10 times higher than present ones. Additionally, research carried out by the 'Institut National de Recherches Agronomiques du Niger' (INRAN) and the 'International Crop Research Institute for Semi-Arid Tropics' (ICRISAT) has shown that grain yields above 1000 kg ha^{-1} can easily be achieved when adequate nutrients (annual manure application of 3 - 14 ton ha^{-1}) are applied under optimal conditions in research stations (Gandah et al., 2003). Hence, both major limiting factors (i.e. water availability and soil quality) for crop production in the Tillaberí region can be tackled by innovative practices with optimized water and soil management.

Several water and soil conservation (WSC) techniques have therefore been developed in the region. These techniques aim at increasing water availability for crop production, while conserving soil resources and are thought to ease some of the constraints concerning growing food demands and degrading resources being experienced in Niger (Wani et al., 2009). Zaï (Z), demi-lunes (DL) and scarification (SCAR) are three common WSC techniques in the region. They are proclaimed to combat land degradation and to enhance water availability in the rootzone by harvesting run-off water and reducing rainwater lost as evaporation and deep percolation (Shaxson and Barber, 2003). These WSC techniques are commonly regarded as appropriate for a wide range of biophysical and socio-economic conditions, but this is often assumed without rigorous evaluation or detailed testing (Molden, 2007). In Niger, very few studies provide scientific evidence of the biophysical impact of WSC techniques or offer technical improvements regarding their design. Most papers on the effects of WSC techniques only report promising results on yield increases (Roose, 1999; Sidibé, 2005; Sawadogo et al., 2008; Tabor, 1995) or focus on the evaluation of nutrient efficiency and nutrient-water interaction (Fatondji et al., 2006, 2009; Zougmoré and Ouattara, 2004). To our knowledge, no studies have focused on the water dynamics in and around WSC techniques, their impact on soil quality or the constraints to their adoption.

This dissertation aims to provide scientific verification of the potential of certain WSC techniques to be of value in rainfed agriculture in Niger. The overall objective is to evaluate the biophysical and socio-economic viability of small-scale water and soil conservation (WSC) techniques in the Tillaberí region of Niger. The WSC techniques to be evaluated are zaï (Z), demi-lunes (DL) and scarification (SCAR). The findings of this study will pinpoint the major bottlenecks for large-scale WSC dissemination and will provide insight in the water and nutrient shortages that are key factors in the low crop productivity contributing to Niger's food insecurity.

The underlying, general scientific hypotheses can be formulated as:

1. low yields (reduced crop production and crop failure) in the Tillaberí region of Niger are mainly due to a deficiency in available water in the rootzone caused by erratic rainfall and imbalanced partitioning of water over the rootzone;
2. imbalanced rainfall partitioning over the rootzone can mainly be attributed to severe land degradation;
3. a significant amount of rainfall does not enter the soil, but is lost to surface run-off. Rainwater that does enter the soil is to a large extent lost as soil evaporation, before plants can take it up for biomass production;
4. drought stress can be mitigated by WSC techniques that combine run-off reduction with soil structure-enhancing manure application;
5. WSC techniques rehabilitate degraded land by improving chemical, physical and biological soil quality;
6. rainwater use efficiency of WSC techniques can be further improved by optimizing their design
7. optimization of WSC designs can be done with the help of hydrological models developed to couple surface and subsurface water flow; and
8. WSC techniques are currently not adopted on a large scale because farmers are not well aware of soil erosion and the WSC measures to combat it, and even if they were, they would not have adequate resources to implement them.

This research aims to:

1. gain insight into the mechanisms behind crop yield loss due to the occurrence of drought stress by characterizing agricultural, meteorological and soil-water drought;
2. evaluate the potential of small-scale WSC techniques (Z, DL and SCAR) in mitigating drought stress by assessing crop response and monitoring soil-water content during the cropping season;
3. evaluate the soil rehabilitating capacity of small-scale WSC techniques (Z, DL and SCAR) by monitoring their impact on a number of physical, chemical and biological soil quality parameters;
4. quantify water loss caused by imbalanced rainfall partitioning over the rootzone and evaluate the effect of WSC techniques (Z, DL and SCAR) on rainwater use efficiency through assessment of surface run-off, evaporation, transpiration, deep percolation and storage of water in the rootzone;
5. optimize the design of demi-lunes with a hydrological model that couples surface with subsurface flow to simulate the hydrological behaviour of the WSC technique; and
6. better understand why farmers in the study area do not adopt small-scale WSC techniques on a larger scale.

Each of these objectives is addressed in one or more research chapters (**Chapters 4, 5, 6, 7 and 8**) in this dissertation. In the introduction of these chapters, the specific scientific hypotheses corresponding to these objectives are presented.

Introductory **Chapters 2 and 3** frame this study within the national and international research context and provide background information on the agro-economic and biophysical setting in Niger. **Chapter 2** provides a general overview of the global water and soil crises and the response of the scientific community. This chapter shortly describes how conservation of water on the one hand and conservation of soil on the other, evolved towards combined strategies under influence of the ‘green and blue water paradigm’ introduced by Falkenmark (1995). Furthermore a list of research gaps was deduced from literature, which helped us formulating research questions that are relevant for the international WSC research community. **Chapter 3** discusses the importance of agriculture in Niger and provides general information on climate, land use and soil types, after which the specific research needs in Niger are presented. Since this research focuses on the production of millet (*Pennisetum glaucum* (L.) R. Br.), a concise summary of the taxonomy and description of this crop is provided, together with some general information about its environmental requirements and management.

Chapters 4, 5 and 6 describe and analyze a WSC field experiment at Sadoré village in the Tillaberí region of Niger installed in cooperation with the department of Natural Resource Management, INRAN.

Chapter 4 starts with investigating whether agricultural drought in the study area is related to a changing climate (meteorological drought, i.e. deficit of rainfall or unfavourable rainfall distribution) or rather to poor land use and land degradation (soil-water drought, i.e. decreased water infiltration and water holding capacity). The chapter continues by examining soil-water and crop response data to assess the potential of WSC techniques (Z, DL and SCAR) to mitigate agricultural drought. **Chapters 5 and 6** subsequently clarify how soil-water increases under WSC.

Chapter 5 evaluates the potential of WSC techniques to rehabilitate degraded lands by assessing their impact on chemical (SOC, nutrient content and pH), physical (bulk density, porosity and hydraulic conductivity) and biological (nematode abundance) soil quality indicators. The chapter also discusses the potential of WSC techniques to sequester soil organic matter and analyses the relation between increased soil-water content and improved physical soil properties under WSC techniques.

Chapter 6 evaluates the potential of WSC techniques (Z, DL and SCAR) to improve the partitioning of rainwater over the rootzone in order to increase water availability for crop production. The partitioning of rainfall into surface run-off, soil evaporation, transpiration and soil-water storage is quantified for the different treatments, which allows the formulation of some design recommendations to further reduce water loss. In the last part of this chapter, also the impact of WSC techniques on water dynamics on watershed scale is discussed.

Chapter 7 evaluates the application of the hydrological model HydroGeoSphere (HGS) to optimize the design of demi-lunes (DL). The model is calibrated with data obtained from the field experiment at Sadoré and then used for prediction of rainfall partitioning under different optimized system designs (DL+ and DL++). These designs were based on the findings in **Chapter 6** which demonstrated a suboptimal spacing of DL bunds.

Chapter 7 evaluates the socio-economic viability of WSC techniques in the Tillaberí region of Niger. It investigates the presence and extent of WSC adoption constraints related to the different phases (defined by de Graaff et al. (2008)) farmers go through during the WSC-adoption process. It discusses the results of a survey designed to collect information on soil erosion awareness of farmers, their knowledge of WSC techniques (i.e. acceptance phase) and their resource availability (manure, labour, implements) (i.e. actual adoption phase).

Finally in **Chapter 9**, the main findings are summarized in a set of conclusions and some recommendations are formulated for future research and practical implementation.

2

Water and soil conservation: origin, necessity and research gaps

2.1 Declining global water and soil resources

Global water scarcity analyses unanimously conclude that, as a consequence of population growth, a large part of the world population will be affected by water scarcity over the next decades, especially in areas where rainfall is low and population density high (Bouwer, 2000; Gleick, 2013; Rijsberman, 2006; Rockström and Karlberg, 2009). Water scarcity does generally not imply water for domestic use, which has a basic requirement of only 50 l per capita per day, but rather refers to water shortages for food production, for which water requirements amount to - on average - 3500 l per capita per day (Molden, 2007). To boost water availability for food production, international water management policy in the past mainly focused on irrigation development. However, since the vast majority of agricultural land relies directly on rain (95% in Africa), attention has now shifted to techniques unlocking the large potential of rainfed agriculture (Wallace, 2000; Wani et al., 2009).

Besides its water resources, the world's soil resources are declining as well, especially in Asian, South American and African drylands, where population growth is high and a substantial increase in food production is demanded (Wallace and Batchelor, 1997). In these continents, drylands typically suffer from severe soil erosion by wind and water, which degrades soil fertility and results in an important biomass productivity decline. Another major problem for dryland soils rises when nutrients harvested in crops are not replaced. The availability of cattle manure and crop residues is limited and chemical fertilizers are typically too expensive for resource-poor farmers.

While water and soil resources are under increasing pressure in drylands, immense population growth pushes farmers to produce more food. Increasing food production to match growing demands hence calls for innovative cropping practices that combine improved production with sustainable water and soil management (Foley et al., 2011).

Conserving water and soil resources, while achieving food security is a concern high on the international research agenda (Pretty et al., 2010). Until the end of the 20th century, water and soil conservation were largely treated separately by hydrologists, geologists and agronomists. Research concentrated on 'harvesting water to reduce rainfall-induced production risk' on the one hand and 'combating land degradation' on the other. Recently, this has evolved towards an approach that combines the efforts to conserve water and soil by integrating soil-fertility management with improved soil-water management (Lal, 2008). In the following sections, a short introduction is given to the concepts of water harvesting and soil conservation. After this the evolution towards strategies tackling both the declining water and soil resources is discussed.

2.2 Water harvesting

Rainfed agriculture is the dominant source of food in dryland Africa, which constitutes 43% of the continent's surface area (Wani et al., 2009). Within the agricultural system of drylands, rainfall is the main random production factor and water shortage often leads to reduced crop production. According to Critchley et al. (1991), farmers should therefore first reduce the rainfall-induced production risk, before investing in e.g. fertilizer or improved planting material. In their excellent comprehensive assessment of water management in agriculture, Falkenmark et al. (2001) demonstrate that water shortages in rainfed agriculture can be tackled with low-cost methods referred to as 'Water harvesting' (WH).

WH is defined as 'the collection of run-off water for its productive use' and generally consists of three components: a catchment area, a storage facility and a target (Oweis and Hachum, 2009). The catchment area, which can be a rooftop or a part of the land surface, produces run-off which is directed to the storage facility. This can be a cistern, pond or the soil profile and holds the water until it is used by a target, which, in case of agricultural production, is the crop or animal (Critchley et al., 1991).

A wide range of WH systems exists and they have been classified in many ways. Critchley et al. (1991) give a well-known overview of WH techniques (reissued as Critchley et al. (2013)). Recently, also WOCAT (World Overview of Conservation Approaches and Technologies) has published an overview of WH systems (Studer and Liniger, 2013). Critchley et al. (1991) have subdivided WH systems into micro- and macrocatchment systems. Microcatchment systems directly supply run-off water from a small catchment area to an adjacent cropping area, whereas macrocatchment systems divert water with dams and canals from a bigger catchment area or a wadi (natural channel) to nearby land. Since microcatchment systems are low-cost methods, individually implementable and efficient in reducing run-off water loss, they are generally preferred to macrocatchment systems (Oweis and Hachum, 2009).

Numerous WH projects with microcatchment systems have been set up, but few have resulted in large-scale adoption. A lack of local technical expertise hampered their implementation, as farmers experienced difficulties with required ‘know-how’ like following the contour (Prinz, 1996).

2.3 Soil conservation measures

Land degradation in agro-ecosystems is mainly caused by inappropriate land use and management, resulting in loss of topsoil, surface crusting, soil structure degradation and declining soil fertility (Lal, 1998). The most widespread form of land degradation is soil erosion which removes fertile soil by wind and water much more rapidly than soil-forming processes allow. These soil removal rates are highest in Africa, Asia and South America. Where on average, they range from 30 to 40 Mg ha^{-1} year^{-1}, whereas in North America and Europe average soil removal rates only amount to 17 Mg ha^{-1} year^{-1} (Pimentel et al., 1995). In addition to suffering from erosion, soils also undergo depletion of soil organic matter. This results in declining macronutrient supply to plants (N, P) and weakening soil properties (soil structure, water retention capacity, aeration, aggregation and cation exchange capacity) (Lahmar et al., 2012; Sterk et al., 1996; Tittonell et al., 2012).

In drylands, land degradation is often referred to as desertification (UNCCD, 1994), but there is some confusion concerning this term. Desertification is commonly seen as the environmental crisis resulting from land degradation that produces ‘desert-like’ conditions and is not necessarily related to an actual desert. The expansion of deserts, or desert creep, accounts only for 10% of desertification processes (Kassas, 1999). Nevertheless, most international attention goes to desertification interventions involving measures against desert creep. The most illustrious example is ‘The African Great Green Wall Initiative’ (APGMV, 2012), which is known to the general public as a belt bordering the Sahara that must stop the desert from expanding. Other forms of land degradation in drylands are hardly ever mentioned.

The scientific community dealing with desertification on the other hand, not only addresses desert creep, but also investigates dryland restoration through the implementation of soil conservation measures like stone bunds, increased vegetation cover, strip cropping, terracing, check dams, windbreaks and reforestation (Hudson, 1987; Shaxson and Barber, 2003; Slegers and Stroosnijder, 2008; Roose, 1996; UNEP, 1997).

2.4 Combining the effort: water and soil conservation

Ever since the establishment of the UNCCD (United Nations Convention to Combat Desertification) in 1994, desertification became a buzzword resulting in more attention for soil conservation measures than for water harvesting (Molden, 2007). In this context, run-off was primarily perceived as an enemy to the soil causing severe water erosion and not as a source of water loss for crop production. Enhanced water infiltration that went hand in hand with run-off-reducing measures for soil conservation was merely regarded as a positive side effect of the latter. Gradually, however, a major shift in perception took place. Run-off evolved from a 'problem' causing soil erosion to a manageable 'resource' for land productivity enhancement and yield increase (Slegers and Stroosnijder, 2008).

This perception shift was driven by the 'green and blue water paradigm' introduced by Falkenmark (1995) (Fig. 2.1). The latter paradigm distinguishes two types of water resources: the blue water resource, referring to water in aquifers, lakes and dams; and the green water resource, representing moisture in the soil. Falkenmark (1995) stated that current low yields in drylands largely result from an imbalanced partitioning of water in the rootzone. An important part of the rainfall is lost by surface run-off (blue water), soil evaporation (unproductive green water) and deep percolation (blue water) beyond the rootzone. As a result little water is available in the rootzone for transpiration (productive green water).

The unfavourable partitioning of rainfall is largely attributed to severe land degradation (Wani et al., 2009). Crusted soils hamper the infiltration of high intensive rains, while low organic matter content and poor soil structure restrict soil-water retention. Hence, strategies tackling the decline in either soil or water resources have evolved towards strategies combining conservation of soil with increased water availability for crop production (Wallace, 2000).

This rising awareness of the need for integrated water and soil management is reflected in the evolution of nomenclature used for measures conserving water and soil resources. Commonly used terms like water harvesting (WH) systems and soil conservation measures are gradually being substituted by umbrella terms referring to more integrated systems such as 'sustainable land management (SLM)' in publications of WOCAT (World Overview of Conservation Approaches and Technologies) (Schwilch et al., 2012) and

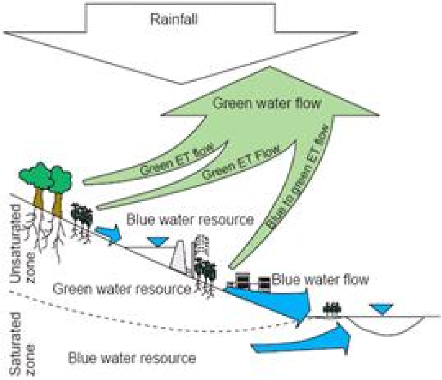

Figure 2.1: A schematic representation of the green and blue water paradigm of Falkenmark (1995). Rainfall is partitioned in a green water resource as moisture in the soil and in a blue water resource in aquifers, lakes and dams

Terrafrica (Liniger et al., 2011), ‘integrated genetic and natural resource management (IGNRM)’ by Wani et al. (2009) or ‘integrated soil fertility management (ISFM)’ in policy documents of Worldbank (2004). More recently FAO (2014a) even went a step further and linked improved water and soil management to the resilience to climate change and now refers to ‘climate-smart agriculture (CSA)’.

The techniques studied in this dissertation (zaï, demi-lunes and scarification) could be classified under each above-mentioned umbrella term. They are WH techniques, as well as soil conservation-, SLM-, IGNRM-, ISFM- and CSA-techniques. However, since this study deals with both water and soil conservation, with an emphasis on eliminating the water constraint within the Sahelian agricultural context, we preferred to call them ‘water and soil conservation (WSC)’ techniques, as suggested by Shaxson and Barber (2003).

Along with a more comprehensive view on water and soil resource management, another very important perception shift took place. Strategies for water and soil management shifted from a mere technical approach towards a farmer-participatory approach. The focus on only soil loss or only water loss as the major issue for crop production resulted in sophisticated interventions designed by North-American or European experts. Still, these engineering solutions did not bring about the awaited production increase and were often rejected by local farmers. In reaction tot this, WSC experts like Reij et al. (1996) argued that technology should not only exist as engineering design, but should be imbedded in a social, environmental and economic context. This prompted the emergence of a ‘new style’ of water and soil management interventions based on holistic resource management involving participatory planning and implementation of indigenous WSC techniques. According to Reij et al. (1996), these ‘new style’ interventions are much more flexible in design, respond better to environmental change (e.g. wet and dry climate cycles) and improve the spreading of labour requirements for construction and maintenance.

2.5 Research gaps for WSC research

WSC techniques have already been extensively described in scientific literature, but many research gaps remain. In order to formulate research questions in this study that are relevant for the international WSC research community, we extensively examined international scientific literature. Many studies report yield increases by applying above-mentioned integrated practices (Lahmar et al., 2012; Oweis and Taimeh, 1996; Rockström and Karlberg, 2009; Shemdoe et al., 2009; Tennakoon and Hulugalle, 2006), a great number of reviews and manuals provide good inventories of these techniques together with information for their implementation (Biazin et al., 2012; Critchley et al., 1991; Studer and Liniger, 2013; Reij et al., 1996; Liniger et al., 2011; Schwilch et al., 2012; Liniger and Critchley, 2007) and networks have been set up to share expertise among researchers, users and policy makers (e.g. IRHA, International Rainwater Harvesting Alliance; WOCAT, World Overview of Conservation Approaches and Technologies; ACTN, African Conservation Tillage Network). Very few studies, however, provide quantified, scientific verification of the global impact of these techniques. A number of reports, reviews and research papers report several research gaps for practices integrating water and soil conservation (Falkenmark et al., 2001; Giller et al., 2009; Lahmar et al., 2012; Pender, 2009; Vohland and Barry, 2009; Wani et al., 2009). The following list summarizes the research gaps which have barely been touched upon in international literature. They can be grouped into four major categories: those related (1) to characterization of drought stress, (2) to soil quality, (3) to hydrology and (4) to transferability. They are expressed here as research gaps for WSC techniques, but hold for any of the above-mentioned umbrella terms (e.g. ISFM, CSA, SLM) that combine water and soil conservation.

Group 1 includes the issues related to:

- the role of climate-induced and human-induced drought stress;
- the impact of hydroclimatic conditions (specifically the occurrence of dry spells) on crop yields; and
- the extent to which WSC techniques mitigate drought stress.

Group 2 includes the issues related to:

- the effect of WSC techniques on organic matter content and soil fertility;
- the feasibility of the soil fertility management practices included in WSC;
- the effect of WSC techniques on biodiversity; and
- quantitative assessment of WSC effect on soil quality.

Group 3 includes the issues related to:

- the hydrology of WSC techniques at farm level;
- the consequences of upscaling WSC techniques (including upstream/downstream effects); and
- the impact of WSC techniques on ecosystem services at watershed scale.

Group 4 includes the issues related to:

- the biophysical ‘fit’ of WSC in a region and the design optimizations needed;
- the socio-economic ‘fit’ of WSC in a region; and
- the possibility to integrate WSC techniques with legal issues and land tenure.

This dissertation provides valuable insights in many of these issues. However, the gaps related to upscaling of WSC, legal issues and land tenure, and ecosystem services at watershed scale are not covered in this dissertation.

3

Focus on Niger and pearl millet (*Pennisetum glaucum* (L.) R. Br.)

3.1 Niger, a feudal society with agricultural challenges

3.1.1 Current agro-economic setting

Niger is regularly listed among the world's five poorest nations on the UN Human Development Index (HDI) and its GDP in 2013 was only 415 US dollars per capita. The country has a high level of malnutrition, a low life expectancy and low literacy levels. The Nigerien population is among the fastest growing in the world (with an annual growth rate of 2.87%) and it is the youngest worldwide (Guengant et al., 2003). The population is projected to increase from 19 million in 2014 to 26 million by 2025 with 50% of the inhabitants in the age class under 15 (Rinaudo and Yaou, 2009).

The number of people facing chronic food insecurity is high (2 million) and Niger has witnessed several serious famines (1968-1974, 1983-1984, 2004-2005 and 2011-2012). (Descroix et al., 2009; UN, 2012). Ensuring food security is given highest priority in the country (UN, 2012).

Over 80% of the working Nigerien population is engaged in agriculture and food production. The production of most farmers is merely sufficient to meet six months of food needs and farmers base their production decisions primarily on risk avoidance rather than on yield maximization (de Rouw, 2004). A third of the rural population migrates abroad during the dry season in search of food and work, which limits their availability to develop improved agricultural practices. Furthermore, very few young people take up farming. Notwithstanding the huge underemployment rates, youngsters tend to migrate to the capital, Niamey, or to neighbouring countries (Guengant et al., 2003).

Agricultural production is mainly subsistence-driven, as the lack of markets, high costs for transportation, expensive or unavailable credit and a low return on investment make agriculture an unlikely target for investment beyond subsistence levels (Tabor, 1995). Agricultural equipment is mainly traditional and most crop management is done manually. Tractors for mechanical tillage are hardly available and donkeys are often too weak to till the soil at the beginning of the rainy season (Boubacar et al., 2005). The main soil fertility management practice consists of corralling, but manure availability is limited in the area due to the disappearance of pasture land and livestock (Guengant et al., 2003). In addition, chemical fertilizer is not easy accessible and is often too expensive for resource-poor farmers.

Besides livestock production, which contributes 35% to the agricultural GDP, farmers are mainly occupied with the production of pearl millet (*Pennisetum glaucum* (L.) R. Br.), the major staple crop in Niger (Fig. 3.1) (for detailed information on millet, see section 3.2) (Gandah et al., 2003). Many Nigeriens rely singularly on millet for their subsistence, which has dramatic consequences when its production fails (de Rouw, 2004).

Figure 3.1: Pearl millet (*Pennisetum glaucum* (L.) R. Br.) is the major staple crop in Niger. Left: a millet panicle head with mature grains, which are usually harvested by clipping the panicle from the stem. Right: millet is generally sown in plant pockets with little or no manure. Sowing, weeding, and harvesting is executed by hand and is very labour demanding

3.1.2 Biophysical conditions

Agricultural production is challenging under Nigerien biophysical conditions, especially due to the adverse climate and the poor land resource.

Climate

As a result of the interseasonal movement of the Intertropical Convergence Zone, rainfall in Niger shows a north-south gradient (Fig. 3.2). Agricultural activity mainly takes place in the southern, wettest part of the country, which on average receives between 400 and 600 mm rainfall a year (Guengant et al., 2003). Rain only falls between June and November and is highly unreliable for agriculture due to the random spatial distribution of convective storms and the large variability of rainfall within and between seasons (Barron et al., 2003; Tabor, 1995). The potential evapotranspiration rate is very high (between

2000 and 4000 mm year^{-1}) (Amadou et al., 1999), which is a consequence of high air temperatures (T_{min}: 11-27 °C, T_{max}: 28-41 °C) and high wind speeds ($\geq$ 28 m s^{-1}). The wind regime during the dry season is characterized by a dry harmattan wind, originating from the Sahara desert, while during the monsoon season, winds are humid and originate from the Atlantic ocean. Average daily relative humidity is low (13-66%) (Sivakumar, 1989).

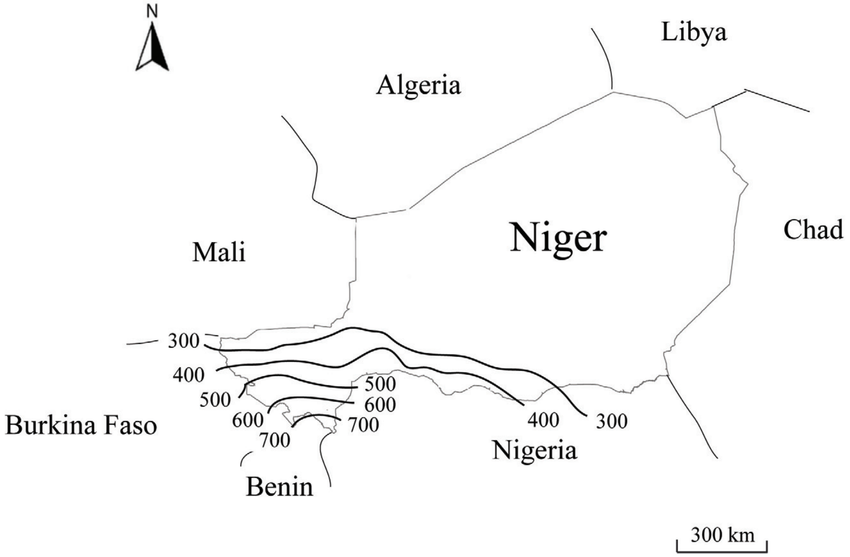

Figure 3.2: Map of Niger and its rainfall distribution as indicated by isohyets of 300-700 mm. Rainfall distribution shows a significant North-South gradient. Agriculture mainly takes place in the southern, wettest part of the country, below the 400 mm isohyet (Guengant et al., 2003)

Land use and the deterioration of the soil resource

Only 15 million hectares or 12% of Nigerien land is suitable for agriculture. Most agricultural land is under rainfed cultivation and only 1% is irrigated. Given the large groundwater potential, an extra 2.2% could be used for irrigation exploitation, but this is currently limited due to drilling and pumping costs. The water table varies between 5

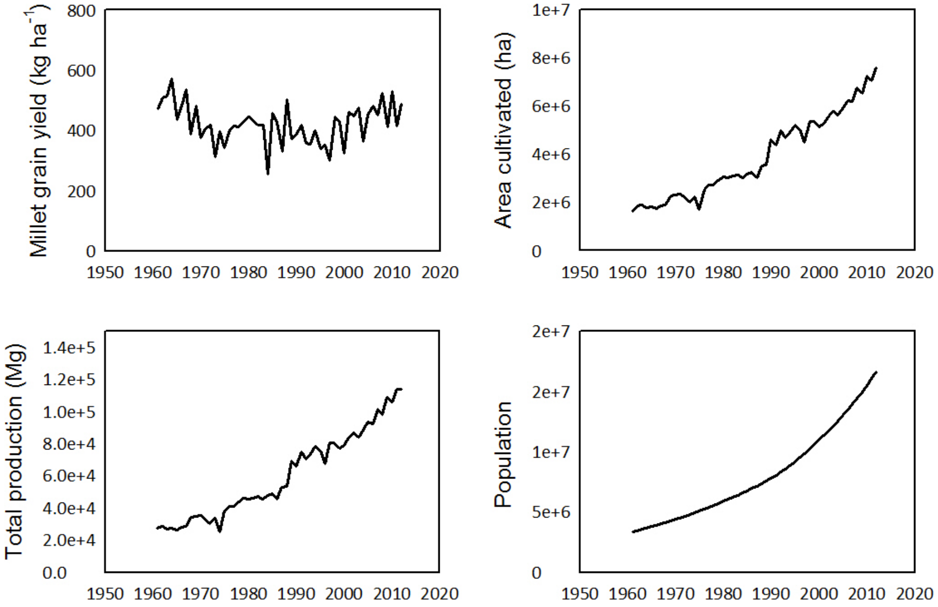

Figure 3.3: Some socio-economic data of Niger for 1950-2013. Total area cultivated (ha), total production (Mg) and population increased steeply, whereas millet yield per surface area (kg ha^{-1}) stagnated (FAO, 2014b)

and 75 m, with an average of 50 m. The only major permanent surface water source is the Niger river (Amadou et al., 1999).

The Nigerien farming system developed from a situation where land was essentially unlimited, but this changed during the second half of the 20th century (Guengant et al., 2003). Fallow periods decreased from 15 years to under five years during this period and according to Descroix et al. (2009), 80% of the cultivable land area was cleared between 1950 and 1992. Fig. 3.3 shows that the total area of land under cultivation as well as the population and total food production increased enormously during this period, whereas the productivity per surface area stagnated. The increase in total food production hence results from the expansion of agricultural area and not from productivity per surface area.

In the course of land clearing, cultivation extended to marginal lands, but farmer practices stayed the same or even intensified (shorter fallow periods). This resulted in increased susceptibility to soil erosion and ultimately caused substantial productivity loss (Tabor, 1995). Aggregates of bare soil easily disintegrate under impact of high intensity Sahelian rains and bare lands are much more susceptible to wind erosion, especially when the soil is dry (Descroix et al., 2009; Sterk et al., 1996). As a consequence of severe soil erosion, available farm land in Niger is shrinking by as much as 200 000 ha year^{-1} (Rinaudo and Yaou, 2009).

Topographical sequence and soil types

Land use and soil type are closely related to landscape position in the Tillaberí region of Niger. The land follows a typical 'inverted' Sahelian toposequence as described by Gandah et al. (2003) (Fig. 3.4). The most elevated area of this toposequence (zone (a) in Fig. 3.4) consists of a dissected plateau capped petroplinthite formed during the Miocene after repeated wetting and drying (Driessen et al., 2001). The plateau is bordered by a steep edge that slopes towards a gently undulation terrace (zone (b) in Fig. 3.4). On the terrace, the petroplinthite is covered with Quaternary eolian deposits, which allows crop production. These deposits range from coarse to very fine sandy and loamy materials and vary in depth from less than 0.5 m to more than 6 m. Lands with a thick layer covering the petroplinthite are considered as fertile, whereas lands with a shallow deposition layer are marginal. The lowest landscape positions (zone (c) in Fig. 3.4) are valleys formed by recent and fossil rivers.

The distribution of the main soil types in the region is closely related to the topographic sequence. In general, three different soil types are distinguished: deep clay soils which are found in the valley (Fluvisols) (20% of the total surface area), sandy soils (Arenosols) with a substantial eolian deposit thickness (50% of area) and marginal soils having the petroplintithe at shallow depth (Plinthosols) (Hoogmoed and Stroosnijder, 1984; WRB, 2006).

The Arenosols are, in spite of their inherent low soil quality, perceived as best suited for crop production, whereas Plinthosols are historically left fallow. Population growth forced farmers to increasingly rely on Plinthosols for food production, even though they are marginal lands and generally produce little or no millet yield (Amissah-Arthur et al., 2000).

This dissertation focuses on Plinthosols (WRB, 2006). These soils show major constraints for agricultural production (Boubacar et al., 2005) and are locally referred to as 'gangani' or 'laterite'. In this study the scientific term Plinthosols will be used. One of the major constraints of these soils is their shallowness due to the presence of a petroplinthite at shallow depth, which is also known as laterite, ferricrete or a hardpan.

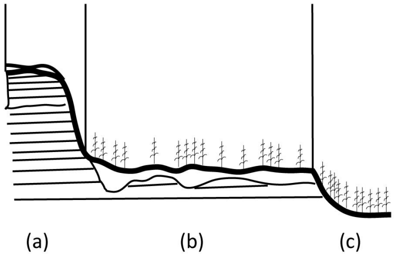

Figure 3.4: A typical toposequence of the 'inverted' Sahelian landscape after Gandah et al. (2003). The most elevated area (a) consists of a dissected capped plateau bordering a steep edge that slopes towards a gently undulating terrace (b) covered with quaternary eolian deposits. These deposits are often affected by serious soil erosion, which exposes the crusty subsurface and causes a poor distribution of water over the rootzone. The lowest landscape position (c) is generally formed by valleys containing drainage channels of varying importance

Petroplinthite was formed during the succession of former wetter and drier climatic conditions (Driessen et al., 2001). Its formation involved the crystallization of iron rich material (plinthite). Under water-saturated conditions this ferrous material is mobile, but precipitates as ferric oxide (petroplinthite) in drier conditions and will not or only partially re-dissolve when conditions become wetter again. It shows as red mottles and slowly forms a kind of cement together with the sand particles. Plinthite formed in depressions during a previous wetter period in the Sahel and hardened into petroplinthite when the climate became drier. Since the petroplinthite was shielded against erosion, former depressions have turned into the highest parts of the landscape and the original relief has inverted.

The major constraints of the petroplinthite for agricultural production are the obstruction of deep water percolation, the limitation of root growth and the low water availability in the shallow rootzone. Due to continuous cultivation, the shallow rootzone moreover faces enormous losses in soil organic matter.

According to Alexander and Cady (1962), the hardening of the petroplinthite is reversible, as the iron can solubilise in a complex with organic matter. Products of decomposing vegetation together with a larger moisture supply could thus decompose the petroplinthic fragments, which would enable roots to penetrate into the petroplinthite.

3.1.3 Policy and research efforts regarding water and soil management

The Nigerien governement, many NGOs and several research institutions are all fully committed to and determined to break the cycle of permanent food insecurity, but there is some disagreement on how to do this. After the last food crisis in 2011, the Nigerien government started the '3N'-initiative (Nigeriens Nourishing Nigeriens). This initiative 'aims at achieving food sovereignty by strengthening the national capacities for food production, supply and resilience' (HC3N, 2012). However, the governmental approach to increase Nigerien food production is still largely influenced by the dominant green re-volution thinking (van Walsum et al., 2014). The government invests in expensive seeds, external fertilizer inputs and large-scale irrigation equipment and gives only little attention to low-cost interventions such as WSC techniques. Given the decline in land resources, water and soil conservation seem essential when combating food insecurity (Foley et al., 2011). The government mostly decouples resource conservation from agricultural production and rather invests in large-scale soil conservation initiatives such as the stabilisation of sand dunes and the creation of green tree belts along the Sahara desert (APGMV, 2012).

Other actors, on the other hand, specifically target natural resource restoration through farmers. 'World Vision Niger' for example drew up the following key recommendations for agricultural development in Niger (Rinaudo and Yaou, 2009):

- invest physical and human resources in agricultural development;
- mobilize communities to restore degraded land;
- make sure that agricultural activities include hard pan rehabilitation activities and aspects of conservation agriculture; and
- tackle the number one issue for food security, i.e. change the people's beliefs and attitude.

Also various research institutes located in Niger (e.g. INRAN, ICRISAT, IRD, University of Niamey, AGHRYMET) are fully committed to contribute to increasing food productivity while safeguarding natural resources. Besides focusing on plant breeding, they also tackle the low soil fertility status of the highly weathered Nigerien soils. A large number of studies have shown that a minimum application of chemical fertilizer or cattle manure can significantly increase crop yields (Bationo and Buerkert, 2001), but these practices are poorly adopted by resource-poor farmers in the Sahel. According to Schlecht and Buerkert (2004), manure and fertilizer are generally applied well below the recommended rates. This is mainly due to poor access to credit, poor manure and fertilizer availability and insufficient knowledge of soil management. To solve this, the AGRA (Alliance for a Green Revolution in Africa) project has been set up, a long-term program to achieve integrated soil fertility management through investments in soil fertilizer for micro-dosing. Furthermore, alternative nutrient resources like termite mound material, compost, phosphate rock and acacia leaves are being investigated for improved soil management (Garba et al., 2010; Lahmar et al., 2012).

Unlike for soil fertility, there is no large-scale, long-term research program that deals with the optimization of soil-water use. The first rootzone water balance studies in Niger were conducted in the frame of the Hapex-Sahel experiment, which studied the effect of drainage on the water table recharge (Boubacar et al., 2005; Marengo et al., 1996; Nicholson et al., 1997). Later Rockström et al. (1998) studied the partitioning of rainfall over the rootzone along a hillslope. They identified that run-off, evaporation and drainage were major sources of water loss and revealed the need for a holistic low-cost approach that converges resource conservation and production efficiency of rainfed agriculture.

Based on these findings, several WSC-projects were initiated. The ‘Keita Integrated Project’ (FAO, 1995) was one of the first projects that succeeded in successfully disseminating WSC techniques among the local population, soon other success stories followed, such as the ‘Farmer Managed Natural Regeneration project (FMNR)’ in Maradi (Sendzimir et al., 2011). However, many other WSC projects failed and the awaited large-scale WSC adoption did not happen. These failures can largely be attributed to the lack of understanding of farmer adoption constraints and the rigid implementation of WSC techniques without transferring them to local socio-economic and biophysical conditions.

Until now, scientific literature on WSC techniques in Niger mainly reports results on yield increases (Roose, 1999; Tabor, 1995), whereas Fatondji et al. (2006) evaluated the effect of different fertilizer types on WSC and Fatondji et al. (2009) documented the decomposition process of manure and chemical fertilizers in zaï pits.

In Burkina Faso, WSC techniques have already been investigated more extensively. There, studies have been analysing yield increases under both zaï and demi-lunes (Roose, 1999; Sawadogo et al., 2008), socio-economic factors related to zaï implementation (Slingerland and Stork, 2000; Sidibé, 2005) and the role of nutrient management for grass strips, stone barriers (Zougmoré and Ouattara, 2004) and demi-lunes (Zougmoré et al., 2003). None of above-mentioned studies followed water dynamics in and around WSC techniques, and very few of them evaluated the impact of WSC on soil quality. Moreover, most of these studies were executed on fields belonging to research institutes, where biophysical conditions are easily controlled, while it is recommended to conduct WSC research on farmer fields, as this ensures the viability of WSC techniques at small-holder farming level (Liniger et al., 2011).

Recently, WSC techniques (like zaï, demi-lunes and scarification) have regained much attention, as the UN launched a global alliance for climate-smart agriculture (CSA). Still, very little is known about climate-induced drought in the Sahel and none of the above-mentioned studies have evaluated the potential of WSC techniques to mitigate drought stress. To our knowledge, only Barron et al. (2010) report about the complex linkages between dry spell mitigation and the soil-water balance. They only suggest WSC techniques as possible mitigation strategies for drought, but this has never been scientifically verified.

3.2 Pearl millet (*Pennisetum glaucum* (L.) R. Br.)

Pearl millet, or, in short, millet, was domesticated 4000 to 5000 years ago and is now widely distributed across the semi-arid areas of Africa and Asia, where it is principally grown for its grains. It appears to have been domesticated in the Sahel zone of West Africa, which is known to be the crop's main center of diversity. India is the largest producer of pearl millet, whereas the major producing countries in Africa are Nigeria, Niger, Burkina Faso, Chad, Mali, Mauritania and Senegal. In the USA, Australia, South America and Europe it is grown as a high-quality, forage crop (Vadez et al., 2012).

In Niger, almost all millet grain is used for human consumption. The grains are the principal source of energy, proteins and minerals for the rural population which consumes it as dough or porridge. The straw is used as thatching material and as a source of fodder during the dry season (Hausmann et al., 2012).

3.2.1 Taxonomy and description

Genus *Pennisetum* belongs to the Poaceae family and the Paniceae tribe. Most of the pearl millet grown in Africa can be divided in two groups: early varieties maturing in 75 to 100 days, and late varieties maturing in 100 to 150 days. Millet is an erect annual and grows to a height of 3 to 6 m, although the most productive hybrids are shorter than this (Hausmann et al., 2012). In contrast with sorghum (*Sorghum bicolor* (L.) Moench) and maize (*Zea mays* L.), pearl millet plants can produce various tillers (de Rouw, 2004). Leaves are flat, green, and up to 8 cm wide; the grain-bearing head of the plant forms a compact, cylindrical panicle. There are between 500 and 3,000 spikelets on a panicle, depending on the variety (Serraj et al., 2003).

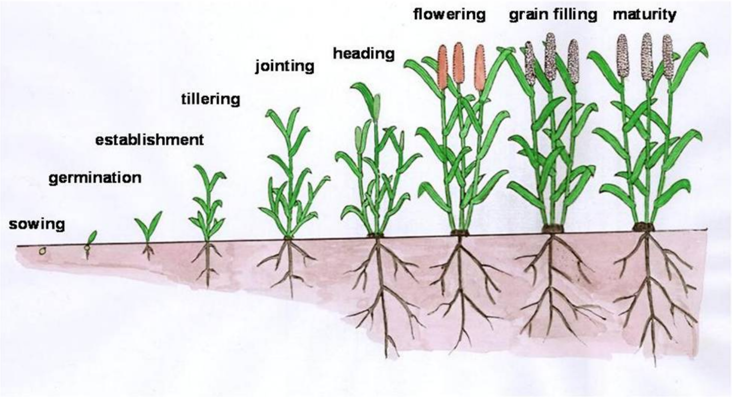

Figure 3.5: The development stages of millet. Sowing to tillering represents the vegetative phase, jointing to flowering the panicle-development phase and grain filling to maturity the grain-filling phase (Maiti and Bidinger, 1981)

The vegetative phase of millet (sowing to tillering in Fig. 3.5) begins with the germination of the grain and continues until panicle initiation. During this phase, the seedling establishes its primary root system and produces secondary, adventitious roots. Tillering starts before the end of the vegetative phase (Loumerem, 2004; Maiti and Bidinger, 1981). During the panicle-development phase (jointing to flowering in Fig. 3.5), leaves expand, tillers elongate and spikelets initiate. The primary tillers develop quickly after the formation of the main stem, but the growth of secondary tillers (from the primary ones) is frequently suppressed by the main stem (Loumerem, 2004). Finally, the grain-filling phase (grain filling to maturity in Fig. 3.5) begins with the fertilisation of the florets in the panicle of the main stem and ends when the grains are physiologically mature.

The duration of each of these growth stages varies considerably and depends on variety and environmental conditions. For West-African late varieties like the one used in this study, the vegetative phase typically lasts 50 to 80 days, whereas the grain-filling phase begins at 80 to 120 days after emergence (Maiti and Bidinger, 1981).

3.2.2 Environmental requirements

Millet resists high temperatures and grows optimally when temperature exceeds 30 °C. The optimal temperature for seed germination is in the range of ± 37-44 °C (Andrews et al., 1993; Loumerem, 2004). Millet endures low soil fertility and high soil acidity, but does not tolerate water-logged or seasonally-flooded soils. Because of its tolerance to challenging environmental conditions, millet is often found in marginal areas where other cereal crops, such as maize or wheat, do not survive. The major soil type on which millet is grown in the Sahel is a coarse-textured soil, containing more than 65% sand (Renard and Kumar, 2001). Millet is generally cultivated in areas where annual rainfall ranges from 200 to 800 mm and its optimal crop water requirement is estimated at 450 mm (Dancette, 1983; Garba and Renard, 1991). Variability in inter-annual rainfall is extremely high in the Sahelian region, resulting in recurrent drought periods. The timing of these drought periods is of paramount importance for their impact on millet crop production, as the sensitivity of millet to drought stress changes throughout its development. During the vegetative phase, millet is little affected by drought stress. On the other hand, drought stress during germination, flowering and grain formation is one of the main threats to millet production (Maiti and Bidinger, 1981).

Despite its sensitivity to drought during certain development stages, millet is well adapted to agricultural areas that are afflicted by severe drought and displays several strategies to resist drought stress.

Tillering

The capacity to tiller is an attribute that millet derived from its wild progenitors and is often referred to as 'developmental plasticity' or 'individual buffering'(Serraj et al., 2003). Millet develops primary and secondary tillers besides the main stem which results in staggered flowering. As such, millet can have tillers at different stages of apical development. This developmental plasticity allows millet to compensate for potential failure of the main or primary tillers in case of mid-season drought (Vadez et al., 2012). This tillering capacity is moreover responsive to environmental conditions. The plant produces little tillers in stress conditions, whereas plenty of tillers are formed during a favourable growing season (Hausmann et al., 2012).

Short development duration

Even under favourable conditions, millet tends to have a shorter crop cycle than other cereals which is a 'built-in' drought escape (Serraj et al., 2003). Its short growing cycle and its short flowering time, allow pearl millet to complete its development with relatively little water. The short flowering period moreover increases the plant's chance to escape drought stress during this sensitive period (Hausmann et al., 2012). In West-Africa the timing of flowering of millet appears to be closely related to the photoperiod corresponding to the end of the rainy season. In other words, millet flowers 'on time' to ensure that it can complete its maturation cycle before the end of the rainy season (Vadez et al., 2012).

Root system

Millet is known to be deep and profusely rooted, which enables water uptake even if only limited water is available. Most of the root system is concentrated in the first 30 cm of the soil, but, depending on the cultivar, roots can grow up to 600 cm deep (Loumerem, 2004). Millet roots furthermore spread laterally, resulting in a soil volume exploration at low planting density of up to 6 m^3 (Vadez et al., 2012). In case of severe drought stress, millet can prevent dessication by adjusting osmotic pressure in its roots through the active accumulation of solutes (Andrews et al., 1993).

Transpiration efficiency

Being a C_4 plant, millet has a high transpiration efficiency. On top of this, millet seems to maximize carbon fixation under optimal conditions by adapting stomatal movement so that transpiration rate and biomass production remain as high as possible when water is available (Vadez et al., 2012).

Drought stress during grain filling is the main threat to millet production in West Africa. The rainy season is often shorter than the crop growth cycle, which induces drought stress at the end of the rainy season. Most millet breeding strategies therefore focus on the identification of terminal drought tolerance to adopt millet to drought stress at the end of the rainy season (Hausmann et al., 2012).

3.2.3 Management

In Niger, millet is produced during the four-month rainy season and has a long-term yield average of $\simeq$ 350 kg grain ha^{-1}. Under optimal conditions, experimental grain yields of 8000 kg ha^{-1} of some millet hybrids have been reported (Andrews et al., 1993), but yield levels can already be increased 2.5 to 3 times on farmer fields if adequate plant material and improved management are applied (Renard and Kumar, 2001).

Millet is generally grown in monoculture, but can also be intercropped with cowpea (*Vigna unguiculata* (L.) Walp) or groundnut (*Arachis hypogaea* L.). It is seeded in pockets, which are opened by hand hoes. In each pocket, 5 to 40 seeds are placed and the clusters of plants emerging are thinned to 3 to 7 plants at first weeding. Farmers traditionally apply a low planting density (10 000 pockets ha^{-1}), as this induces tillering (de Rouw, 2004).

The most important diseases and pests are downey mildew (caused by *Sclerospora graminicola*), stemborer (*Coniesta ignefusalis*) and head miner (*Heliocheilus albipunctella*), whereas *Striga asiatica* (L.) Kuntze and *Striga hermonthica* (Del.) Benth are known to parasitize pearl millet (Renard and Kumar, 2001).

Harvest is usually done by clipping panicles from millet stems. Periodic clipping reduces crop damage by birds, pests and weather. Sowing, weeding, thinning and harvesting is in general executed manually and is very labour demanding (Maiti and Bidinger, 1981; Renard and Kumar, 2001).

4

Agricultural drought trends and mitigation in Tillaberí, Niger [1]

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[1] This chapter is based on the paper 'Agricultural drought trends and mitigation in Tillaberí, Niger' published in Soil Science and Plant Nutrition. DOI:10.1016/j.gloplacha.2008.05.004.

4.1 Introduction

Given the country's reliance on agriculture for livelihood, drought has become a much debated and distressing issue for Niger over the last decades. Agricultural production in Niger frequently suffers reduced crop productivity or even complete crop failure due to drought. The causes for drought in relation to crop production are complex (Mishra and Singh, 2010; Wilhite and Glantz, 1985). Slegers and Stroosnijder (2008) define agricultural drought as a shortage of available water for plant growth which includes two types of drought, meteorological drought and soil-water drought. Meteorological drought refers to a deficit of rainfall or to an unfavourable timing of rainfall distribution within the season, whereas soil-water drought occurs when there is a deficit of water in the rootzone as a result of poor water infiltration and limited water holding capacity. The question is whether agricultural drought in the Sahel is related to meteorological drought or to soil-water drought and whether agricultural drought worsens as a result of climate change, or as a result of declining soil resources in the region (Easterling et al., 2000).

Since the devastating famines following the droughts of the 1970s and 1980s, the international research community has made considerable efforts in analyzing climate variation and meteorological drought. This is either studied by predicting future variation with climate models or by analyzing past meteorological drought trends. However, climate models are no adequate tools to study meteorological drought in the Sahel. They do not allow accurate model prediction of rainfall distribution in the region, as the influence of increasing temperatures on the movement of the Intertropical Convergence Zone (ITCZ) (which drives rainfall in the region) is not sufficiently understood (Elagib, 2010; Giannini et al., 2008; Le Barbe et al., 2002; Nicholson, 2001, 2005). Global climate models to date show little agreement on whether future rainfall in the Sahel will increase, decrease or remain at current level (Mahé and Paturel, 2009; New et al., 2006).

Meteorological drought can also be analysed through the analysis of past rainfall events, but the lack of long-term climatic data, constitutes a major obstacle to do this. Since extensive African climatic records only begin in the 1950s and 1960s (Nicholson, 2001), studies on meteorological drought trends are generally based on short periods. It is therefore difficult to attribute detected trends to climate change or to regular reoccurring variability of the Sahelian climate. Most precipitation statistics do not exhibit consistent decreasing trends across the region (New et al., 2006), but droughts in the 1970s and 1980s have made several studies conclude that trends of rainfall at the end of the 20th century were declining (Balme et al., 2006; Gommes and Petrassi, 1994; Kasei et al., 2009; Tapsoba et al., 2004). Yet, these droughts were not unprecedented, as the Sahel has historically always witnessed alternating humid and arid periods (Mishra and Singh, 2010; Nicholson, 2001). More recent studies in fact speculate about a shift toward a less arid climlate and about rainfall recovery with wetter years from the 1990s onward (Balme et al., 2006; Barron et al., 2010; Elagib, 2010; Mahé and Paturel, 2009; Nicholson, 2005).

Meteorological drought is hardly ever studied in the context of agricultural production. Several studies deal with rainfall prediction and trends in the region (Lebel and Ali, 2009; Kasei et al., 2009), but they mostly report specialized climatic approaches analyzing yearly or monthly data. Drought indexes such as the Standardized Precipitation Index (SPI) or the Palmer Drought Severity Index (PSDI) typically quantify drought events and characterize their return periods, but these do generally not contribute to the specific understanding of crop failure in the Sahel (Mishra and Singh, 2010, 2011). They do not explain rainfall variability relevant within a farmer's reality. Crop production is mainly affected by intra-seasonal rainfall variation characterized by the onset of the rainy season, season length and dry spells (Balme et al., 2006). The variation of these parameters has, however, received little attention in the Sahel region, except for studies by Barron et al. (2003) and Sivakumar (1988, 1992).

Besides meteorological drought, research over the past two decades has also been focusing on soil-water drought. This type of drought is caused by a lack of available water in the rootzone which is a result of an imbalanced partitioning of rainfall over the rootzone due to land degradation (Mahé and Paturel, 2009; Rockström, 2003; Slegers and Stroosnijder, 2008). Unlike meteorological drought, soil-water drought is not related to rainfall patterns. In other words, if soil-drought occurs, crops suffer drought even when rainfall is not deficient. Land degradation leads to the deterioration of physical soil quality and causes a poor water distribution over the rootzone. Rainfall does not infiltrate into a soil with deteriorated physical quality due the presence of a soil crust. Instead, water is lost as run-off water. A poor soil structure furthermore limits the water holding capacity of a soil.

In order to effectively tackle agricultural drought, the causes and extent of both meteorological and soil-water drought need to be understood. However, WSC techniques are proclaimed to mitigate both drought types (Barron et al., 2010). These techniques are said to tackle soil-water drought by altering the rootzone water balance, while they also build resilience to meteorological drought by increasing the amount of water stored in the soil profile. Resilience is here defined according to Gunderson (2001) as 'the capacity of a system to undergo disturbance and maintain its functions and controls'.

Agricultural drought is a major threat to food security and the livelihood of many small-scale farmers in Niger. To gain better insight into the specific causes for crop failure related to drought, this chapter analyses the characteristics of agricultural drought on a farmer's field in the Tillaberí region of Niger. Furthermore, several WSC techniques are presented and evaluated for their potential to mitigate drought stress.

The chapter starts by investigating whether agricultural drought is related to a changing climate (meteorological drought, i.e. deficit of rainfall or unfavourable rainfall distribution) or to land degradation (soil-water drought, i.e. decreased water infiltration and water holding capacity). Rainfall and drought parameters affecting millet crop growth are subjected to trend analysis and soil-moisture recordings throughout three growing seasons (2011-2013) are examined. Finally, this chapter investigates the effect of five treatments (zaï + manure (Z), demi-lunes + manure (DL), scarification + manure (SCAR), control + manure (CF) and control (C)) on soil-water storage and crop performance recorded from an *in situ* field experiment. This allows to evaluate their potential to mitigate agricultural drought stress.

4.2 Materials and methods

4.2.1 Study area

The study area is located at Sadoré (13°15' N 2°17' E, 40 km south-east of Niamey) in the Tillaberí region of Niger. The region is located in the southern, wettest part of the country where most agricultural activity takes place (below the 400 mm isohyet, see Fig. 3.2 and 4.1).

The region is subjected to a Sudano-Sahelian climate with a long, hot and dry season (November-May), and a short cropping season (June-October). Rainfall has an annual average of 550 mm and is highly variable in space and time due to the randomness of

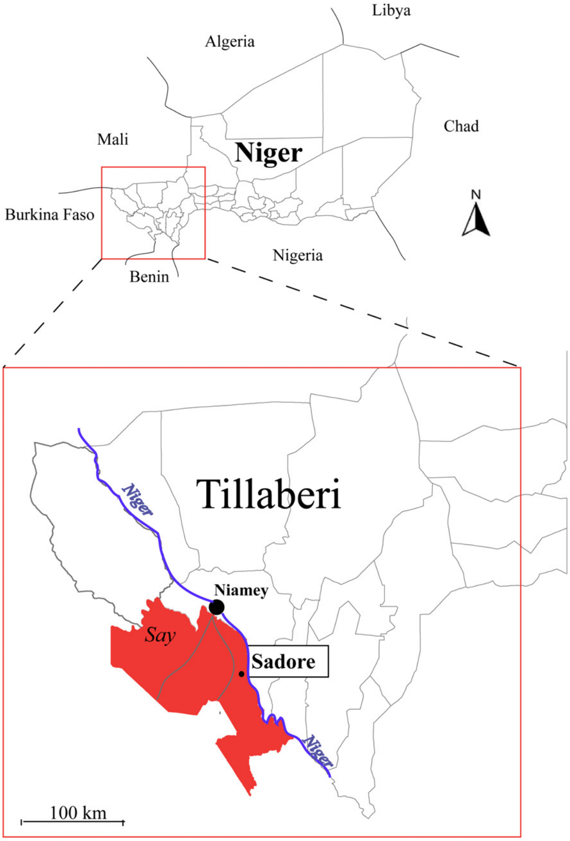

Figure 4.1: Map of Niger and the Tillaberí region (enlarged section). The experimental field is located near Sadoré village (13°15' N 2°17' E, 40 km south-east of Niamey) in the Say department (shaded area) of the Tillaberí region

convective storms. Rainfall intensity is very high with 50% of the events having intensities exceeding 27 mm h^{-1} and with peak intensities of up to 386 mm h^{-1} (Sivakumar, 1989). Potential evaporation is very high and varies between 2000 and 4000 mm per year and daily temperature varies between 25 and 41 °C.

Small-scale farmers relying on rainfed agriculture dominate the region and typically grow pearl millet (*Pennisetum glaucum* (L.) R. Br.) in monoculture. However, sometimes cowpea (*Vigna unguiculata* (L.) Walp) or groundnut (*Arachis hypogaea* L.) are sown as intercrop later in the season. A general description of pearl millet was given in Chapter 3, section 3.2. Since millet cultivation dominates and farmers generally plant local landraces, a local variety of the predominant landrace of western Niger was chosen as test crop. This variety is known as 'Sadoré Locale' and has a growing cycle of 120 days (Fatondji et al., 2006).

4.2.2 Experimental design and site description

An *in situ* experiment was set up on a Plinthosol at Sadoré village. The field site forms part of a typical toposequence of the Sahelian 'inverted' landscape and belongs to the marginal lands situated in zone b in Fig. 3.4. The origin and nature of Plinthosols are described in Chapter 3, section 3.1.2. The field had slope of 1% and a shallow rootzone due to the presence of a petroplinthite at a depth of 0.35 to 0.40 m. The texture in the top 0.35 m as determined by the sieve-pipette method (Gee and Bauder, 1986), was loamy sand (sand: 791 g kg^{-1}, silt: 113 g kg^{-1}, clay: 96 g kg^{-1}).

The study was conducted during three rainy seasons (April 2011- November 2013). To examine crop response of conventional practice and WSC technqies, an experimental field with five treatments was installed. The control (C) and control with manure (CF) treatments are the conventional practices in the region, whereas demi-lunes (DL) and zaï (Z) are common WSC techniques in the region. The scarification treatment (SCAR) was based on farmers' suggestions and instructions of key-informants (see chapter 8) specialized in local WSC techniques. Z and DL are extensively described in scientific literature (Fatondji et al., 2006, 2009; Liniger et al., 2011; Roose, 1999; Zougmoré et al., 2003). Only details of their implementation on the experimental field are given here, together with detailed description of the other treatments (C, CF and SCAR).

- Control (C): this is a conventional practice in the Tillaberí region. No manure was added and no land preparation was applied. Only small planting pockets (1 m x 1 m) were opened at seeding by hand hoes.
- Control with manure, which is locally referred to as 'fumier' (CF): this is a conventional practice in the Tillaberí region, but with cattle manure application (described below). No land preparation was applied, except for the application of manure, which was superficially mixed with the topsoil. Manure was only applied in a circle

of 0.30 m where plant pockets would be opened with hand hoes at seeding.

- Scarification (SCAR) (Fig. 4.2a): this WSC technique can be considered as a conservation agriculture practice. Two of the three key principles of conservation agriculture were applied. The soil was covered year-round and the soil was minimally disturbed. Furrows of 0.05 to 0.07 m depth and 0.10 m width were made parallel to the slope with a distance of 1 m. Cattle manure (similar to CF) was mixed within the furrow with the loosened top soil (Fig.4.3a) and plants were sown in the furrows with 1 m distance. Stubble was not harvested and left on the field after harvest to cover the soil year round. The % soil cover was 4.76 ± 3.60 (as assessed by orthogonal pictures described in Chapter 6, section 6.2.2).
- Demi-lunes (DL) (Fig. 4.2b): this WSC technique consists of installing earth bunds parallel to the contour line. The earth bunds, also known as half moon-shaped bunds, were installed according to the design of Zougmoré et al. (2003), i.e. 4 m in diameter and spaced at 2 m on the contour line with 4 m between two successive lines. The bund was constructed with earth dug from the basin (2-3 cm depth). Manure was mixed with the top soil in the basin (similar to CF). The bunds collect run-off water from the catchment area in between bunds into the basin known as the cropping area (Fig.4.3b).
- Zaï (Z) (Fig. 4.2c): this is an indigenous Sahelian WSC technique which consisted of digging pits of ± 0.3 m diameter and 0.15 m depth during the dry season in which the same amount of manure as for CF was applied (Roose, 1999) (Fig.4.3c). The pits were installed in a 1 m x 1 m grid and collect run-off water originating from the catchment areas in between pits (Fig.4.3d).

The experimental field was laid out with five treatments and three replicates, according to a random block design. Blocks that were 12 m by 16 m with earthen ridges of 0.3 m wide and 0.15 m high separating them. Two trenches at the upslope side of the experimental field prevent run-on to the plots.

As suggested by Fatondji et al. (2009), farmyard manure at an annual rate of 3 ton ha^{-1} was added to all treatments, except for the control treatment (C). It comprised a mixture of urine, cow dung and straw. The millet variety ‘Sadoré Locale’ was sown at

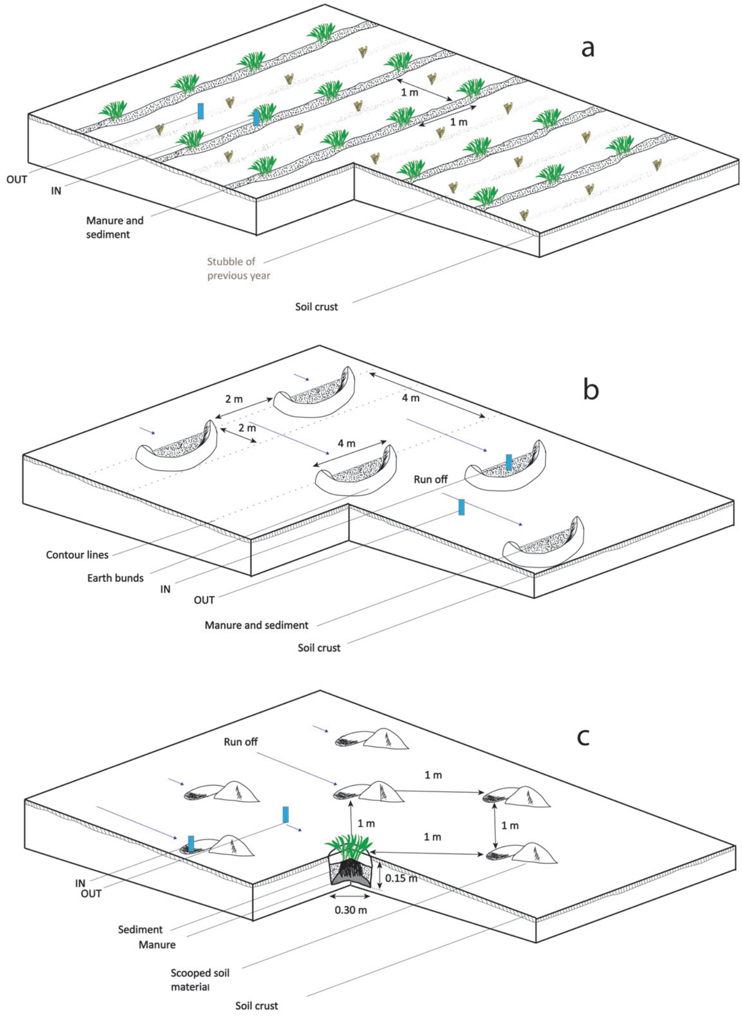

Figure 4.2: Schematic representation of the WSC techniques evaluated on the experimental field at Sadoré village. These techniques were implemented to optimize the root-zone water balance on a Plinthosol in the Tillaberí region of Niger. Soil-water measurements were carried out with a neutron probe, in two access tubes per plot, one placed within the cropping area or next to the plant (IN) and one in between cropping areas in the catchment area (OUT). For the scarification treatment (SCAR) (a) shallow furrows were made in which manure was applied and stubble was left on the field after harvesting to provide year-round soil cover. The demi-lunes (DL) (b) consisted of installing earth bunds parallel to the contour line. Millet is sown in the basin of these bunds, after manure application. Zaï (Z) (c) consisted of digging pits in which millet is sown after manure application.

Figure 4.3: Installation of WSC techniques on the experimental field at Sadoré village. For the scarification treatment (SCAR), manure was applied in shallow furrows and stubble was left to cover the soil year-round (a). The demi-lunes (DL) or half-moon shaped collect run-off water into a cropping area where millet is sown after manure application (b). Manure was also applied in the zaï pits (Z) (c). Together with the collection of run-off water in the pit, manure creates favourable growing conditions for millet growth within the pit (d).

a planting density of 10 000 plant pockets ha^{-1}. The seedlings were thinned, according to farmers' practice, to 3 to 7 plants per pocket five weeks after sowing (Fatondji et al., 2006). In case of demi-lunes, plants were sown in pockets within the basin (the cropping area) and not in the catchment area which resulted in a high planting density in the cropping area (24 plant pockets per basin). To test the effect of planting density, four extra plots were installed in 2013, two with 12 (DL12) and two with 18 (DL18) plant pockets per basin.

To reflect farmers' reality, all management practices were executed by farmers. Pesticides and herbicides were not applied, farmers only removed infested plants. Sowing took place according to farmer perception, i.e. after the first substantial rain event, which in case of our experiment was after 14 mm and 16 mm of rain (on 18 June 2011, on 22 June 2012 and 2 July 2013 (DOY 169,173,183)). At the end of the rainy season, millet was harvested on 12 October 2011, 23 October 2012 and 31 October 2013 (DOY 285,296,300).

To evaluate crop response, stubble and seed dry weight were recorded at harvest on 4 m x 6 m subplots per block. Additionally, the number of empty pockets was recorded towards the end of the vegetative growing phase on 13 July 2011, 16 July in 2012 and 24 July 2013. After this, millet was resown in the empty pockets, according to farmers' practice. Root depth was measured by excavation on 17 September 2012 and 30 September 2013.

4.2.3 Meteorological drought parameters and trend analysis

Two sets of rainfall data were used to analyse meteorological drought in the region. A climate database of FAO (1994) provided monthly rainfall data from Niamey airport and was used to study long-term trends in annual rainfall from 1905 until 1996. Daily rainfall from the ICRISAT Sahelian center at Sadoré from 1983 until 2010 was used to study recent trends in rainfall parameters important for crop management (Le Barbe et al., 2002; Tarhule and Woo, 1998). Number of rain days, season length, number of dry spells, and onset and end of the rainy season were computed according to the definitions of Sivakumar (1988). In brief, a dry spell was defined as a consecutive period of 7 days in the rainy season without rain. The onset of the rainy season was defined by the date after 1 May when accumulated rainfall of three days was at least 20 mm, whereas the end of the rainy season was defined as the date after 1 September after which no rain occurs over a period of 20 days. Season length was calculated as the number of days between onset and end of the season.

To study trends in these parameters, the non-parametric Mann-Kendall test was applied. Its distribution-free approach allows detection of monotonic trends in non-normally distributed climatic data (Mann, 1945; Kendall, 1975) and the rank-based procedure makes the test robust to extreme values and outliers (which are common for Nigerien rainfall data). The method evaluates time series of parameters as follows:

$$S = \sum_{j}^{n-1} \sum_{j=i+1}^{n} sign(T_j - T_i) \tag{4.1}$$

$$sign(T_j - T_i) = \begin{cases} 1 \; if \; T_j - T_i > 0 \\ 0 \; if \; T_j - T_i = 1 \\ -1 \; if \; T_j - T_i < 0 \end{cases} \tag{4.2}$$

where T_i and T_j are the parameter value in years i and j for which $i \leq j$. A standard S is calculated to estimate the significance level of the trend. The null (H_0) hypothesis of no trend was tested at 95% confidence level against the alternative (H_1) hypothesis of a decreasing or increasing trend resulting in respectively a negative or positive value of S.

4.2.4 Soil-water data collection

To evaluate soil-water drought, soil-water content was monitored in 2011, 2012 and 2013 at different depths (15, 30, 45, 60, 75, 90 and 105 cm) using a neutron probe (CPN-503DR hydroprobe) with two aluminum access tubes installed per plot. One was positioned next to the plant and entails in case of the Z, DL and SCAR treatments respectively the pit, the basin and the furrow. The other was placed between plants or in the catchment area. Soil-water data derived from these two tubes were denoted as IN and OUT, respectively (Fig. 4.2). A calibration curve was established to convert measured count ratio (count rate in soil over standard count rate) to volumetric water content and standard counts were made three times before and after measuring in a water drum. Similar to Rockström and Valentin (1997), measurements were taken after each rainfall event ($\geq$ 1 mm), and then minimally three times in the subsequent weeks. The first week measurements were predominantly carried out the first, third and fifth day after the event. Since root depth of the studied millet crop remains shallow (see below, Table 4.1), soil-water storage over the rootzone depth (22.5 cm) was calculated using the measurement at 15 cm depth with trapezoidal integration as described by Gardner et al. (2000). Data are missing between 26 July (DOY 197) and 16 August (DOY 228) 2011 and between 23 September (DOY 266) and 9 October (DOY 282) 2013.

4.2.5 Statistical analysis

A one way ANOVA with treatment as factor was used to test for statistical differences in crop parameters and soil-water storage between the management treatments. When variances were unequal, data were logarithmically or inversely transformed. In case of a significant effect of treatment ($p \leq 0.05$), an LSD test was performed to indicate significant differences. Data were analyzed using SPSS version 20 (SPSS Inc., Chicago) at 0.05 significance level. Frequency distribution analysis of total rainfall amount was performed by RAINBOW, a software package for hydro-meteorological frequency analysis (Raes et al., 2006).

4.3 Results

4.3.1 Meteorological drought analysis

No significant trend was found (p=0.643) in annual rainfall at Niamey airport (Niger) (Fig. 4.4). Annual rainfall was very variable and several long periods with consecutive years of low rainfall can be distinguished, but these are recurrent. They coincide with the well-known droughts of the 1970s and 1980s and a drought period at the beginning of the 20th century.

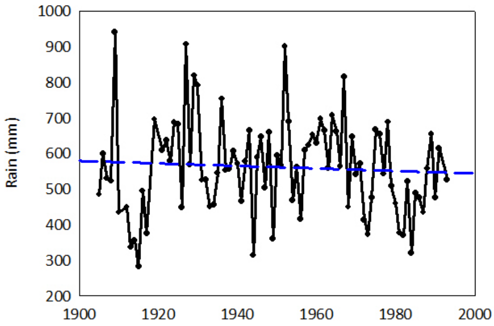

Figure 4.4: No significant (p: 0.643) trend was found in total annual rainfall amount at Niamey airport. The S-statistic representing the magnitude of the (insignificant) trend was -121.

Figure 4.5 shows time series and Man-Kendall trend analyses of daily rainfall parameters at Sadoré. Significant positive trends can be observed for number of dry spells per rainy season (p=0.046) and the end of the rainy season (p=0.049). Season onset, number of rainy days and seasonal rainfall amount did not show any significant trend,

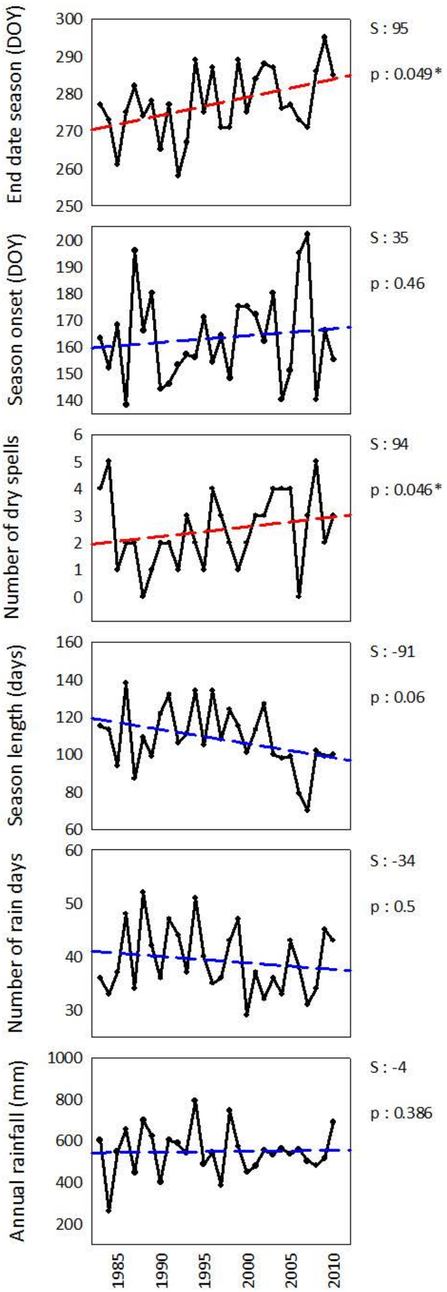

Figure 4.5: Yearly series of daily rainfall parameters at Sadoré and their Mann-Kendall trend analysis. The dotted curve represents the detected trend of which sign and magnitude are presented by the S-value and significance by the p-value. Significant trends at the 0.05 significance level are indicated by *

whereas season length shows a general tendency to decrease (p=0.06). The damage a dry spell causes to millet crop production, depends greatly on the timing of dry-spell occurrence. Fig. 4.6 shows the probability to face a dry spell in every 10-day period of the growing season. During each of the first four 10-day periods of the growing season, which concurs with germination of millet until tillering, the probability to face a dry spell is approximately 30%. During the next four 10-day periods, the probability to face a dry spell remains low (jointing to flowering), but dry-spell probability increases again at the end of the growing season during the grain filling phase of millet.

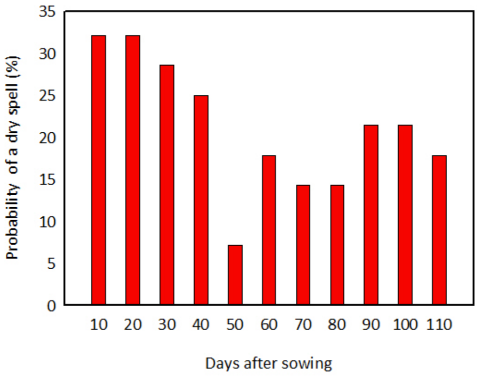

Figure 4.6: Columns represent the probability of dry spells for successive 10-day periods during the growing season. The meteorological drought risk throughout the growing season. Date of sowing was assumed to coincide with the theoretical onset of rains as defined by Sivakumar (1988)

Rainfall data from Sadoré during the growing season of 2011, 2012 and 2013 also show large variability (Fig.4.7). 2011 was characterized by four dry spells and low annual rainfall amount (417 mm), with a probability of exceedance of 88% over the period 1983-2010 (Raes et al., 2006). The 2012 season experienced three dry spells, but rainfall was more evenly distributed over the growing season with substantial rains continuing until September, resulting in a season with above average seasonal rainfall amounting to 687 mm, with a probability of exceedance of 11%. Seasonal rainfall in 2013 was also high (615 mm, probability of exceedance is 14%) but rains commenced very late in the season and ceased abruptly, which resulted in an intensive, but short rainy season.

4.3.2 Soil-water storage analysis

Soil-water storage (S) over the 0-22.5 cm rootzone layer during the growing seasons of 2011, 2012 and 2013 is shown in Fig. 4.7. The graphs denominated by IN refer to measurements in the cropping area or next to the plant, whereas graphs denominated by OUT refer to measurements in between plants or in the catchment area (see Fig. 4.2). In general, S slightly increased at the onset of the rainy season and gradually augmented, with peaks responding to large rain events, after which it decreased again towards the end of the rainy season. Maximum S was recorded in August as a result of the typical heavy rains. The moment of sowing and harvesting is indicated by vertical dotted lines.

The critical soil moisture level in the rootzone CRIT corresponds, according to Allen et al. (1998), to the level below which drought stress occurs and was found to be 24 mm. CRIT was calculated from the total available water in the rootzone derived from a lab-determined soil water retention curve (see Chapter 5) and a depletion factor (so called ‘p-value’), i.e. the crop specific fraction of the total available water content that is allowed to deplete from the rootzone before crop-water uptake can no longer respond optimally to the transpiration demand (Allen et al., 1998). Total available water content was calculated as the soil-water storage between field capacity (FC, 36 mm) and permanent wilting point (PWP, 15 mm) and the ‘p-value’ for millet was taken at 0.6 after having adjusted the tabulated value for climate (through average potential crop evapotranspiration over the cropping seasons) and texture.

Since soil-water storage in the cropping area (S_{IN}) for the conventional treatments and SCAR only surpassed CRIT after heavy August rainfall, the millet crop regularly experienced soil-water drought for these treatments. In 2011 S_{IN} remained low throughout the year, whereas in 2012 and 2013 S_{IN} levels at the beginning of the growing season seemed problematic. For all treatments S_{IN} remained surprisingly high at the end of 2013, even though rains abruptly held off in September.

WSC techniques on the other hand induced an important increase in S_{IN} throughout the growing season. Inside the cropping area of DL, water was remarkably well conserved in the rootzone, with S_{IN} being considerably higher as compared to all other treatments throughout the three growing seasons. Likewise, S_{IN} of Z increased substantially, but in

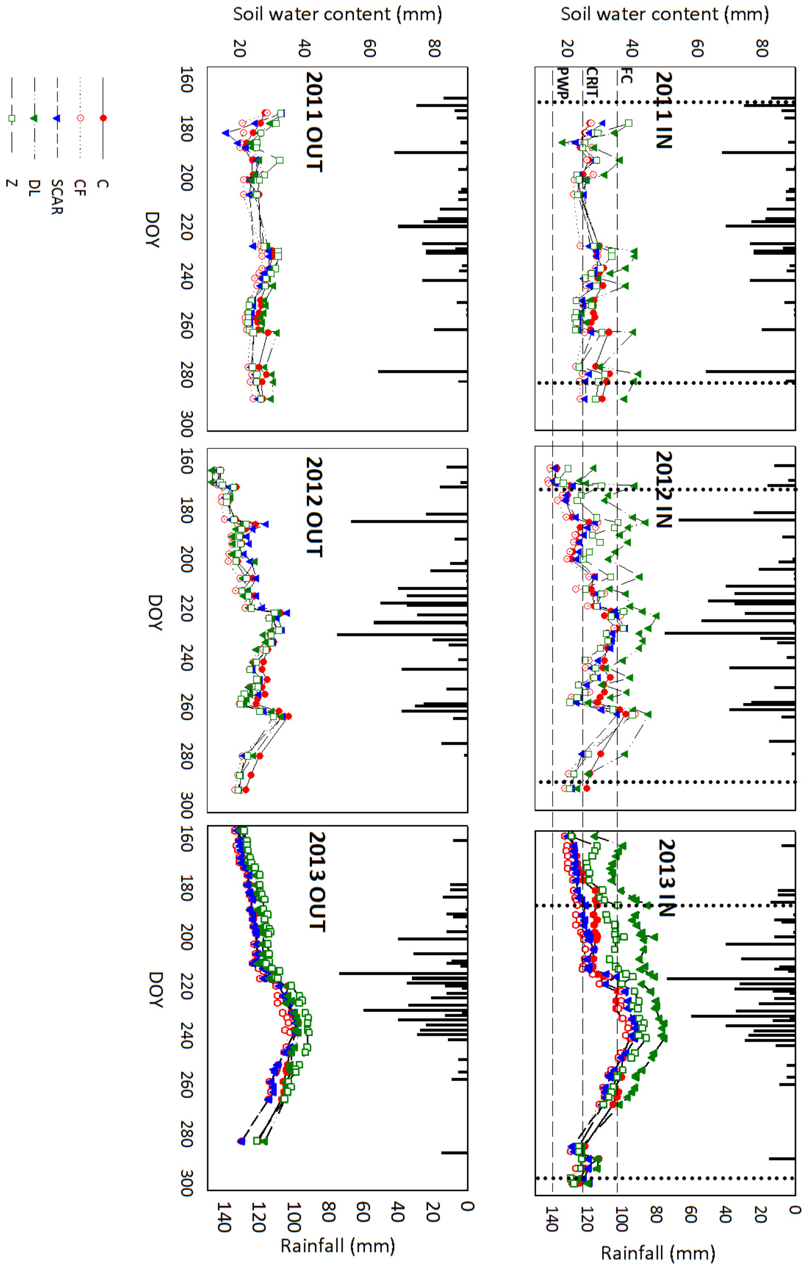

Figure 4.7: Rainfall distribution on the experimental field of Sadoré in 2011, 2012 and 2013 with corresponding soil-water data of the 0-22.5 cm rootzone layer of different treatments (C = control, CF = control + manure, SCAR = scarification + manure, DL = demi-lunes + manure, Z = zaï + manure). The charts denominated (IN) depict soil-water storage within the cropping area or next to the plant and the ones denominated (OUT), in between cropping areas or in the catchment. Soil moisture contents at field capacity (FC), permanent wilting point (PWP) and the critical soil moisture level (CRIT) in the rootzone, which were derived from a lab-determined soil water retention curve, are indicated. Vertical dotted lines in the rain charts represent time of sowing and harvesting

Table 4.1: Agronomic parameters representing millet crop response on WSC treatments (C = control, CF = control + manure, SCAR = scarification + manure, DL = demi-lunes + manure, Z = zaï + manure, DL12 and DL18 = demi-lunes with respectively 12 and 18 plants instead of 24 (DL) within the catchment) including average grain yield (n=3), straw yield (n=3) and rooting depth (n=9) and the percentage of pockets where plants did not emerge in 2011, 2012 and 2013. Straw yield for SCAR is absent, since for this treatment, stubble was left on the field. With ± standard deviations and values labelled with the same letter indicating no significant differences between treatments at $p \leq 0.05$

Year	Treatment	Grain yield (kg ha^{-1})	Straw yield (kg ha^{-1})	No emergence pockets (%)	Root depth (cm)
2011	C	0 ± 0	11 ± 10a	19 ± 12a	-
	CF	1 ± 1a	406 ± 379b	29 ± 28a	-
	SCAR	15 ± 10ab	-	3 ± 4b	-
	DL	40 ± 12 bc	1149 ± 106c	0 ± 0c	-
	Z	134 ± 37c	1672 ± 118d	1 ± 1b	-
2012	C	0 ± 0	0 ± 0	40 ± 16a	13 ± 2a
	CF	149 ± 77a	1198 ± 123a	13 ± 6ab	20 ± 4ab
	SCAR	246 ± 110b	-	7 ± 4b	22 ± 3ab
	DL	249 ± 123b	2188 ± 294ab	12 ± 1 b	19 ± 1ab
	Z	651 ± 160c	3000 ± 1301b	14 ± 10 ab	26 ± 5b
2013	C	0 ± 0	49 ± 32a	9 ± 2a	7 ± 2a
	CF	49 ± 53ab	858 ± 473b	2 ± 2b	16 ± 8b
	SCAR	117 ± 52ab	-	1 ± 2b	15 ± 8b
	DL	161 ± 37bc	861 ± 111b	8 ± 4ab	14 ± 7b
	Z	268 ± 40c	1274 ± 70b	2 ± 2b	18 ± 7b
	DL12	143	760	-	-
	DL18	119	916	-	-

2011 and 2012, short periods of low S_{IN} prevailed in the rootzone around DOY 250 (Fig. 4.7), causing water stress at sensitive growing phases of pearl millet development, i.e. at flowering and grain filling. S_{IN} never dropped well below CRIT for DL.

Although S_{IN} of DL remained higher than S_{IN} of Z throughout both seasons, they were never significantly different during the dry rainy season of 2011, whereas three observations differed significantly in 2012 and eight observations in 2013. In turn, S_{IN} within the zaï pits was substantially higher as compared to SCAR, CF and C after rain events in the first half of the growing seasons only, when crop transpiration for Z was still limited. S_{IN} of SCAR was similar to S_{IN} of C and CF, which could indicate that the augmented soil-water storage for SCAR was effectively used for transpiration (Fig. 4.7).

The soil-water storage between plants (S_{OUT}) was largely similar for all treatments throughout the three growing seasons, except for slightly higher values in case of zaï pits in 2013, suggesting an improved infiltration or water retention capacity due to the yearly build up of sediments captured in between pits.

4.3.3 Crop response

Table 4.1 presents several agronomic parameters representing pearl millet crop response for the growing seasons of 2011, 2012 and 2013. In general, millet yields showed large variation between growing seasons and depended much on rainfall distribution. They were highest in 2012, when rainfall was relatively abundant and evenly distributed, while yields suffered from the short rainy season in 2013 and from an overall dry rainy season with severe dry spells in 2011.

Millet crop production encountered severe problems under both control treatments (CF and C) (Table 4.1). Grain yield for all seasons was zero for C and remained very low under CF. Applying manure only (CF), however, did enable significant straw production, which was also absent for C.

WSC techniques clearly improved millet crop growth, resulting in both higher straw and grain yields in all years. The highest grain yield was produced by Z, which was approximately two to three times higher than that of DL for all years and of SCAR for 2012 and 2013.

Reducing planting densities for DL only reduced grain yield marginally, from 160 kg ha^{-1} for a planting density of 10000 plants ha^{-1} to 144 and 120 kg ha^{-1} for respective planting densities of 5000 and 7500 plants ha^{-1}, while straw yields respectively reduced or even increased slightly.

Rooting depth was significantly increased under CF, SCAR, DL and Z. It was higher in 2012 than in 2013, with a maximum of 26 cm for Z in 2012. Approximately 10 to 40% of the plants did not emerge for C and CF in 2011 and 2012, while in 2013 more plants emerged, but this was because plant pockets were regularly resown at the beginning of the rainy season due to the late establishment of the season.

4.4 Discussion

This study shows that large inter-annual and intra-seasonal rainfall variability is inherent to the Sahelian climate and that meteorological droughts related to below average annual rainfall amount did not increase with time, whereas meteorological drought related to poor rainfall distribution within the season, did.

There is an increasing prevalence of dry spells which demands an adjustment of crop water management, that enables bridging several days without rain. Dry spells often cause major crop failure (e.g. in 2011). Besides prevalence, the timing of dry spells is crucial. Although our results indicate that there is a high dry-spell risk during the first crop growth stages of millet, water stress within this period will probably not greatly affect agricultural production, as, according to Sivakumar (1992), millet is not highly sensitive to moisture stress during the early growth phase. On the contrary, excessive rainfall in the first days might even result in poor germination. Flowering and grain filling phase of millet on the other hand are more sensitive to drought stress and face elevated probabilities for dry spells. The period between jointing and flowering (40-80 days after sowing) encounters a lower risk for dry spells, presumably because the ITCZ is more regularly positioned in the middle of the rainy season than at the beginning and end of the season.

Besides timing of dry spells, rainy season length highly determines crop yields as well. Often, rainy seasons appear too short for the growing cycle of pearl millet, like in 2013 on the experimental field. 75% of registered years in Sadoré had a season length shorter than 120 days, which is, according to Fatondji et al. (2006), the duration of the growing cycle of the locally cultivated millet variety.

It is important to keep in mind that our results are limited to one location and that spatial variability in the region is typically very high due to the characteristic convective systems. As such, dry conditions on one field can occur together with wet conditions on another one in the same year. Farmers therefore tend to cultivate fields scattered around the village, to reduce risk and avoid total yield loss (Graef and Haigis, 2001). Nevertheless, the presented results agree with recent findings in literature and can therefore be assumed to correspond to a general tendency. Barron et al. (2010) and Balme et al. (2006) also indicated a recovery of total rainfall amount at the end of the 20th century in the region and respectively point to an increase in dry spell occurrence and a decrease in number of rainfall events.

The great variability in grain yields obtained in our field experiment in Sadoré confirms millet's crop growth dependency on the prevailing meteorological conditions. As such, crop production suffers from meteorological drought in the region. Grain yield is remarkably lower when dry spells occur during crucial growth stages such as in 2011 and when the growing season is short like in 2013.

Furthermore, millet production also suffers from soil-water drought in the region. Crop response under the conventional treatments (C and CF) prove that the shallow and crusted Plinthosols subjected to high evaporation rates do generally not contain sufficient soil-water to sustain considerable crop growth. The low germination rate and minor rooting depth under the conventional practice C (Table 4.1) considerably hampered biomass production. Application of manure significantly improved root development which is known to be stimulated by phosphorus availability. However, without the implementation of a WSC technique, the young roots of seedlings cannot attain enough water in the hard soil. This problem is typically worsened by adding nutrients without securing water supply and resulted in an elevated rate of non-emergence in 2011 for the CF treatment.

WSC techniques on the other hand seem to mitigate both meteorological and soil-water drought, as they tackle the adverse intra-seasonal rainfall variability and enable important increases in available soil-water storage S_{IN} (Wani et al., 2009). It was found that especially the system design of the zaï and demi-lunes treatments elevated S_{IN} substantially above the level of critical soil-water storage CRIT and could hence tackle agricultural drought. DL mitigates agricultural drought throughout the entire season, whereas crops under Z still seem to experience some (but limited) drought stress when dry spells coincide with a millet growth phase sensitive to drought stress, even though they are generally regarded as techniques well-suited for water and soil conservation (Fatondji et al., 2011; Roose, 1999). Note however that the critical value for drought stress was only estimated based on lab-determined FC and PWP values and an assumed 'p-value' for all millet varieties and should not be considered exact.

Despite short periods of theoretical water stress inside the pits, Z produced by far the highest grain yield and crop biomass. DL produced lower grain yield which might be surprising at first sight considering their higher water conservation capacity. This can largely be explained by the high planting density inside the cropping areas. Since a general planting density of 10 000 plants ha^{-1} was respected in the experimental lay out and no plants were sown in between the demi-lunes, the actual planting density in the cropping area was much higher. High planting density might cause competition for root growth, nutrients or light and typically suppresses millet's tillering capacity. Tillering allows staggered flowering and enables the spreading of sensitive stages (e.g. flowering and grain filling) over a longer period, which protects the plant from total yield loss due to one dry spell (de Rouw, 2004). The suppression of tillering in DL might therefore explain why grain yields for DL were low, despite the good straw yields. Tillering also explains why grain yields are similar for lower planting densities in the DL basin. Hence, if grain yield remains the same for lower planting densities, farmers might as well sow at a lower density inside one DL-basin. Moreover, if besides a lower number of plants per DL, also more DL bunds per surface area would be installed, potential yield would increase substantially. Chapter 7 therefore investigates the optimization of the DL system design by simulating the rootzone water balance under systems with increased numbers of DL bunds per surface area.

The SCAR treatment produced very little grain in 2011. This can be attributed to crop failure as a result of the limited rainfall amount in 2011, but also to the absence of stubble in 2011, at the start of the experiment. Stubble was only left on the field after the first growing season and only beneficially affected crop growth in 2012 and 2013. How stubble beneficially affected crop growth for SCAR is further discussed in Chapter 5 and 6.

Although even the highest millet yields produced by the WSC techniques seem overall low, they are comparable to the long-term average yields (422 kg ha^{-1} ± 0.064) on regular

Arenosols in Niger which are perceived as more fertile than Plinthosols. The obtained yields furthermore agree with grain yields produced on Arenosols in the region in 2011 (270 kg ha^{-1} ± 0.145) and 2012 (545 kg ha^{-1} ± 0.105)(RNMA, 2012a,b). Our yields for Z are comparable to those reported by Fatondji et al. (2006) and Roose (1999), but the observed grain yield for DL was low compared to the grain yield of approximately 500 -1500 kg ha^{-1} reported by Zougmoré et al. (2003), whereas observed straw yield was lower but in the same order of magnitude. Their study, however, was conducted with a higher total rainfall amount (± 690-740 mm), higher rates of manure application and involved sorghum (*Sorghum bicolor* (L.) Moench) instead of pearl millet (*Pennisetum glaucum* (L.) R. Br.). Millet is more tolerant to drought than sorghum, but is more sensitive to water logging. Flooding of the DL cropping areas after heavy rain events might be prevented by increasing the number of DL bunds per surface area (see Chapter 7).

4.5 Conclusion

In the region, both meteorological drought, related to poor rainfall distribution, and soil-water drought, related to poor distribution of rainfall over the rootzone, occur. In addition, the number of dry spells even seems to increase (Roose, 1999; Sawadogo et al., 2008; Tabor, 1995). Hence, drought mitigation to improve crop production and livelihood should always take both drought types into account. It is important to keep in mind that policies to tackle or halt meteorological (or climate) change depends on long-lasting international action with uncertain agreement, while policies concerning land degradation and land use to build resilience against soil-water drought can be dealt with locally and are more straightforward.

WSC techniques show potential to mitigate both drought types and increase crop production on Plinthosols by increasing soil-water storage. Since the combination of the zaï pitting system design and manure application enabled the highest yield, zaï pits seem best suited for improved millet crop production. However, this treatment still seems to encounter some drought stress near the end of the growing season despite the treatments' water harvesting features. The zaï treatment could therefore possibly be optimized by integrating other advanced crop management technologies such as the application of supplemental irrigation when rain events fail at the end of the season. Given the decrease in rainy season length and the long duration of the growing cycle of the local millet variety

'Sadoré Locale', short duration varieties could further ameliorate agricultural production. In contrast, the demi-lunes treatment demonstrates continuous high soil-water storage for all seasons, but does not seem best suited for pearl millet production, at least not when planting densities of 24 plant pockets per DL are taken. Since lower planting densities show similar grain yields, optimizing DL system design with lower planting densities, but more DL bunds per surface area is warranted. Given the demonstrated suitability of demi-lunes to increase water availability in the rootzone, impacts of demi-lunes on the productivity of other crops should be studied as well.

Despite the potential of Z and DL to tackle both soil-water and meteorological drought, several socio-economic obstacles need to be dealt with if large scale dissemination is to be promoted (see Chapter 8). A remaining question is moreover whether WSC techniques will continue to mitigate drought when the trend in increasing occurrence of dry spells would persist in the region and when land degradation would not be tackled but would continuously aggravate. Therefore the underlying features enabling increased soil-water storage including soil physical properties and the partitioning of rainfall over the rootzone water balance were investigated in Chapter 5 and Chapter 6. These should be understood in order to optimize the design of WSC techniques.

5

Effect of water and soil conservation on the chemical, biological and physical soil quality of a Plinthosol in Niger[1]

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[1] This chapter is based on the eponymous paper accepted in Land Degradation & Development

5.1 Introduction

Land degradation associated with rapid depletion of soil organic carbon (SOC) stocks is severely affecting agricultural livelihoods in the developing world (Stocking, 2003). Farmers therefore need to apply improved nutrient management practices designed to rehabilitate or maintain their soil's productivity, but they often cannot afford chemical fertilizers and the amount of local crop residues and animal manure is typically limited (Tittonell et al., 2012).

Poor nutrient management leads to the incessant decline of soil organic matter content which ultimately results in large-scale deterioration of soil quality (Kintché et al., 2010; Lahmar et al., 2012). Soil quality is widely known as the capacity of a soil to perform its functions, which include sustaining agricultural production and maintaining environmental quality within certain ecosystem and land use boundaries (Lal and Shukla, 2004). Usually, a distinction is made between physical, chemical and biological aspects of soil quality. However, since no single indicator is able to describe all aspects of soil quality, preferably a variety of indicators is used to monitor soil quality.

Soil tests typically focus on chemical soil-quality indicators as they provide information on plant nutrient availability, but physical and biological aspects of a soil are equally important to evaluate soil quality. Physical soil-quality indicators evaluate soil structure, soil strength, water transmission and water storage. They are examined by analysis of the soil pore system. A soil should provide adequate plant support and allow unrestricted root development and fluid transmission (Doran et al., 1996). Although well-recognized nowadays, biological soil quality is generally not properly integrated into soil-quality monitoring (Neher, 2001). Nevertheless, biological soil health is of paramount importance for vital soil ecological processes like nitrogen cycling and organic matter decomposition. Several parameters can be used to indicate biological soil quality. Since nematode abundance correlates well with soil ecological processes it is considered as a good indicator of biological soil quality (Neher, 2001).

Small-scale farmers in the Tillaberí region of Niger rely on agricultural production for their livelihoods and hence on their soil's ability to sustain this production. Given the deteriorated Nigerien soil resource, innovative nutrient management practices aiming at improved soil quality are urgently needed. Several techniques, which we refer to as water and soil conservation (WSC) techniques, were developed in Niger to rehabilitate Plinthosols for improved crop production. Zaï, demi-lunes and scarification are three common WSC techniques in the region (see Chapter 4).

Although scientific literature often attributes soil rehabilitating properties (i.e. improving soil quality) to these WSC techniques, quantitative research investigating the effect of WSC on soil quality is lacking. The proclaimed soil rehabilitating capacity of WSC in the Sahel is, until now, only reported by means of qualitative scoring methods and has not been verified by quantitative soil quality monitoring. The well-known WOCAT data base (Liniger et al., 2011), for example, evaluates WSC techniques based on the appreciation of WSC specialists. According to those WSC specialists, zaï pits improve infiltration capacity, soil structure, soil fertility, organic matter and water storage, but quantitative data supporting this is not given. Fatondji et al. (2006, 2009) did report on the nutrient balance and efficiency of plant nutrient-uptake in zaï pits in Niger, but did not investigate the effect of zaï on soil quality. Furthermore Zougmoré et al. (2003), Zougmoré and Ouattara (2004) and Sawadogo et al. (2008) did assess effects of demi-lunes on chemical soil restoration in Burkina Faso, but overlooked the physical and biological aspects of soil quality.

In contrast to the Sahel, several studies elsewhere have already been evaluating the effect of improved management practices on soil quality. Thanks to the popularity of conservation agriculture (CA), many studies have been reporting on the positive effect of reduced tillage, crop rotation and residue management (the three key principles of CA) on chemical, physical and biological soil quality indicators in Europe and North-America (Arthur et al., 2011; Strudley et al., 2008; Vermang, 2012) and also in SSA soil quality has been found to improve under different improved management practices, e.g. forestry (De Boever et al., 2014), application of termite mound material (Garba et al., 2010) and CA (Araya, 2012; Thierfelder et al., 2013).

WSC techniques are widely promoted in the Sahel for their beneficial impact on crop production and soil-water storage (see Chapter 4), but their capacity for land rehabilitation has not been evaluated yet. Given the severely degraded land resources in the region, it is essential to quantify the effect of WSC techniques on soil quality.

To quantify the impact of WSC techniques on soil quality, several soil quality indicators were monitored during three growing seasons on a WSC field experiment in Tillaberí, Niger. The techniques to be evaluated are zaï, demi-lunes and scarification. In order to evaluate the integrated effect of the techniques on soil quality, chemical (SOC, nutrient content and pH), as well as physical (bulk density, porosity and hydraulic conductivity) and biological (nematode abundance) soil-quality indicators were evaluated. Given the incessant decline of soil organic matter in the region, this study also elaborates on the potential of WSC to sequester soil organic matter. Furthermore the relation between increased soil-water content and improved soil physical properties under WSC is analysed (see Chapter 4).

5.2 Materials and methods

5.2.1 Experimental design and site description

The experimental field was installed on a Plinthosol with shallow rootzone (± 0.35-0.40 m). The soil's structure stability index, as designed by Pieri (1992), was 3.3%, which indicates a structurally degraded soil. The field experiment at Sadoré village was extensively described in Chapter 4, section 4.2. Only a brief description will be given here.

Figure 5.1 shows the cumulative rainfall distribution at the experimental field in 2011, 2012 and 2013.

Farmyard manure mixed with straw was applied at an annual rate of 3 ton ha^{-1} or 300 g per plant pocket as suggested by Fatondji et al. (2006). Manure was applied within the zaï pit (Z) (Fig. 4.3c), mixed with the top soil inside the demi-lunes cropping area (DL) (Fig. 4.3b), mixed within the furrow with loose top soil for the scarification treatment (SCAR) (Fig. 4.3a), and superficially mixed with topsoil in a circle of 0.30 m around the plant pockets for the CF treatment. This was done before the onset of the rainy season with applications on 28 May in 2011 and 2013, and on 27 May in 2012.

Besides manure application, SCAR also included crop residue management. Stubble was not harvested and left on the field to cover the soil year round. The % soil cover was 4.76 ± 3.60. Note that stubble was only left on the field from October 2011 and onwards and was not present during the first growing season. Since, in case of SCAR, furrows were annually made at a different location to avoid removing stubble remaining from the previous growing season, manure was annually applied on a different location for SCAR.

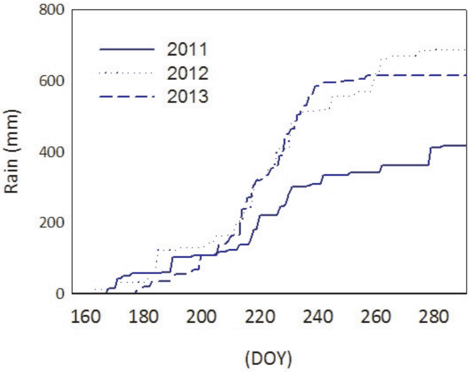

Figure 5.1: Cumulative rainfall at the experimental field at Sadoré during the growing seasons of 2011, 2012 and 2013. 2011 was a very dry year, whereas 2012 and 2013 were years with above average seasonal rainfall. Rainfall was, however, very poorly distributed in 2013

In contrast, for CF, DL and Z, it was annually applied on the same location. Fertility management for SCAR is therefore different than for CF, DL and Z, since the latter three treatments rather experienced a concentration of manure application on a fixed spot.

5.2.2 Chemical soil quality indicators: soil acidity and nutrient content

Six bulk soil samples were taken per treatment from the 0-10 cm layer after each growing season for chemical analyses. pHK_{Cl} of the air-dried soil samples was measured in 1:2.5 soil:1M KCl extracts using a glass electrode. Total soil N and C contents were measured by dry combustion at 850 °C with a Variomax CNS-analyzer (Elementar Analysesysteme, Germany). Available K, Na, Ca, Mg and P were determined by dissolving 2 g of soil in ammonium lactate (pH 3.75) followed by analysis by Inductively Coupled Plasma-Atomic Emission Spectroscopy ICP-AES on an iCAP 6300 series (Thermo Scientific).

5.2.3 Physical soil quality indicators: bulk density, soil porosity parameters and hydraulic conductivity

In order to determine the effect of WSC techniques on bulk density and soil porosity parameters, 24 undisturbed core samples (100 cm^3) were taken per treatment after each growing season. This was done using 5 cm diameter steel rings. Four rings were collected from each replicate, two of which next to the plants or in the WSC cropping area and two in between plants or outside of the cropping area, at 0-5 cm and 5-10 cm depth.

Bulk density (ρ_b) was determined from the oven dry mass (105 °C) and the volume of the soil cores. The soil-water retention curve (SWRC) was constructed following the procedure described by Cornelis et al. (2005). Saturated soil cores were subjected to pressure potentials between 0 kPa and -10 kPa using the sand box method (Eijkelkamp Agrisearch Equipment, the Netherlands), whereas for lower pressure potentials (up to -1500 kPa), the pressure membrane method (Soilmoisture Equipment, USA) was applied. RETC software was subsequently used to fit the water retention model of van Genuchten (1980) to the desorption data:

$$\theta = \theta_r + \frac{\theta_S - \theta_r}{[1 + (\alpha.h)^n]^m} \tag{5.1}$$

where θ_r ($\text{m}^3\ \text{m}^{-3}$) is residual volumetric water content, θ_S ($\text{m}^3\ \text{m}^{-3}$) saturated volumetric water content, h (cm) is pressure potential head, and α (cm^{-1}), n and m are fitting parameters, with m = 1- 1/n.

The soil water retention curve allowed the calculation of some indicators related to the soil's pore network (soil porosity parameters) (Reynolds et al., 2009). As such, field capacity (θ_{FC}, $\text{m}^3\ \text{m}^{-3}$), i.e. the volumetric water content at pressure potential of -10 kPa, permanent wilting point (θ_{PWP}, $\text{m}^3\ \text{m}^{-3}$), i.e. the volumetric water content at -1500 kPa, plant available water capacity (PAWC), $\text{m}^3\ \text{m}^{-3}$), calculated by θ_{FC} - θ_{PWP}, air capacity (AC) calculated by θ_S - θ_{FC} and macroporosity, calculated by θ_{FC} - $\theta_{at-1kPa}$ were determined.

The effect of WSC techniques on hydraulic conductivity was determined by means of infiltration measurements. Saturated (K_{sat}) and unsaturated (K_{ψ}) hydraulic conductivity were determined in 2011 with a Model 2825 tension infiltrometer adaptor module

(Soilmoisture Equipment, Santa Barbara, CA) with a diameter of 0.20 m and attached to the Mariotte system of a Guelph permeameter. For each treatment, 10 to 12 replicates of infiltration measurements were executed with three successive negative pressures, -0.29, -0.59 and -1.18 kPa for at least 15 min or until the infiltration rate of three consecutive time intervals was constant. Saturated and unsaturated hydraulic conductivity were subsequently calculated with the method of Logsdon and Jaynes (1993), a method based on Wooding's equation for unconfined steady state flow, which was found to perform accurately by Verbist et al. (2009).

5.2.4 Biological soil quality indicator: nematode abundance

In order to study the nematode abundance in the soil, three bulk soil samples were taken per treatment close to millet plants at the end of the growing season in 2011 and 2012. All samples were immediately stored in a cool box to avoid a reduction in nematode numbers due to excessive temperatures and sunlight. Within 48h after sampling, nematodes were extracted from 100 g of fresh soil according to the decanting method (van Bezooijen, 2006). The soil sample was first stirred in water to detach the nematodes from the soil particles. When these particles settled, the nematode suspension was poured over a 25 μm sieve (in contrast to van Bezooijen (2006), who used a set of four 45 μm sieves) to eliminate tiny and light particles that remained in suspension at the time of decanting. The debris on the sieves was washed and poured on a paper nematode filter. Subsequently, the nematodes were left for 24 h, during which they migrated through the filter into distilled water. This resulted in a clear suspension with active nematodes, which was examined under a microscope to determine and count free-living or plant-parasitic nematodes.

5.2.5 Statistical analysis

To evaluate the effect of WSC techniques on soil quality, a one way ANOVA with treatment as factor was performed. In case of a significant effect of treatment ($p \leq 0.05$), an LSD test, as suggested by Webster (2007), was executed to indicate significant differences. When variances were unequal, data was logarithmically or inversely transformed. In case data was not normally distributed, the non-parametric Kruskall Wallis test was applied.

5.3 Results and discussion

5.3.1 WSC effect on chemical soil quality

In general, manure application (CF, SCAR, DL and Z) gradually improved the soil's chemical quality over three growing seasons compared to the conventional treatment (C) (Table 5.1 and 5.2). In 2012 and 2013, significant increases in total soil organic carbon (SOC) content were observed for all treatments with manure, except for SCAR and for Z in 2012. Note however that even though SOC content increased significantly, SOC levels are still very low ($\leq$ 6 g kg $^{-1}$). In a survey of 31 millet producing soils in the Sudano-Sahelian zone, Bationo et al. (2001) reported an average SOC content of 7.6 g kg $^{-1}$ with a range from 0.8 to 29.4 g kg $^{-1}$. Values for total N content of DL and CF are higher than of C, but significant differences were not detected due to the large variability within and between treatments. In general, the total N content remained low with levels ranging from 0.18 g kg $^{-1}$ to 0.57 g kg $^{-1}$. Bationo et al. (2000) reported total nitrogen levels ranging from 0.03 to 2.26 g kg $^{-1}$ in 30 West African semiarid soils.

The less pronounced build-up of SOC in case of SCAR might be explained by manure not being applied at the same fixed spot each year for SCAR, unlike for CF, DL and Z. The lower SOC content of Z on the other hand might be due to the higher biomass production compared to CF and DL (Table 5.1), which results in a higher population of decomposing soil organisms responsible for the mineralization of the manure applied. Similarly, the large variability in SOC content of CF may be explained by a variable mineralization rate due to variable populations of decomposing soil organisms. Where millet seeds did not germinate, soil organic matter decomposing micro-organisms were not active, and hence, the applied soil organic matter remained in place.

Soil pH under the control treatment (C) was very low (i.e. acidic, pH ± 4.0), which limited plant availability of essential nutrients (e.g. N, P, Ca, Mg). Although no significant differences were detected (due to the large variability within and between measurements), pH raised to 4.2 - 5.0 following the application of manure in the other treatments (CF, SCAR, DL and Z). This increase in measured pH values was probably due to the increase in SOC content. Organic matter components contain cation exchange sites, which can adsorb H^+ leading to an increase in pH. Application of manure hence increased the pH buffer capacity of the soil, which is of great importance for coarse textured soils with low

Table 5.1: Average (n=3) contents of soil organic carbon (SOC), total nitrogen (N) and available phosphorus (P) and, pH(KCl) for different treatments (C = control, CF = control + manure, SCAR = scarification + manure, DL = demi-lunes + manure, Z = zaï + manure) in 2011, 2012 and 2013 in the 0-10 cm soil layer with ± standard deviations and averages labelled with the same letter indicating no significant differences between treatments at $p \leq 0.05$

	SOC (g kg^{-1})			pH(KCl)		
	2011	2012	2013	2011	2012	2013
C	2.32 ± 0.82a	2.42 ± 0.20a	2.54 ± 0.23a	3.9 ± 0.2a	4.0 ± 0.0a	4.0 ± 0.1a
CF	2.43 ± 0.84a	3.90 ± 1.23bc	6.12 ± 2.58c	4.2 ± 0.1a	4.8 ± 0.6a	5.3 ± 1.2a
SCAR	2.38 ± 1.23a	3.32 ± 0.76ab	3.07 ± 1.72ab	4.2 ± 0.3a	4.8 ± 0.9a	4.2 ± 0.8a
DL	5.94 ± 1.03b	4.75 ± 0.06c	4.58 ± 0.52bc	4.7 ± 0.1b	5.2 ± 0.3a	4.6 ± 0.3a
Z	3.02 ± 0.06a	2.92 ± 0.85ab	3.63 ± 0.49bc	4.2 ± 0.1a	4.5 ± 0.4a	4.7 ± 0.3a
	N (g kg^{-1})			P (g kg^{-1})		
	2011	2012	2013	2011	2012	2013
C	0.18 ± 0.08a	0.23 ± 0.14a	0.19 ± 0.06a	0.06 ± 0.03a	0.04 ± 0.01a	0.04 ± 0.01a
CF	0.19 ± 0.07a	0.30 ± 0.18a	0.57 ± 0.28a	0.06 ± 0.05a	0.10 ± 0.10a	0.03 ± 0.01a
SCAR	0.19 ± 0.11a	0.24 ± 0.07a	0.27 ± 0.15a	0.09 ± 0.07a	0.14 ± 0.12a	0.10 ± 0.12a
DL	0.50 ± 0.08a	0.36 ± 0.13a	0.40 ± 0.06a	0.08 ± 0.02a	0.04 ± 0.07a	0.06 ± 0.03a
Z	0.25 ± 0.03a	0.20 ± 0.07a	0.33 ± 0.07a	0.08 ± 0.05a	0.14 ± 0.03a	0.10 ± 0.05a

Table 5.2: Average (n=3) soil contents of calcium (Ca), potassium (K), magnesium (Mg) and natrium (Na) for different treatments (C = control, CF = control + manure, SCAR = scarification + manure, DL = demi-lunes + manure, Z = zaï + manure) in 2011, 2012 and 2013 in the 0-10 cm soil layer, with ± standard deviations and averages labelled with the same letter indicating no significant differences between treatments at $p \leq 0.05$

	Ca (g kg^{-1})			K (g kg^{-1})		
	2011	2012	2013	2011	2012	2013
C	0.21 ± 0.05a	0.26 ± 1.20a	0.24 ± 0.10a	0.05 ± 0.03a	0.06 ± 0.01a	0.01 ± 0.02a
CF	0.25 ± 0.14a	0.39 ± 1.94a	0.28 ± 0.23a	0.05 ± 0.03a	0.11 ± 0.01a	0.14 ± 0.02b
SCAR	0.35 ± 0.12a	0.42 ± 1.95a	0.64 ± 0.55a	0.09 ± 0.03a	0.17 ± 0.01a	0.07 ± 0.02a
DL	0.36 ± 0.14a	0.17 ± 0.58a	0.38 ± 0.16a	0.07 ± 0.02a	0.05 ± 0.01a	0.02 ± 0.02a
Z	0.29 ± 0.85a	0.32 ± 1.17a	0.56 ± 0.07a	0.08 ± 0.02a	0.07 ± 0.01a	0.03 ± 0.02a
	Mg (g kg^{-1})			Na (g kg^{-1})		
	2011	2012	2013	2011	2012	2013
C	0.02 ± 0.01a	0.02 ± 0.01a	0.02 ± 0.01a	0.06 ± 0.03a	0.08 ± 0.01a	≤0.01
CF	0.02 ± 0.02a	0.03 ± 0.05a	0.02 ± 0.04a	0.06 ± 0.05a	0.05 ± 0.02a	≤0.01
SCAR	0.04 ± 0.03a	0.08 ± 0.06a	0.09 ± 0.02a	0.09 ± 0.07a	0.06 ± 0.03a	≤0.01
DL	0.03 ± 0.01a	0.02 ± 0.03a	0.02 ± 0.01a	0.08 ± 0.02a	0.05 ± 0.02a	≤0.01
Z	0.03 ± 0.00a	0.07 ± 0.03a	0.03 ± 0.01a	0.08 ± 0.05a	0.07 ± 0.01a	≤0.01

Table 5.3: Average (n=3) bulk density (ρ_b) for different treatments (C = control, CF = control + manure, SCAR = scarification + manure, DL = demi-lunes + manure, Z = zaï + manure) in 2011, 2012 and 2013 in the 0-5 cm and 5-10 cm soil layers, with ± standard deviations and values labelled with the same letter indicating no significant differences between treatments at $p \leq 0.05$

	ρ_b (Mg m^{-3})					
	0-5 cm			5-10 cm		
	2011	2012	2013	2011	2012	2013
C	1.62 ± 0.16a	1.64 ± 0.08a	1.58 ± 0.12a	1.56 ± 0.06a	1.45 ± 0.26a	1.59 ± 0.14a
CF	1.57 ± 0.11a	1.43 ± 0.18a	1.36 ± 0.23a	1.48 ± 0.28a	1.31 ± 0.16a	1.35 ± 0.19a
SCAR	1.53 ± 0.18a	1.41 ± 0.16a	1.46 ± 0.11a	1.61 ± 0.13a	1.27 ± 0.15a	1.34 ± 0.05a
DL	1.42 ± 0.22a	1.37 ± 0.14a	1.51 ± 0.09a	1.43 ± 0.22a	1.27 ± 0.12a	1.44 ± 0.15a
Z	1.56 ± 0.02a	1.53 ± 0.08a	1.58 ± 0.08a	1.47 ± 0.09a	1.55 ± 0.11a	1.48 ± 0.12a

clay content and inherent low buffering capacity (Hoogmoed and Stroosnijder, 1984).

Differences in available P, Ca, Mg, Na and K content between treatments were insignificant at $p \leq 0.05$, except for a significant higher K content for CF in 2013. Available P content is often the most limiting nutrient for crop growth in the Sahel. Available P content was higher for SCAR and Z than for CF and DL (though only at $p \leq 0.1$). This might be explained by an extra nutrient source for SCAR and Z, which for SCAR consisted of millet stubble and for Z of tree leaves caught in the planting pit during the dry season. Despite this slighly higher available P content, the crop residue management of SCAR (millet stubble) did not show a large effect on the chemical soil quality in the present study. In contrast, Akponikpe et al. (2008) did find a positive and synergistic effect of crop residue and manure on chemical soil properties of a sandy soil in Niger.

5.3.2 SOC sequestration

According to our results, a slight SOC build-up is possible under WSC, but combining SOC build-up with continued biomass production is difficult. Biomass production induces a high population of decomposing soil organisms, which mineralize the manure applied. As such, the applied SOC-resource is ‘consumed’ and does not accumulate in the soil. Turnover rates of organic material are high in the farming systems in the Sudano-Sahelian zone due to high temperatures and the presence of termite and microorganism populations. According to Bationo et al. (2001), average annual losses in soil organic matter content may be as high as 4.7%.

Several authors (Sawadogo et al., 2008; Zougmoré and Ouattara, 2004) have reported higher impacts of both demi-lunes and zaï treatments on chemical soil properties in Burkina Faso. In these studies, manure was applied at a much higher (3 to 5 times) rate than in our study, but, given the general manure shortage in the region, farmers will more likely apply a lower rate of manure. Williams et al. (1995) reported that household herds can only provide manure for 0.5-0.6 ha and we similarly found in Chapter 8 that only 40% of the farmers can apply manure to all their fields. Authors such as Roose and Barthès (2001) and Fatondji et al. (2009) who used realistic annual manure doses similar to our study (i.e. 3 ton ha^{-1}), observed only a modest SOC build-up as well.

Hence, if manure shortage in the Sahel is taken into account and a substantial build-up of SOC is aimed at, other forms of nutrient management strategies are required. Kintché et al. (2010) and Rusinamhodzi et al. (2013) question whether crop residue management and fertilizer inputs can reverse SOC losses from degraded sandy soils under continuous cultivation, even when applied at high rates. Lahmar et al. (2012) therefore propose to encourage the regeneration of Native Evergreen Multipurpose Woody Shrubs (NEWS), such as *Guiera senegalensis* (J.F.) Gmel. and *Philiostigma reticulatum* (DC.) Hochst. These shrubs can be associated with traditional cereal crops (whether or not cultivated under WSC) and provide leaves and twigs as mulch, while also reducing wind erosion. Such shrubs serve as 'fertility islands' which improve soil characteristics (Wezel et al., 2000).

Additionally, crop rotation could be explored to further enhance soil rehabilitation. Crop rotation is known to favour the development of extensive rooting zones and rotation with legumes could add nitrogen to the soil (Vermang, 2012). Currently millet and sorghum are mostly cultivated in monoculture, but intercropping with cowpea or groundnut is successfully being introduced.

5.3.3 WSC effect on physical soil quality

No significant differences in bulk density were observed due to the large variability within and between treatments, but bulk density of the top 0-5 cm was for all years consistently lower for the treatments with manure (CF, SCAR, DL and Z) compared to the conventional treatment (C) (Table 5.3). A similar trend can be noticed at 5-10 cm depth, except for the bulk density under Z which showed relatively high values. Overall, measured soil bulk densities ranged from normal to very high values for a loamy sand and agree with previously reported values for Plinthosols in Niger (Fatondji et al., 2009; Gandah et al., 2003).

Figure 5.2 shows that both at 0-5 cm and at 5-10 cm depth, none of the indicators derived from the soil water retention curve were significantly affected by the WSC techniques, except for θ_S under SCAR which showed an increase in 2012. The higher θ_S values under SCAR might be associated with an increase in 'structural' pores. These pores presumably result from the crop residue left on the field, which was found to attract termites that induce soil pore formation through tunnelling (Tilahun et al., 2012).

Overall, PAWC values were low, and varied from 0.05 to 0.15 m^3 m^{-3}, which according to the critical levels proposed by Reynolds et al. (2009), correspond to limited to droughty

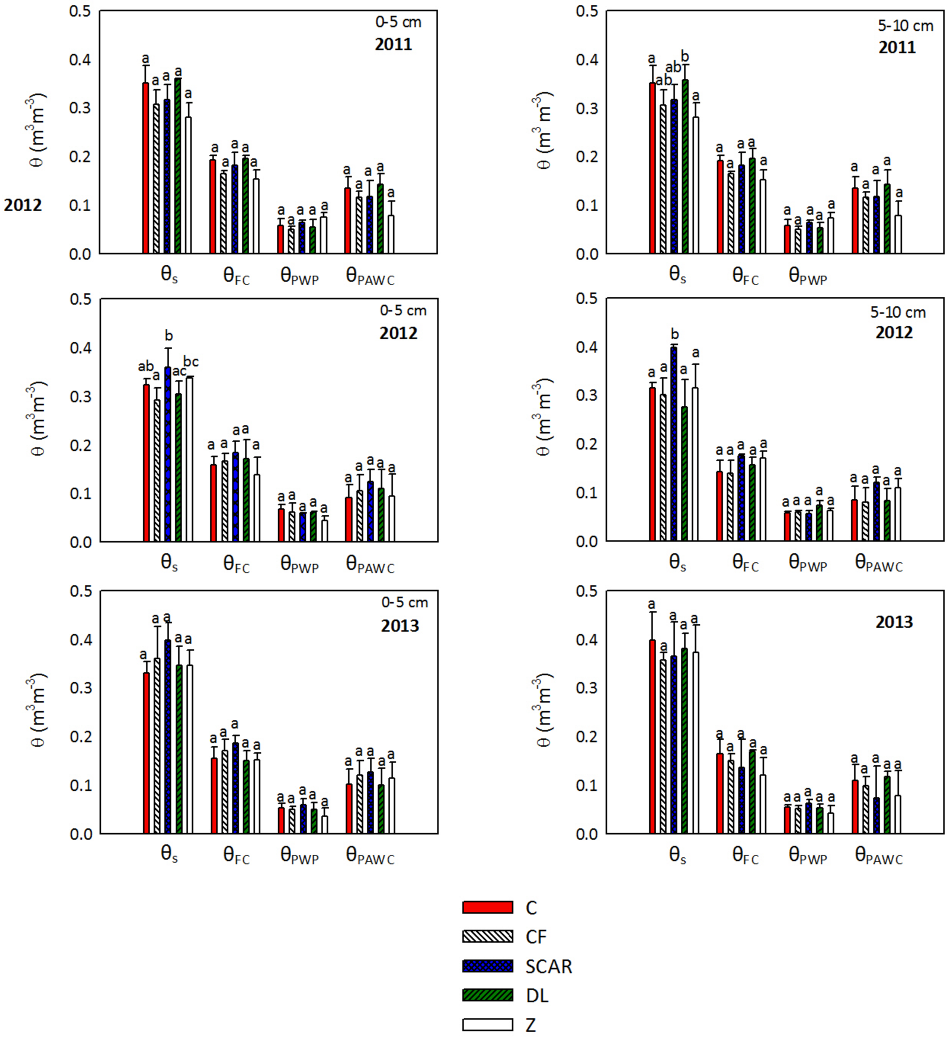

Figure 5.2: Physical soil quality indicators (n=3) derived from the soil water retention curves including the water content at saturation (θ_s), field capacity (θ_{FC}) and permanent wilting point (θ_{PWP}) and the plant available water content (θ_{PAWC}) for different treatments (C = control, CF = control + manure, SCAR = scarification + manure, DL = demi-lunes + manure, Z = zaï + manure) in 2011, 2012 and 2013. Columns represent averages and error bars standard deviations. Values labelled with the same letter are not significantly different at $p \leq 0.05$

conditions. Values for macroporosity also remained consistently below a 'lower critical limit' of 0.04 m^3 m^{-3}, which is typical for compacted and degraded soils. Values for AC, on the other hand, (not shown) were mostly higher than required for all treatments ($\geq$ 0.14 m^3 m^{-3}) (Reynolds et al., 2009). This means that the soil under study produces primarily 'textural' pores. Since the loamy sand texture of the studied soil is close-to-single-grain, the pore size distribution is very narrow. Hardly any secondary 'structural' pores important for a soil's physical quality are present. There were no significant differences in saturated (K_{sat}) and unsaturated ($K_{\psi:\ -0.03\ m}$, $K_{\psi:\ -0.09\ m}$ $K_{\psi:-\ 0.12\ m}$) hydraulic conductivities between the treatments (Fig. 5.3) and as expected from the rather high bulk density values and the absence of 'structural' pores, measured hydraulic conductivities were low.

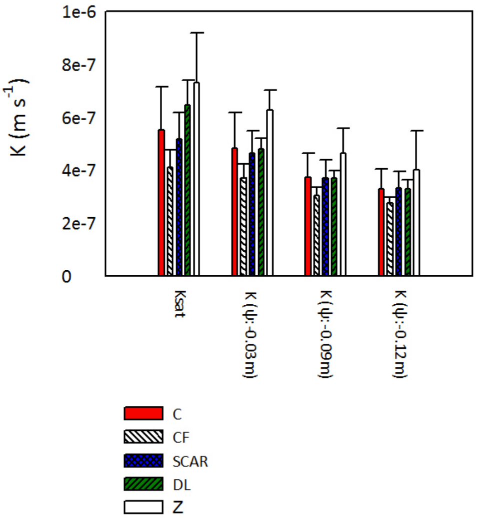

Figure 5.3: Saturated and unsaturated hydraulic conductivities (K) (n = 12) for different treatments (C = control, CF = control + manure, SCAR = scarification + manure, DL = demi-lunes + manure, Z = zaï + manure) in 2011 measured with the tension infiltrometer and calculated using the method of Logsdon and Jaynes (1993). Columns represent averages and error bars standard deviations. No significant differences were detected

5.3.4 Altering soil hydraulic properties for optimized rainfall partitioning

Since physical soil quality relates to a soil's structure and its ability to store and transmit water, physical soil quality indicators are very useful to monitor the potential of WSC techniques to optimize the soil's water household. A rehabilitated soil structure should favour water retention and infiltration capacity. As such, many WSC practices are reported to alter and enhance soil hydraulic properties (Pagliai et al., 2004; Thierfelder et al., 2013).

Given the close-to-single-grain condition of the studied loamy sand soil and its very low SOC content, substantially enhancing the soil's structure is not straightforward. Nevertheless, it is remarkable that the hydraulic properties under Z and DL did not significantly change after years of implementation. This was particularly surprising for Z, as the structure of the material within the zaï pit (a mixture of decomposed manure and sediments supplied by wind and water) is expected to differ greatly from the original soil structure. However, samples were taken at harvest when most organic material was mineralized, leaving primarily sediment in the pit. These sediments must have settled as a uniform soil matrix of loam and sand, similar to the one of the original, degraded soil. This contradicts descriptive literature, which has widely been assigning optimized hydraulic soil properties to zaï pits and demi-lunes (Liniger et al., 2011). Rusinamhodzi et al. (2013) on the other hand, did not observe changes in infiltration rate either after manure application and increased SOC content on a sandy loam. Also in this context, intercropping with regenerated shrubs (NEWS) might be considered, as even in sandy to sandy loam soils, hydraulic conductivity under tree canopies have been shown to increase (De Boever et al., 2014).

WSC techniques did not have a significant affect on the hydraulic soil properties. The improved rootzone water balance under WSC, as reported in Chapter 4, results from the system design of WSC (bund, pit and stubble), rather than from their improved soil hydraulic properties.

5.3.5 WSC effect on biological soil quality

Prior to our experiments, active nematodes were not present in the soil, but after the growing seasons of 2011 and 2012, a considerable amount of active nematodes was detected (Fig. 5.4). Plant-parasitic (harmful for agricultural production) nematodes were absent in this study, so only the abundance of free-living nematodes was reported.

In 2011, the abundance of nematodes for Z was significantly greater than for C, CF and SCAR. Dormant nematode eggs, which can be present for several years, either hatched the moment soil moisture and nutrition conditions were suitable, migrated into the field on tools, shoes and manure, or were dispersed by windstorms.

Since free-living species feed on decomposing bacteria and fungi, their abundance is used as an indicator for the intensity of nutrient cycling and organic matter decomposition in a soil (Neher, 2001). The higher abundance of nematodes within the zaï pit compared to the other treatments with manure (CF, SCAR and DL) hence supports the above-mentioned idea that higher biomass production results in larger populations of decomposing soil organisms responsible for the mineralization of manure. Since CF produces less biomass, biological activity in the soil is lower, which results in the accumulation of applied organic matter.

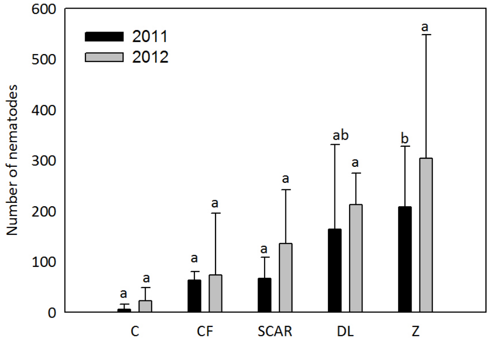

Figure 5.4: Nematode abundance for different treatments (C = control, CF = control + manure, SCAR = scarification + manure, DL = demi-lunes + manure, Z = zaï + manure) in 2011 and 2012. Columns represent averages and error bars standard deviations. Values labelled with the same letter are not significantly different at $p \leq 0.05$

Besides a higher abundance of nematodes, also a higher number of insects and even fungi were noticed in the cropping areas of DL and Z during field observations, which similarly suggests that ecological processes improve under these treatments. Although WSC techniques did not affect soil porosity after three growing seasons, this activated soil life might, in time, induce the formation of biopores and enhance water movement and root development (Pagliai et al., 2004; Tittonell et al., 2012; Hauser et al., 2012; Ngwira et al., 2012).

5.3.6 Effect of soil quality on crop response

Crop response to WSC was discussed in Chapter 4, section 4.3.3. Since not much difference in soil quality was observed between Z and DL on the one hand, and CF on the other, the higher biomass productivity of Z and DL mainly results from increased soil moisture contents (see Chapter 4), as both zaï pits and demi-lunes are designed to catch run-off water in their cropping areas and give it time to infiltrate. However, WSC also enhanced root growth. As seen in Table 4.1, millet roots of Z were growing significantly deeper into the soil than millet roots of C in 2012, while in 2013 millet root depth of all manure treatments (CF, SCAR, DL and Z) exceeded the millet root depth of the conventional practice (C).

5.4 Conclusion

Our results suggest that the intrinsic manure shortage is problematic when the optimization of plant production is to be combined with sustainable soil rehabilitation.

WSC only slightly improved the overall very poor soil quality. Applying manure evidently increased the SOC content of a sandy loam soil, but from this study we infer that SOC accumulation is very much depending on the biomass productivity of the WSC technique applied. From the SOC data, crop yield and the abundance of nematodes, it appears that seemingly contradictory, elevated SOC levels are accompanied with the lowest biomass production. Hence, the nutrients supplied by manure and the increased soil moisture lead to an improved crop yield, rather than lifting SOC.

Furthermore WSC techniques do not show the beneficial (short-term) effects on soil structure and soil hydraulic properties for which WSC techniques have been widely proclaimed for. It seems challenging to induce structural changes on a loamy sand soil with such low SOC content, but since soil structural changes are related to time consuming processes, changes might be foreseen in the long term. These changes are not expected to be related to SOC content, since SOC accumulation in the loamy sand soil under study stayed limited. Nevertheless, decomposed roots together with the induced activity of soil organisms could stimulate important soil structural enhancement. Long-term studies relating agricultural productivity with soil quality are therefore recommended.

Given the limited manure resources, alternative management strategies for WSC are required to combine adequate plant productivity with soil rehabilitation. These strategies could consist of crop rotation or NEWS, or combinations of these within an integrated management strategy. However, farmers do not easily adopt strategies that require long-term sustained efforts of resources, additional labour and know-how, if they only generate little revenues on the short-term.

Future studies on WSC should combine the assessment of crop response with a quantitative evaluation of effects on physical, biological and chemical soil parameters.

6

Imbalanced rainfall partitioning on degraded lands in Niger and the beneficial effect of WSC for crop production [1]

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[1] This chapter is based on the eponymous paper which will be submitted to Water Resources Management.

6.1 Introduction

There is growing concern for a water crisis in the Sahel. Niger already ranks among the five lowest countries on the water poverty index (Lawrence et al., 2002) and it is expected that water availability will drop below the threshold level for chronic water scarcity (1500 m^3 per year per capita) by 2030 (Rijsberman, 2006). This not only affects the general well-being of people, but also provokes severe economic stress, as rainfed agriculture is the dominant source for food and forms the backbone of the Nigerien economy. Developing and optimizing sound strategies for efficient water resource exploitation in Niger is therefore urgently needed.

Water is both a nuisance and a lifesaving resource across Niger. When in excess, water causes major damage as floods, but when water shortage prevails, complete crop failure is at risk. Besides adverse climatic conditions this has much to do with land cover conditions. In the 1950s and 1960s 10% of Nigerien surface area was cultivated, whereas now more than 80% is under cultivation, in order to feed the continuously growing population (Descroix et al., 2009). Together with shortening vegetative fallow periods, this has lead to dramatic degradation of the soil resources with distorted hydraulic conditions as a result (Tabor, 1995). In order to increase crop production without further damage to the soil resource, a holistic approach is needed which combines water and soil resource conservation with productivity increase per surface area.

Water shortage for crop growth is the result of two main processes, uneven rainfall distribution accompanied by increasing dry spell occurrence (i.e. meteorological drought) and a deficiency in available soil water due to imbalanced partitioning of rainfall over the rootzone (i.e. soil-water drought) (see chapter 4) (Gaze et al., 1997; Marengo et al., 1996; Rockström et al., 2010). The first is difficult to influence, but the rootzone water balance which determines the amount of water in the soil, is pliant to human management.

The water balance is expressed by following equation:

$$\Delta S = P - E_S - E_T - R - D \tag{6.1}$$

where ΔS is the change in soil-water storage in the rootzone, P is precipitation, E_S is soil evaporation, E_T is transpiration (or root water-uptake), R is run-off and D is drainage across the lower boundary of the rootzone. According to the ‘green and blue water’ concept, as introduced by Falkenmark (1995), run-off (R), drainage (D) and precipitation (P) feed the blue water resource, which is the water found in aquifers, lakes, and dams. However, precipitation (P) is also vital for replenishing the green water resource, which is defined as moisture in the soil and has a productive flow, transpiration (E_T), and a nonproductive flow, evaporation (E_S). Since worldwide only small a percentage of rainfall is used productively, there is great potential to optimize the use of green water to lessen the deficiency of available soil water (Falkenmark, 1995).

Rainfall in Niger is currently lost primarily as run-off (25-50%), drainage (10-30%) and evaporation (30-50%) (Rockström et al., 1998). To maximize plant available water in the soil, management strategies are needed that alter the rootzone water balance in favour of transpiration. This can be accomplished with management practices that reduce run-off and deep drainage and promote infiltration and water retention in the soil. Water and soil conservation (WSC) techniques show great potential to successfully converge crop productivity with water balance optimization.

The WSC techniques to be evaluated in this study are zaï (Z), demi-lunes (DL) and scarification (SCAR), three common WSC techniques in the region. These techniques are commonly regarded as appropriate for a wide range of conditions.

This is often an assumption and is not based upon rigorous evaluation or detailed testing (Giller et al., 2009). While several authors have published promising results on yield increases of WSC techniques in the Sahel (Adekalu et al., 2009; Fatondji et al., 2009; Forzieri et al., 2008; Roose, 1999; Sawadogo, 2011; Zougmoré and Ouattara, 2004), to our knowledge, very few studies have examined the infield water dynamics related to these WSC techniques. Some studies report the effect of WSC on soil-water content (Fatondji et al., 2011; Zougmoré et al., 2003), but no studies have tested WSC in terms of their water balance. Understanding the impact of WSC techniques on water dynamics is a prerequisite to evaluating the impact of WSC on drought stress and to optimizing WSC design.

This chapter therefore studies the hydrological impact of three WSC techniques in Niger (SCAR, DL and Z) and compares them with two conventional local practices (C and CF) by means of an *in situ* rootzone water balance experiment. The partitioning of rainfall into surface run-off (R), evaporation (E_S), transpiration (E_T) and soil-water storage (ΔS) is quantified WSC techniques and conventional treatments and some WSC design recommendations are given. In the last part of the chapter, the impact of the WSC techniques on 'green' and 'blue' water pathways as introduced by Falkenmark (1995) are discussed.

6.2 Materials and methods

6.2.1 Study area and experimental design

The study area and experimental design were described in Chapter 4, section 4.2.

6.2.2 Field measurements

Precipitation and other meteorologic data

Rainfall was measured daily with a cylindrical, non-recording rain gauge in the middle of the field. In order to calculate daily reference evapotranspiration, maximum (T_{max}) and minimum (T_{min}) temperature, wind speed (u), maximum (RH_{max}) and minimum (RH_{min}) relative humidity, and solar radiation (u_s) were measured daily at the weather station of the ICRISAT Sahelian centre which is situated less than 2 km away from the experimental field.

Soil-water storage

As described in Chapter 4, soil water was monitored using a neutron probe (CPN-503DR hydroprobe). To assess soil-water profiles, measurements were taken at different depths with 15-cm increments, at 15, 30, 45, 60, 75, 90 and 105 cm. Calibration curves were calculated separately for 15 cm, 30 cm and the rest of the profile and standard counts were made three times before and after measuring in a water drum. Similar to Rockström and Valentin (1997), measurements were taken after each rainfall event ($\geq$ 1 mm), and then minimally three times in the subsequent weeks. The first week measurements were predominantly carried out the first, third and fifth day after the event. The first week measurements were predominantly carried out the first, third and fifth day after the event.

Run-off

In 2013, each plot was equipped with a run-off collecting system at its downslope end. A cemented gutter directed run-off into a collecting tank with a multi-pipe divisor which reduced the volume of water reaching the second tank by a factor of 12. Both tanks were covered with a metal lid to prevent evaporation and direct precipitation. Run-off data was collected each morning after a rainfall event by measuring the height of the water in both tanks.

Although the tanks were designed to cope with exceptional run-off of 80 mm, the gutters were not. Rain events larger than 20 mm already resulted in flooding and spill over in the gutter, causing erroneous run-off measurements. Therefore we could only use run-off data from rain events up to 16 mm.

Evaporability

According to Stroosnijder (1987), daily evaporation (E_S) can be calculated from the reference evapotranspiration ($\mathrm{ET_0}$) and the evaporability ($\mathrm{k_r}$), which 'represents the capacity of a soil to evaporate' and depends on the time after the rainfall event. The evaporability was determined from a microlysimeter experiment based on the method of Boast and Robertson (1982). The method allows the assessment of actual evaporation ($\mathrm{E_a}$) in the course of a 10-day drying cycle, by weighing and reinstalling undisturbed soil cores. These cores, known as microlysimeters are capped at the bottom to prevent drainage. In this setup, water loss is only possible due to evaporation at the surface, which can be recorded by difference in weight over time. On each plot an experimental area of 1 $\mathrm{m^2}$ was saturated, covered by plastic to prevent evaporation and drained for 24 h to reach field capacity as described by Boesten and Stroosnijder (1986). Then, two microlysimeters per plot were inserted, one close to the plant, and one randomly. The microlysimeters were 8 cm in diameter, and 10 cm in length and were weighed daily with a field balance.

Reference evapotranspiration for this 10-day drying cycle was calculated based on daily climatic data and the Penman-Monteith equation as described in Allen et al. (1998).

The dimensionless evaporability ($\mathrm{k_r}$) for the soil depending on the time (t) after the rainfall event was then calculated as:

$$k_r(t) = \frac{E_a(t)}{ET_0(t)} \tag{6.2}$$

Where $E_a(t)$ is the actual evaporation at time t, derived from weighing the microlysimeter.

Canopy cover

Canopy cover was estimated five times in 2012 and six times in 2013 throughout the growing season at intervals of approximately two weeks, using digital images based on the method of Lee and Lee (2011) with three replicates per plot. The images were taken orthogonally, from a random area of each plot and at a constant height of 2 m resulting in a field of view at soil surface of 2.4 m x 1.4 m. The software package APS Assess 2.0 was then used for quantitative analysis of the plant cover by estimating the percentage of soil cover based on RGB values.

Crop transpiration and soil evaporation

The FAO-56 dual crop coefficient method was used to estimate crop transpiration and soil evaporation as illustrated in Fig. 6.1 (Allen et al., 1998). Parameters for this method are assembled and calculated from both field observations and scientific literature. The reference evapotranspiration (ET_0) was determined daily for the 2012 and 2013 growing seasons based on the Penman-Monteith equation as described in Allen et al. (1998). Crop transpiration rate (E_T) relates to the ET_0 by a crop coefficient (k_{cb}) which changes according to crop development stage:

$$E_T = ET_0 k_{cb} \tag{6.3}$$

The crop growth stage-dependent factor, k_{cb}, follows a ‘crop coefficient curve’, representing the changes in the crop coefficient during the growing season. This curve was constructed according to the method of Allen et al. (1998). In brief, length of growing seasons was determined based on field observations. Values for millet for the initial, mid and end phase of millet were selected from default values proposed by Allen et al. (1998) ($k_{cbini} = 0.15$, $k_{cbmid} = 0.95$ and $k_{cbend} = 0.20$). As an example, the k_{cb}-curves for different treatments in 2012 are given in Fig. 6.2. k_{cb} represents the crop coefficient for a subhumid climate and a ‘full’ canopy cover, and needs to be adjusted to a semi-arid climate and sparse vegetation to represent conditions in Niger.

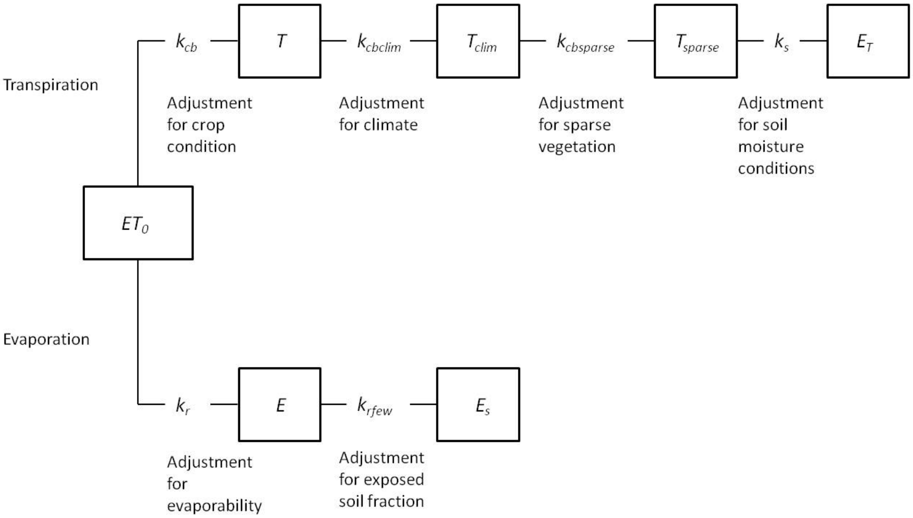

Figure 6.1: A flow chart depicting the approach followed according to the FAO-56 dual crop coefficient method to compute crop transpiration (E_T) and soil evaporation (E_S) (Allen et al., 1998). These are calculated from the reference evapotranspiration (ET_0), which is determined from daily meteorological data, and coefficients (k) adjusted for given field conditions. These coefficients are assembled and calculated from both field observations and scientific literature

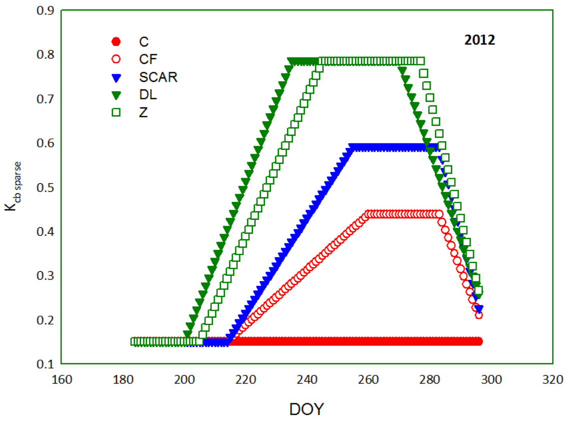

Figure 6.2: Crop coefficient curves of millet for different treatments (C = control, CF = control + manure, SCAR = scarification + manure, DL = demi-lunes + manure, Z = zaï + manure) in 2012 according to the method of Allen et al. (1998)

Adjustment for climate is done through an empirical equation proposed by Allen et al. (1998) whereby k_{cbclim} is calculated using k_{cb}, the average daily wind speed at 2 m height and the average daily minimum relative humidity during the given growth stage. Adjustment for sparse vegetation involves another empirical equation proposed by Allen et al. (1998), that calculates $k_{cbsparse}$ from k_{cbclim} and the canopy cover (f_c).

In addition to climate and sparse vegetation, also the available water in the rootzone needs to be taken into account, since transpiration rate reduces when water is not optimally available in the rootzone.

Transpiration ($\mathrm{E_T}$) reduces according to water stress coefficient ($\mathrm{k_s}$) (Allen et al., 1998):

$$k_s = \frac{TAW - D_r}{(1-p)TAW} \tag{6.4}$$

where TAW is total available water in the rootzone, $\mathrm{D_r}$ the rootzone depletion and p an empirical fraction of TAW at which drought stress occurs. TAW is the total amount of water that a crop can extract from the rootzone and can, according to Allen et al. (1998), be calculated as the fraction between field capacity (FC) and permanent wilting point (PWP) of a soil, both of which were derived from lab-determined soil-water retention curves constructed using a sandbox and pressure plate measurements of undisturbed soil core samples (see Chapter 5). $\mathrm{D_r}$ is zero at field capacity and increases when soil water is extracted by evapotranspiration. $\mathrm{D_r}$ was calculated from volumetric soil moisture content measured with a neutron probe and root depth, which is measured with three replicates per plot at the end of each season (see Chapter 4).

Soil evaporation ($\mathrm{E_S}$) is maximal when the topsoil is wet following rain, but soon drops according to the evaporability ($\mathrm{k_r}$) which was calculated with the aid of the microlysimeter experiment. Because soil evaporation occurs predominantly between plants, where soil is exposed it does not occur uniformly over the entire field area. Therefore a fraction of soil surface from which most evaporation occurs, i.e. the exposed and wetted soil fraction ($\mathrm{f_{ew}}$), was calculated from canopy cover ($\mathrm{f_c}$).

Statistical analysis

To compare water balance components and canopy cover as influenced by WSC techniques, a one way ANOVA with treatment as factor was performed. In case of a significant effect of treatment ($p \leq 0.05$), an LSD test was executed to indicate significant differences. In case data was not normally distributed, the non-parametric Kruskall Wallis test was applied

6.3 Results

6.3.1 Precipitation

Precipitation showed high variability over the three studied rainy seasons and showed large intra-seasonal variability each year. It was described in detail in Chapter 4, section 4.3.1 and depicted in Fig. 4.7 and Fig. 5.1.

6.3.2 Soil-water storage

Soil-water storage S over the rootzone (22.5 cm) for the growing seasons of 2011, 2012 and 2013 was given in Chapter 4, section 4.3.2. To evaluate rainfall partitioning over the soil profile, additional soil-water content profiles in the catchment or close to the plant are shown for the 2012 growing season in Fig. 6.3 at different time steps, which are also indicated in Fig. 6.4. The wetting front of the control treatments (C and CF) did not considerably exceed 40 cm, illustrating the absence of any drainage beyond the rootzone, and SCAR shows only minor water percolation into deeper soil layers. On the other hand, Z and DL, resulted in a considerable amount of water penetrating from the upper rootzone layer to deeper soil layers. The increased soil-water content was observed in these layers after periods of heavy rainfall (e.g. DOY 227 and 262), and then declined when rains were absent for some days. We also noted that soil-water content for DL and to a lesser extent for Z, decreased abruptly for all soil depths at the end of the rainy season.

6.3.3 Run-off

The effect of WSC techniques on the average run-off coefficient is shown in Fig. 6.5. Approximately 25% of rainfall was lost as run-off under C. Under CF, there was less run-off, but the difference with C values was not significant. Run-off decreased significantly under the WSC techniques to less than 10% for SCAR and less than 5% for DL and Z. The highest percentage of run-off (38%) was recorded on 10 July 2013 for C, with a

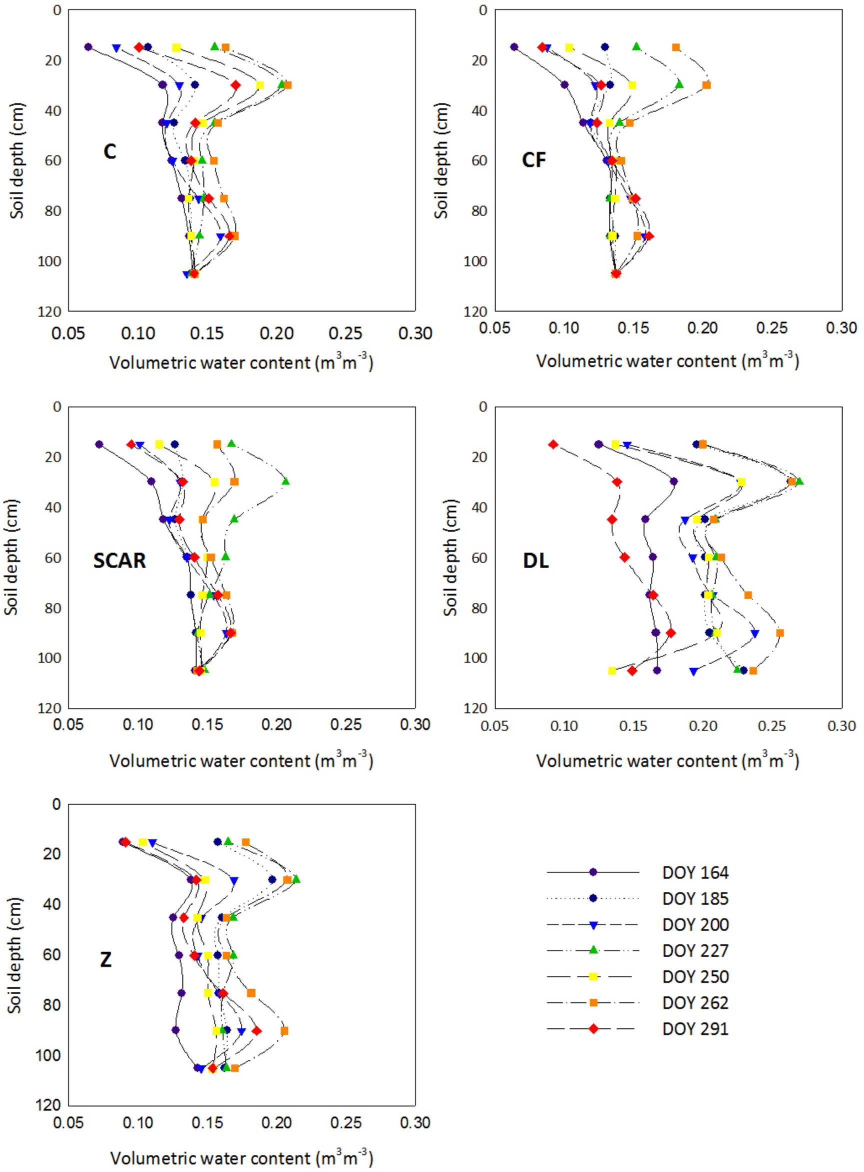

Figure 6.3: Volumetric soil-water content profiles (n=3) for different treatments (C = control, CF = control + manure, SCAR = scarification + manure, DL = demi-lunes + manure, Z = zaï + manure) at different time steps of the 2012 growing season. Time steps are indicated by arrows in Fig. 6.4

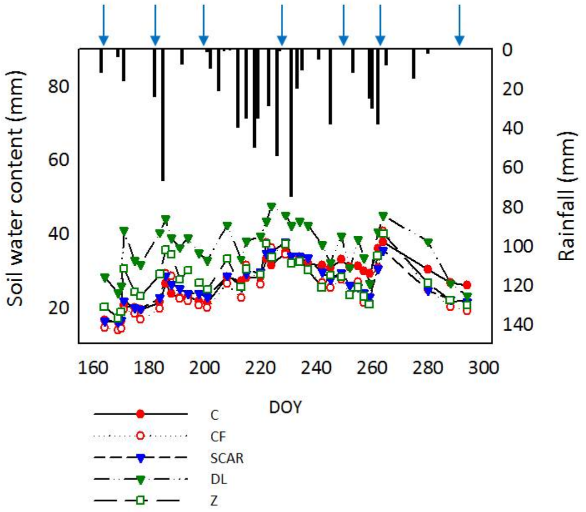

Figure 6.4: Rainfall distribution on the experimental field of Sadoré in 2012 with corresponding soil-water data from the 22.5 cm root zone layer within the catchments for different treatments (C = control, CF = control + manure, SCAR = scarification + manure, DL = demi-lunes + manure, Z = zaï + manure). The arrows above the chart indicate days for which soil-water profiles are given in Fig. 6.3

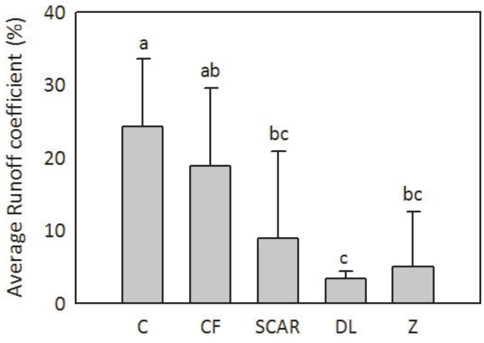

Figure 6.5: Average (n=2) run-off coefficient for different treatments (C = control, CF = control + manure, SCAR = scarification + manure, DL = demi-lunes + manure, Z = zaï + manure) in 2013. Columns represent averages and error bars standard deviations. Averages labelled with the same letter are not significantly different at $p \leq 0.05$

corresponding run-off percentage of 12% for CF, of 3% for SCAR and DL and of 2% for Z.

6.3.4 Evaporability, canopy cover and soil evaporation

WSC techniques did not significantly affect the actual evaporation rate (E_a) during the 10 day drying cycle of the microlysimeter experiment (not shown), which is why evaporability ($\mathrm{k_r}$) was considered equal for all treatments. As can be seen in Fig. 6.6, E_a dropped far below ET_0. Hence the energy limiting stage ($\mathrm{k_r}$=1), in which water evaporates from the topsoil without restriction, lasted only briefly and soon shifted to the falling rate stage ($\mathrm{k_r} \leq 0$).

Since $\mathrm{k_r}$ is constant across treatments, variation in soil evaporation between treatments originates from variation in canopy cover ($\mathrm{f_c}$). Table 6.1 presents the evolution of $\mathrm{f_c}$ under the different WSC techniques throughout the growing seasons of 2012 and 2013. While the initial f_c of the millet was statistically similar for all treatments, $\mathrm{f_c}$ development from the crop development stage onwards ($\simeq$ DOY 200 in 2012 and $\simeq$ 217 in 2013) varied greatly. The canopy under C stayed very low and under CF increased only slightly, while $\mathrm{f_c}$ increase for the other treatments (SCAR, DL and Z) was much greater. Expansion was most rapid for DL, followed by Z and SCAR. Overall, $\mathrm{f_c}$ was greater in 2012 than in 2013, except for CF.

Generally, the exposed and wetted surface ($\mathrm{f_{ew}}$ = 1-$\mathrm{f_c}$) remained fairly large throughout the growing seasons (sparse vegetation), but due to a relatively small evaporability ($\mathrm{k_r}$), the cumulative amount of water lost as soil evaporation ($\mathrm{E_S}$) was limited (Fig. 6.7). In the case of C, 83 mm water evaporated in 2012 and 78 mm in 2013, which was approximately 12% of the total seasonal rainfall amount. This was reduced only slightly by the WSC techniques to 8-11%, with DL having the greatest effect, followed by Z. Variations in $\mathrm{E_S}$ among treatments started around DOY 220, when canopy cover development under WSC began reducing the exposed and wetted surface $\mathrm{f_{ew}}$. Variation in $\mathrm{E_S}$ was biggest in 2012, as rainfall, and hence evaporation, continued until late in the season, when the largest variations in $\mathrm{f_c}$ occurred. The rate of $\mathrm{E_S}$ on the other hand, was highest at the start of the 2013 season, when the rapid succession of rains frequently wetted the soil surface.

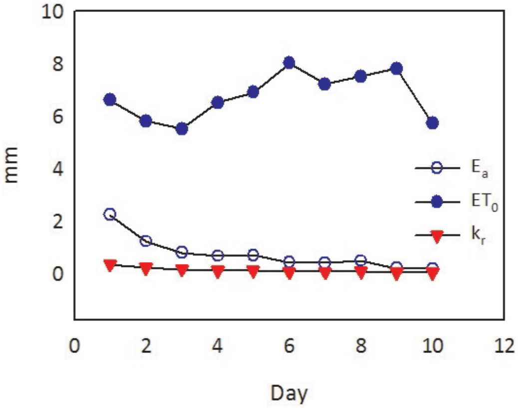

Figure 6.6: Evaporability (k_r) (n = 15) as calculated from the reference crop evapotranspiration (ET_0) and the actual evapotranspiration (ET_a), which was assessed during a 10 day drying cycle with a microlysimeter experiment

Table 6.1: Evolution of canopy cover (n=9), f_c (%), for different treatments (C = control, CF = control + manure, SCAR = scarification + manure, DL = demi-lunes + manure, Z = zaï + manure) in 2012 and 2013, with ± standard deviations and values labeled with the same letter indicating no significant differences between treatments at $p \leq 0.05$

	DOY	C	CF	SCAR	DL	Z
2012	184	1.70 ± 1.27a	1.69 ± 1.27a	3.23 ± 1.64 a	5.39 ± 4.40a	4.37 ± 5.41a
	200	2.69 ± 2.19a	2.68 ± 2.19a	3.06 ± 1.72a	7.21 ± 6.83a	3.23 ± 2.55a
	214	2.60 ± 1.71a	2.60 ± 1.71a	4.89 ± 1.83a	24.50 ± 17.62b	7.07 ± 3.97b
	235	2.33 ± 2.27a	18.74 ± 5.18b	20.48 ± 8.02b	45.60 ± 7.96c	40.56 ± 14.36c
	250	0.79 ± 0.22a	25.73 ± 10.03b	43.33 ± 12.29b	48.01 ± 3.08b	62.00 ± 6.13c
2013	217	0.87 ± 0.42a	2.91 ± 1.70ab	9.03 ± 10.09ab	12.34 ± 4.40b	5.73 ± 5.36ab
	231	0.55 ± 0.36a	14.88 ± 4.06b	20.76 ± 5.27bc	27.64 ± 6.83c	19.42 ± 5.35bc
	238	2.23 ± 1.27a	24.32 ± 8.42b	39.93 ± 13.98b	38.67 ± 17.62b	25.82 ± 9.63b
	245	1.78 ± 0.76a	21.83 ± 9.12b	30.06 ± 13.31bc	36.00 ± 7.96c	31.74 ± 8.63bc
	252	3.20 ± 2.09a	13.66 ± 6.01b	25.87 ± 13.50bc	31.54 ± 3.08c	26.24 ± 11.86bc
	259	5.11 ± 5.38a	13.83 ± 5.54ab	24.75 ± 12.57bc	30.67 ± 4.08c	26.71 ± 11.55bc

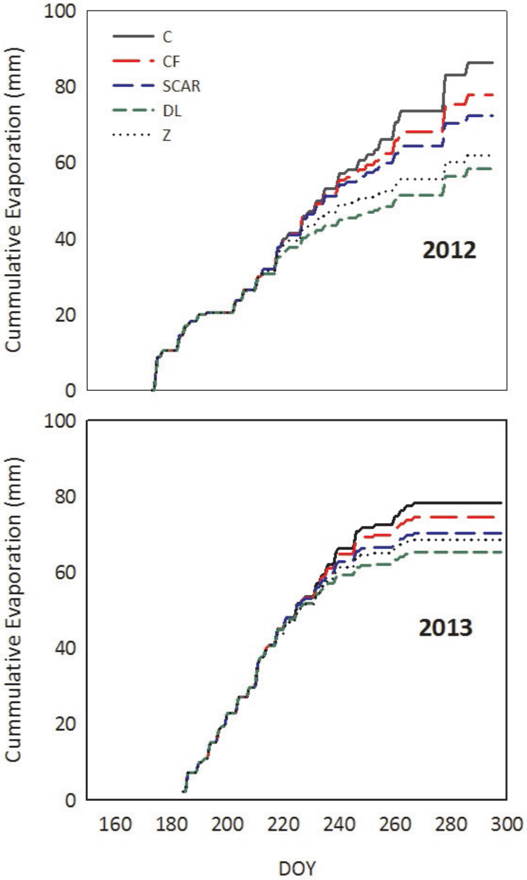

Figure 6.7: Cumulative soil evaporation (E_S) for different treatments (C = control, CF = control + manure, SCAR = scarification + manure, DL = demi-lunes + manure, Z = zaï + manure) in 2012 and 2013, as assessed by the FAO-56 dual crop coefficient method (Allen et al., 1998)

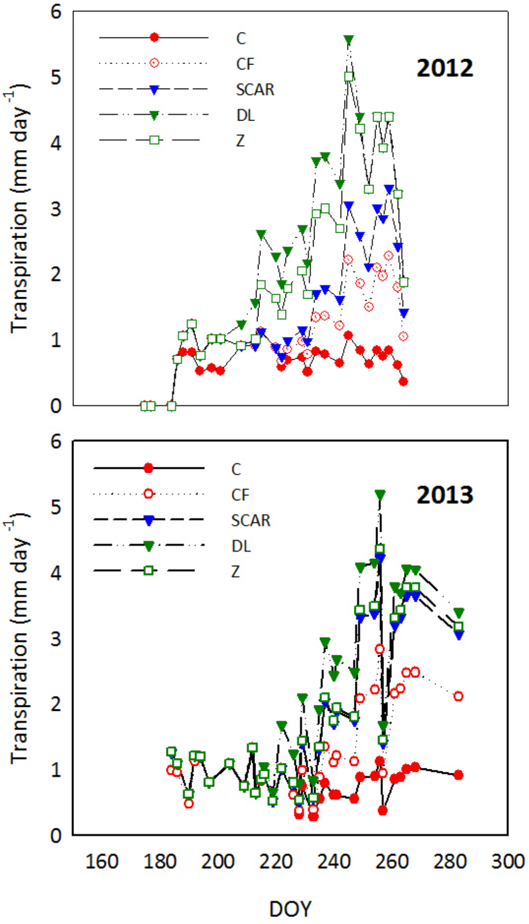

Figure 6.8: Theoretical crop transpiration (E_T) for different treatments (C = control, CF = control + manure, SCAR = scarification + manure, DL = demi-lunes + manure, Z = zaï + manure) in 2012 and 2013, as assessed by the FAO-56 dual crop coefficient method (Allen et al., 1998)

6.3.5 Crop transpiration

Figure 6.8 displays the effect of WSC on theoretically derived transpiration rates (E_T) for 2012 and 2013. For both seasons, WSC techniques increased maximum daily transpiration rates from approximately 1.1-1.3 mm day^{-1} (C) and 2.2-2.5 mm day^{-1} (CF) to 3.3-4.2 mm day^{-1} for SCAR, 5-5.6 mm day^{-1} for DL and 4.4-5 mm day^{-1} for Z. Variation in E_T rate among treatments started around DOY 220 when f_c also started to vary. E_T is related to soil-water content, explaining why transpiration rate follows the course of rainfall distribution with peaks in August ($\simeq$ DOY 210 -240).

6.3.6 Crop response

Results for crop response were given in Chapter 4, section 4.3.3, Table 4.1.

6.4 Discussion

6.4.1 WSC effect on rainfall partitioning

Rockström et al. (1998) reported that the imbalanced rainfall partitioning they observed over the rootzone in Niger, resulted in large water losses negatively affecting transpiration. Our findings for current local practice, C, confirm that water distribution over a Plinthosol is unfavourable. Run-off (R) was the most important source of water loss for C, while deep percolation (D) and soil evaporation (E_S) values remained low, indicating that they are less of a factor in water loss in this region.

Installation of WSC techniques proved to positively modify the imbalanced partitioning of rainfall. The run-off coefficients that we measured for C in this study (10 to 40%) are in the same range as those reported in literature (Hoogmoed and Stroosnijder, 1984; Rockström and Valentin, 1997). However, modeled water balance assessments in the area have attributed largest water losses to evaporation while, as noted, run-off was the greatest contributor in this study (Marengo et al., 1996; Nicholson et al., 1997). In these other modelling studies, run-off was never measured, but was estimated based only on soil texture and frequency distributions of total daily rainfall. As previously emphasized by Rockström and Valentin (1997), water loss due to run-off in Niger has been seriously underestimated or even ignored (Klaij and Vachaud, 1992; Payne, 1999).

Total run-off coefficients for our site presumably greatly exceed the average run-off coefficients presented in this study since only run-off from rain events smaller than 20 mm could be considered. Run-off for events larger than 20 mm can be expected to increase considerably. Since events with more than 20 mm of rain constitute 31% of the events in 2011, 47% in 2012 and 36% in 2013 and amount to respectively 67, 82 and 72% of the total rainfall amount, larger amounts of run-off than suggested by our measurements are almost certain.

These high run-off rates are due to high rainfall intensity and the presence of a soil crust created by destruction of aggregates by immersion or direct raindrop impact. While rainfall intensity cannot be managed, the soil crust can be subjected to management. When installing WSC techniques the soil crust is broken, leading to improved infiltration for a short period. However, the crust reestablishes quickly due to stormy rains, which explains why tillage does not prove to be an effective way to promote infiltration in this area (Hoogmoed and Stroosnijder, 1984). Z and DL on the other hand are more effective at enhancing infiltration potential, mostly because the pit and bund act as temporary storage structures which allow a larger residence time for rainwater to infiltrate. Similarly, crop residue seems to serve as a barrier obstructing run-off water and creating a ponding effect. In many semi-arid and arid zones, other WSC techniques have been shown to significantly reduce run-off water loss (Araya and Stroosnijder, 2010; Araya et al., 2012; Temesgen et al., 2012). Our research verifies for the first time that this is also true in the most important production area of Niger.

Although soil evaporation was not the major factor in water losses in our research, every source of water loss should be diminished maximally to improve crop production. Given the inherent sparse canopy cover and high evaporative demand in Niger, evaporation seems less easy to affect (Rockström and Karlberg, 2009). In many rootzone water balance studies, soil evaporation (E_{S}) is not adequately estimated, as it is mostly considered under a single variable of evapotranspiration together with crop transpiration (E_{T}) (Payne, 1999; Rockström and Valentin, 1997; Ward et al., 2012). Yet, when growing conditions are not favourable and plant establishment is slow or canopy cover is sparse, E_{S} could become the dominant factor in ET and should be considered separately (Stroosnijder and Hoogmoed, 1984). This is particularly true when the effects of WSC techniques in terms of water management are being assessed and the reduction of E_{S} in favour of E_{T} is under evaluation.

Given the high potential evaporation rate in the area of our research and the sparse canopy cover, E_S estimated for our plots seems relatively low in comparison to earlier reported evaporation losses which amount to 50% of the total rainfall amount (Gaze et al., 1997; Rockström et al., 1998). These low values are not surprising given the sandy nature of the studied soil. It is well-known that hydraulic conductivity of sandy soil drops very drastically when they dry out, an attribute known as self-mulching behaviour (Hillel, 1998). The thin, dry layer in the topsoil of the studied soil hence obstructed water transmission to the soil surface and prevented water to evaporate into the atmosphere. Since potential evaporation is high, the topsoil in the study area dries out remarkably fast and quickly inhibits large evaporation rates.

Nevertheless, the soil evaporation loss that did occur, was reduced by the WSC techniques. Typically, WSC techniques are designed to reduce E_s by covering the soil surface either by sowing cover crops, by applying mulch or by managing crop residues to reduce the area under bare soil evaporation (Araya et al., 2012; Temesgen et al., 2012; Ward et al., 2012). However, in our research this approach was not effective. The crop residue that was left for SCAR after harvesting was largely blown away by the harmattan wind, and those few wilted stalks that remained, did not seem to increase soil cover sufficiently to influence soil evaporation. On the other hand, the other WSC techniques we evaluated (DL and Z) did affect soil evaporation indirectly by enhancing crop growth, which resulted in an increased, although still sparse canopy cover.

Regarding deep drainage water losses, Z and DL lost productive water due to drainage beyond the rootzone, while this did not occur for C, CF and SCAR. The petroplinthite at approximately 35-40 cm depth typically slows down water infiltration beyond $\simeq$ 40 cm, but for Z and DL water infiltration beyond this layer was possible due to a ponding effect and the high amount of water captured by both the pit and the bund. The loss of productive water (i.e. infiltration beyond the rootzone) might be prevented by increasing the number Z and DL per surface area.

Notwithstanding their water conserving features, none of the WSC techniques resulted in higher θ_S at the end of the season. This suggests that all the water gained is converted to productive crop transpiration and not stored inside the rootzone.

6.4.2 More crop per drop

In general, different strategies can be followed to produce more crop with less water. As such, plant breeders are increasing yield per unit (or drop) of transpiration, while agronomists seek to increase the water available for transpiration per unit (or drop) of rainwater (Vohland and Barry, 2009). Since resource-poor farmers relying on rainfed agriculture often do not have easy access to improved varieties, the first step for them to undertake is to increase production by augmenting the share of rainwater that goes to crop transpiration through modifying the rootzone water balance (Temesgen et al., 2012).

Our results confirm that the WSC techniques tested in our study (SCAR, DL and Z) allow a more efficient utilization of the limited rainwater generated in semi-arid regions. They can increase millet production with more than 400% just by improving soil-water availability in the rootzone, (see Chapter 4).

Water - and not just soil fertility - is a major limiting factor for pearl millet production in Niger. Earlier research concluded that soil fertility rather than water was the most limiting factor in Niger because pearl millet is very water use efficient. According to Payne et al. (1991) for example, plants did not make optimal use of the available soil water because their growth was restrained by soil-nutrient shortage. However, if soil fertility were the most limiting factor, simply providing soil nutrients would increase crop production per drop. Notwithstanding the essential contribution of nutrients for optimal plant production and water use efficiency, our results prove that providing manure alone does not suffice, as CF did not attain desirable grain yields.

That water is a major limiting factor for crop production also becomes obvious when rainfall partitioning and crop water requirements are considered together. Generally, the crop water requirement for pearl millet transpiration is estimated at approximately 450 mm (Dancette, 1983; Garba and Renard, 1991). Hence, if at least 25% of total rainfall amount is lost by run-off and 12% by evaporation, the total seasonal rainfall amount needs to exceed 715 mm while the long-term average in Niger only amounts to 550 mm.

Interestingly, our findings suggest that soil-water and nutrient availability were not the only restrictions pearl millet was facing in this study, as theoretically derived transpiration rates do not follow the same trends as crop yields. These rates were highest for DL, whereas DL did not produce highest grain yields. As mentioned before (Chapter 4), it was not soil water that restricted plant growth within the demi-lunes catchments, but the planting density that appeared too high. In the case of DL, system design optimization would hence allow an improved water use efficiency and more crop per drop. This will be tested in Chapter 7.

6.4.3 Impact of WSC on watershed scale

Besides water loss for crop production, an imbalanced rootzone water balance can also lead to excessive erosion, causing among others siltation of rivers and dams. Optimizing the partitioning of rainfall over the rootzone is therefore of paramount importance to respond to the larger pressing issue of sound environmental resource conservation (Molden, 2007).

As a result of dramatic land cover changes in Niger in the last century, there has been an increase in discharges in stream flows provoked by increasing run-off (Descroix et al., 2009). The consequences of this run-off generation for the land and water resources greatly depend on the hydrology of the watershed, i.e. whether the area is endhoreic or exhoreic. Run-off from an endorheic area does not reach large rivers draining to the ocean, while run-off from exhoreic does.

An increase in exhoreic run-off generation results in peak discharge flow, which causes short and strong floods. Such intensive floods are known to cause vast economical damage to constructions downstream or to high value horti- and riziculture in the valley. On top of that, other environmental changes are triggered, such as the falling of the water table level due to the reduction of water infiltration and the disturbance of the sedimentary balance within a watershed. As such, sediment loaded run-off results in morphological changes in the hydrographical pattern by raising riverbed levels and the notable widening of river beds. Moreover, the sediment that silts up these rivers, originates from fields where the loss of topsoil reduces soil quality for crop production.

By controlling run-off, WSC techniques have the potential to make important contributions to the restoration of natural resources in the region. They replenish green water resources by capturing run-off and restore the sedimentary balance within a watershed.

However, it is important to realize that run-off can also be endorheic and provide water to downstream crop producers or to ephemeral ponds, which are used extensively by the local population (Gaze et al., 1997). Water from these ponds infiltrates and drains, causing a rise in the water table, which in contrast to exhoreic run-off, slowly but steadily feeds an important base flow replenishing surface water. When implementing WSC techniques, their effect on run-off generation should hence be evaluated together with the overall hydrology of the watershed.

6.5 Conclusion

Millet crop production in Niger is currently well below its potential due to inefficient rainwater use. A major part of rainwater is lost as unproductive water due to an imbalanced rainfall partitioning of rainfall over the rootzone, making crop production on Plinthosols under conventional practices unproductive. Implementation of WSC techniques, such as zaï, demi-lunes and scarification, can alter the adverse rootzone water balance in favour of soil-water availability for crop transpiration. The techniques did not have a very large effect on soil evaporation, but did greatly reduce run-off water loss.

Although overall water loss by soil evaporation was considerably limited by the self-mulching capacity of studied soil, the sparse canopy cover, resulted in the exposure of major parts of the soil surface area to soil evaporation. Crop residue management included in the scarification technique, did not succeed in significantly reducing the exposed and wetted surface area, but did reduce run-off by forming, just like the demi-lunes bunds and zaï pits, a physical barrier for overland flow. By reducing run-off these WSC techniques replenish green water resources and limit flows to blue water resources thus creating, depending on their location within the watershed, beneficial off-site effects by reducing floods and erosion during heavy storms.

Since the importance of run-off water loss was underestimated in previous studies, this study emphasizes the need for rootzone water balance studies to correctly evaluate strategies for land and water resource management. Such studies are challenging in Niger, due to limited soil databases and the difficulties regarding measuring of flood generating rain events.

In terms of water conservation, demi-lunes seemed to outperform the other techniques, whereas zaï pits produced highest yields and hence can be said to have converted the most rainwater to crop transpiration. The zaï pits can be perceived as the most efficient in terms of rainwater use. Rainwater use efficiency of DL can possibly be optimized by increasing the number of bunds per surface area, while decreasing planting density within the pit. This will be tested in Chapter7.

7

Optimizing WSC design with a fully coupled surface/subsurface hydrological model in Tillaberí, Niger [1]

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[1] This chapter is based on the eponymous paper which will be submitted to Journal of Hydrology

7.1 Introduction

Drylands relying on rainfed agriculture are hotspots for poverty, malnutrition, water scarcity and severe land degradation. Improving water management in drylands for crop production is therefore broadly recognized as a matter in need for attention (Molden, 2007). Since food production in these areas mainly suffers from inefficient rainwater use due to run-off losses, limited water infiltration and deep percolation, the main challenge is to increase water use efficiency of small-scale rainfed agriculture (Rockström et al., 2010).

Many water and soil conservation (WSC) techniques aim at increasing plant water availability in the rootzone. Several of these techniques follow the concept of water harvesting (WH), i.e. depriving part of the land of its precipitation share to supply it to another part where total amount of water is thus increased to fulfill rop water requirements (Critchley et al., 1991). WH is especially interesting in arid and semi-arid regions, where annual potential evaporation greatly exceeds annual precipitation, and rainfall originates from intensive run-off generating storms. The most-promising WSC techniques in Niger (like e.g. zaï pits and demi-lunes, see Chapter 4, 5, 6) therefore apply the WH principle and collect run-off water from microcatchments within the field into small cropping areas, where improved water management is combined with local manure application.

A large number of studies have been dealing with the ancient practice of water harvesting. These reported the general requirements for various WH systems (Critchley et al., 1991; Prinz, 1996), revealed optimized crop yields (Roose, 1999) and demonstrated increased plant water availability in the cropping area (Makurira et al., 2010; Schiettecatte et al., 2005). However, despite the importance of microcatchment design for the water use efficiency of WH systems, design optimization did, until now, not receive wide attention and remains a major research need (Falkenmark and Rockström, 2006; Molden, 2007). According to Prinz (1996), one of the limitations of WH is that the techniques are often based on farmers' experience and trial and error rather than on scientifically well-established techniques. When designing microcatchments, the challenge generally consists of identifying the optimal ratio between catchment and cropping area to ensure an adequate partitioning of rainfall into evapotranspiration, run-off and deep percolation. Over-design (i.e. harvesting too much water) leads to water-logging and subsequent crop failure, whereas under-design (i.e. harvesting too little water) leads to drought stress

(Oweis and Hachum, 2006). Some studies have tried to tackle this with field experiments (Li et al., 2005; Oweis and Taimeh, 1996) and provided valuable insights in design effects on water use efficiency, but field experiments prove very time-consuming for design optimization and the number of design options under evaluation is typically very limited. Evaluating the potential of hydrological models to simulate rainfall partitioning of different microcatchment designs is therefore of great value for WSC research.

The development of hydrological models has recently been triggered, not only by enhanced computational capacity, but also by the demand for quantitative understanding of the hydrological cycle as a result of the continuously growing anthropogenic water need. These models range from very simple, functional models to so-called physically based models and offer useful tools to evaluate the effect of agricultural and human management on hydrological processes. Until now, most studies on WH design have been applying one-dimensional, functional water balance models which often use conceptual descriptions of land and water interactions (Ouessar et al., 2009; van Loon and Stroosnijder, 2000; Sanchez-Cohen et al., 1997). However, these empirical models do not offer insights into the underlying physics of the soil-water system and errors associated with simplifications are unknown. A proper evaluation of more complex microcatchment systems therefore demands a realistic, three-dimensional representation of water flow in the subsurface domain, which exchanges water with a surface domain where partitioning of overland flow between cropping areas is possible. This calls for hydrological models that solve differential equations derived from mathematical conservation equations.

The HYDRUS (2D/3D) subsurface model (and its predecessors) is one of the most popular models to numerically solve the Richards equation in saturated/unsaturated water flow. However, HYDRUS does not simulate overland flow and does not take run-off redistribution into account, which is a key-element when evaluating WH systems. To our knowledge, Boers et al. (1986) were one of the first (and only) who attempted to include surface run-off to evaluate microcatchment system design. They combined the subsurface SWATRE model (Belmans, 1983) with a linear regression model for surface flow. The main drawback of this model is that surface and subsurface domains do not interact, as the model does not allow simultaneous description of run-off and infiltration.

It was not until Verbist et al. (2012) demonstrated the potential of the three-dimensional hydrological model Hydrogeosphere (HGS) to evaluate the efficiency of infiltration trenches in a semi-arid environment, that a WH system was first evaluated with a fully coupled surface-subsurface model. Originally, HGS, predominantly focused on simulations on watershed level (Pérez et al., 2011), but more recently it is also being applied to hydrological management at a smaller scale. Walsh et al. (2014) for example quantified the benefits of rooftop rainwater harvesting in a urbanized watershed, whereas Ruidisch et al. (2013) predicted the effect of fertilizer placement on NO_3^{-1} leaching at field scale and Opolot et al. (2014) investigated the water use efficiency of WSC practices in Ethiopia. To our knowledge, HGS has not been applied to optimize the microcatchment design of a WSC technique.

The purpose of this study is therefore not only to apply this coupled surface-subsurface physically based model (HydroGeoSphere, HGS) to a typical demi-lunes practice in Niger, but also to evaluate its potential for design optimization by simulating different demi-lunes system designs for improved water use efficiency.

7.2 Materials and methods

7.2.1 Demi-lunes and experimental site

The rootzone water balance field experiment was previously presented in Chapter 4, section 4.2 and Chapter 6, section 6.2.2.

Daily meteorological data was obtained from the ICRISAT Sahelian center (maximum, T_{max}, and minimum, T_{min}, temperature, wind speed, u, maximum, RH_{max}, and minimum, RH_{min}, relative humidity and solar radiation, u_s). From these meteorological records, the daily potential evapotranspiration (ET_p) was calculated using the Penman-Monteith approach (Allen et al., 1998). Rainfall (P) was measured from a rain gauge in the middle of the field after each rain event. During the three studied rainy seasons, P followed typical Sahelian precipitation patterns and showed great inter-annual variability (Fig. 4.7 and Fig. 5.1).

In this chapter, rainfall partitioning over the rootzone is examined for the conventional practice in the study area (CF) and for different system designs of demi-lunes (DL, DL+ and DL++). Demi-lunes form a typical microcatchment system in which surface run-off produced from a catchment area is received by a cropping area where it is stored in the soil profile. The demi-lunes bunds on the experimental field at Sadoré village (DL) were constructed according to the design of Zougmoré et al. (2003), i.e. 4 m in diameter, and spaced at 2 m on the contour line and with 4 m between two successive lines (Fig. 7.1). A 120-day millet variety 'Sadoré Locale', a local source of a late millet variety, was sown at 10 000 plants ha^{-1} in a 1 m by 1 m grid for CF, and only within the cropping area for DL, which resulted in a very high actual planting density. On the experimental field, both CF and DL received the same annual rate of manure (3 ton ha^{-1}) as discussed in Chapter 4 and 5.

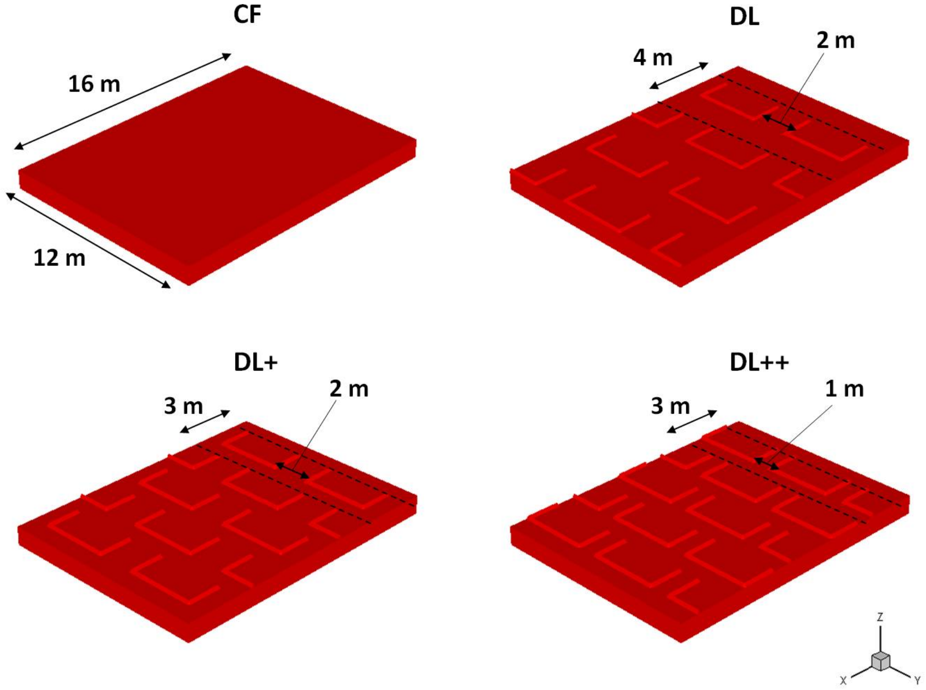

Figure 7.1: Schematic configuration of the control treatment (CF) and original (DL) and optimized (DL+ and DL++) demi-lunes designs with indication of the demi-lunes bund spacing

7.2.2 Optimized designs

In Chapter 4, we demonstrated that the spacing of the demi-lunes was not water efficient and that the planting density within their cropping area was too high. Increasing the number of catchments per surface area, while reducing planting density inside the DL cropping area was therefore suggested to optimize the rain water use efficiency of the DL system. As such, two modified demi-lunes designs (DL+ and DL++) (Fig. 7.1) were introduced to simulate the effect of design optimization on the water balance.

The original DL design, which was based on Zougmoré et al. (2003), has a catchment to cropping ratio of 3:1, which lies just within the range of 1:1 - 3:1 as proposed for microcatchments by Critchley et al. (1991). In order to improve the water use efficiency of demi-lunes this catchment to cropping ration needs to be reduced. Since farmers are acquainted with the dimensions of DL bunds (see Chapter 4), the number of DL bunds per surface area was increased, rather than that their cropping area was enlarged. For the first optimized design, DL+, the distance between two successive DL bund lines was reduced from 4 m to 3 m (Fig. 7.1), resulting in a catchment to cropping ratio of 2.2:1. In addition to that, distance between two DL bunds on the contour line was decreased from 2 m to 1 m for the second optimized design, DL++ (Fig. 7.1), resulting in a catchment to cropping ratio of 1.7:1. Note that instead of 24 plant pockets ha^{-1} for DL, DL + and DL ++ require respectively only 19 and 16 plant pockets (lower plant density within basin) to keep the planting density at 10 000 plants ha^{-1}.

7.2.3 Coupled surface/subsurface hydrological modelling

Hydrogeosphere (HGS) was applied to simulate coupled surface and subsurface flow in a three-dimensional environment by using a finite-element approach that produces simultaneous solutions for the transient overland flow and the unsaturated to saturated subsurface flow. For a detailed description of the model, the reader is referred to Therrien et al. (2009), but a brief overview of the governing equations for surface and subsurface flow, the model control programs, the input and output files, as well as a description of the grid construction and parameter estimation and optimization are given below.

Governing equations

The variable subsurface flow is described by a modified Richards (1931) equation in three dimensions:

$$-\bigtriangledown .(\omega_m q) + \sum \Gamma_{ex} \pm Q = \omega_m \frac{\delta}{\delta t}(\theta_s S_w) \tag{7.1}$$

where θ_s ($m^3 m^{-3}$) is the saturated moisture content, S_w (-) is the degree of water saturation and ω_w the fraction of the total porosity occupied by the porous medium, which all represent the change in water storage in the subsurface as a function of time t (s). Γ_{ex} (m^3 m^{-3} s^{-1}) on the other hand represents the volumetric fluid exchange rate between the surface and the subsurface flow domains, Q (m^3 m^{-3} s^{-1}) represents the fluid exchange with the outside of the simulation domain, and q (m s^{-1}) is the unit water flow based on Darcy's law:

$$q = -K_{sat} k_r(\psi) \bigtriangledown (\psi + Z) \tag{7.2}$$

where K_{sat} (m s^{-1}) is the saturated hydraulic conductivity, k_r (-) the relative permeability of the medium that depends on the pressure head ψ (kPa) as described by the van Genuchten-Mualem equation (van Genuchten, 1980), and $\bigtriangledown(\psi + Z)$ the pressure gradient caused by the elevation head Z (kPa) and ψ.

To describe the surface flow, on the other hand, HGS applies a two dimensional flow equation, which is the diffusion-wave approximation of the Saint Venant equations, consisting of a momentum equation for both the x and y direction and following mass balance:

$$\frac{\delta h_o}{\delta t} - \frac{\delta}{\delta x}(d_o K_{oy} \frac{\delta h_o}{\delta x}) - \frac{\delta}{\delta y}(d_o K_{oy} \frac{\delta h_o}{\delta y}) + d_o \Gamma_o \pm Q_o = 0 \tag{7.3}$$

where h_o (m) represents the water surface elevation and d_o (m) the depth of flow. Γ_o (m^3 m^{-3} s^{-1}) is again the volumetric exchange rate between the surface flow and the subsurface flow and Q_o (m s^{-1}) the volumetric flow rate per unit area representing external sinks and sources. K_{ox} and K_{oy} (m s^{-1}) are surface conductance in x and y directions, calculated with the aid of Manning coefficients.

The coupling of the surface and subsurface flows, which is a key feature of this model, is done by means of the Darcy flux relation to transfer water from one layer to the other. This approach assumes a third, not visualized layer in between layers, which controls the flows between both. The exchange term is given by:

$$d_o\Gamma_o = \frac{K_{sat}(h - h_o)}{\lambda_c} \tag{7.4}$$

where h and h_o (kPa) are the pressure heads of the subsurface and the surface layers, and λ_c the coupling length which determines the connection between both. As mentioned before, Γ_o represents the flow between the surfaces and subsurface, and is positive when upward and negative when downward. Furthermore, HGS models evapotranspiration as a combination of transpiration and evaporation which are boundary conditions to both surface and subsurface flow. Transpiration (T_p) (m s^{-1}) is restricted to the rootzone of the subsurface and depends on the vegetation ($f_1(LAI)$), soil moisture content ($f_2(\theta)$) and the root distribution function (RDF) as described by Kristensen and Jensen (1974):

$$T_p = f_1(LAI)f_2(\theta)RDF(ET_p - E_{can}) \tag{7.5}$$

where ET_p (m s^{-1}) is the potential evapotranspiration and E_{can} (m s^{-1}) is the evaporation of intercepted water by the canopy. The vegetation term is expressed as:

$$f_1(LAI) = max\{0, min[C_2 + C_1LAI]\} \tag{7.6}$$

where C_1 and C_2 are dimensionless empirical constants. The RDF was chosen as a constant function, a recommended for shallow depth crops by Feddes and Raats (2004). The moisture content term relates transpiration to different saturation degrees according to the model of Feddes et al. (1976) given by:

$$f_2(\theta) = \begin{cases} 0 \text{ for } 0 \leq \theta \leq \theta_{PWP} \\ f_3 \text{ for } \theta_{PWP} \leq \theta_{FC} \\ 1 \text{ for } \theta_{FC} \leq \theta \leq \theta_{OX} \\ f_4 \text{ for } \theta_{OX} \leq \theta \leq \theta_{AN} \\ 0 \text{ for } \theta_{AN} \leq \theta \end{cases} \tag{7.7}$$

$$f_3 = 1 - \left[\frac{(\theta_{FC} - \theta)}{\theta_{FC} - \theta_{PWP}}\right]^{C_3} \tag{7.8}$$

$$f_4 = 1 - \left[\frac{(\theta_{AN} - \theta)}{\theta_{AN} - \theta_{OX}} \right]^{C_3} \tag{7.9}$$

According to this model, transpiration is unlimited when soil moisture content (m^{3}m^{-3}) varies between field capacity (θ_{FC}) and the oxic limit (θ_{OX}), while it stops and drops to zero at both the wilting point (θ_{PWP}) and the anoxic limit (θ_{AN}). When soil moisture content varies between θ_{FC} and θ_{PWP}, and between θ_{OX} and θ_{AN}, the empirical parameter C_3 (-) determines the rate of change in transpiration.

Soil water evaporation (E_s) (m s^{-1}) is assumed to occur along with transpiration as:

$$E_s = \alpha(ET_p - E_{can})[1 - f_1(LAI)]EDF \tag{7.10}$$

where α is a wetness factor describing the dependency of evaporation on moisture availability for the subsurface domain. It depends on the soil moisture content at the end of the energy-limiting stage (θ_{e1}), above which full evaporation can occur, and the limiting moisture content (θ_{e2}), below which evaporation is zero (Allen et al., 1998). EDF is the evaporation distribution function that describes the reduction of the energy penetration with depth.

Determination of input parameters

HGS requires a number of input parameters to calculate the processes described above. These were obtained from detailed field measurements of physical soil properties and crop parameters, from scientific literature and from the HGS manual (Therrien et al., 2009). Table 7.1 gives an overview of the HGS parameters used in this study together with their source.

Since the studied soil consisted of two distinct layers, different parameters were defined for the porous media describing the rootzone and the petroplintite. For the rootzone, K_{sat1} was determined by means of 54 infiltration measurements with a Model 2825 tension infiltrometer adaptor module (Soilmoisture Equipment, Santa Barbara, CA) and subsequently calculated with the method of Logsdon and Jaynes (1993) (see Chapter 5). The van Genuchten parameters for the rootzone, i.e. saturated moisture content θ_{s1} (m^{3}m^{-3}),

Table 7.1: HGS input parameters with indication of their source. 1 refers to parameters describing the porous medium of the rootzone layer, whereas 2 refers to petroplinthite

Parameter	Value	Source
K_{sat1} (m s^{-1})	5.53 x 10^{-7}	measured
K_{sat2} (m s^{-1})	2.77 X 10^{-7}	(Chen et al., 2014)
θ_{s1} (m^3 m^{-3})	0.39	measured
θ_{s2} (m^3 m^{-3})	0.39	(Chen et al., 2014)
θ_{r1} (m^3 m^{-3})	0.05	measured
θ_{r2} (m^3 m^{-3})	0.09	(Chen et al., 2014)
α_1 (ms^{-1})	3.78	measured
α_2 (ms^{-1})	5.9	(Chen et al., 2014)
β_1 (-)	1.72	measured
β_2 (-)	1.48	(Chen et al., 2014)
n_x (s m$^{-1/3}$)	0.001	(Chow, 1959)
n_y (s m$^{-1/3}$)	0.001	(Chow, 1959)
Root depth (m)	0.2	measured
θ_{FC} (m^3 m^{-3}))	0.16	measured
θ_{PWP} (m^3 m^{-3})	0.06	measured
θ_{OX} (m^3 m^{-3})	0.25	measured
θ_{AN} (m^3 m^{-3})	0.31	measured
θ_{e1} (m^3 m^{-3})	0.12	measured
θ_{e2} (m^3 m^{-3})	0.06	measured
C_1 (-)	0.5	(Therrien et al., 2009)
C_2 (-)	0	(Therrien et al., 2009)
C_3 (-)	1	(Therrien et al., 2009)

residual moisture content θ_{r1} (m^{3}m^{-3}), scaling parameter α_1 (m^{-1}) and fitting parameter β_1 (-) were obtained from soil water retention Curves (SWRC) that were constructed from 45 undisturbed soil samples (100 cm^3) as described in Chapter 5. For the petroplintite, initial estimates of both K_{sat2} and the van Genuchten parameters were obtained from Chen et al. (2014), who determined the permeability characteristics of unsaturated Plinthosols. With respect to the parameters describing the surface flow, the Manning coefficients (n_x and n_y) for a bare field were taken from Manning's n reference tables (Chow, 1959).

Since the parameter that couples surface and subsurface flow, i.e. the coupling length (λ_c), is based on the virtual surface-subsurface interface and cannot be directly measured, its initial value was set at 10^{-2} m as proposed by Ebel et al. (2009). However, the coupling length should be considered as a calibration parameter, as Verbist et al. (2012) demonstrated that coupling length is the most sensitive parameter when simulating both surface run-off and soil moisture content. After manual calibration, λ_c was set at 50 cm. This seems high when interpreted physically, but λ_c is generally used to control the (de)coupling of the surface/ subsurface flow. As such, λ_c represents the impact of surface sealing on reduced interface permeability. Since Sahelian sandy soils are very prone to crust formation (Visser et al., 2005), a high λ_c value is warranted.

Besides parameters describing the porous medium, HGS also requires crop and soil physical parameters to simulate the evapotranspiration process. Root depth was measured as described in Chapter 4 and LAI values throughout the growing season were determined for both CF and DL. These were based on estimated canopy cover percentages (see Chapter 6), which were converted to LAI values with an extinction coefficient for pearl millet of 0.41 as proposed by Wallace et al. (1990). Furthermore both the transpiration limiting and evaporation limiting water content are related to the soil's pore network and were therefore calculated from aforementioned SWRC. Field capacity (θ_{FC}, m^{3}m^{-3}) and permanent wilting point (θ_{PWP}, m^{3}m^{-3}) were determined according to Reynolds et al. (2009) (see Chapter 5), whereas soil moisture contents at the oxic (θ_{OX}, m^{3}m^{-3}) and anoxic limit (θ_{AN}, m^{3}m^{-3}) were determined according to Feddes et al. (1976) for sweetcorn at the respective pressure potentials of -3.4 kPa and -1 kPa and the evaporation limiting content (θ_{e1} and θ_{e2}, m^{3}m^{-3}) were calculated based on Allen et al. (1998) and the microlysimeter measurements described in Chapter 6.

Model set-up

Based on measurements of the slope, plot size and demi-lunes geometry, two-dimensional grids were generated using Grid Builder, a pre-processor software with build-in graphical interface. For all treatments, a variable rectangular grid size was chosen with small grid elements forming the cropping area and larger grid elements in between. Subsequently the three-dimensional grid was created by vertically projecting in HGS to a depth of 1.05 m. Three sublayers were added to the rootzone and three to the petroplinthe at depths where soil moisture measurements were taken (45, 60, 75 and 90 cm). Since millet had as sparse planting density for CF and was confined to the cropping area for DL, DL+ and DL++, the soil surface was divided into zones with different evapotranspiration properties. As such certain elements were introduced as bare soil where only evaporation occurred and others as crop zone where both evaporation and transpiration took place.

Evapotranspiration was, just like rainfall, expressed as flux (cm min^{-1}) and imposed as a boundary condition. The rain flux was composed by daily rainfall measurements and rainfall intensity was calculated from rain event duration. Furthermore, since the water table was much below the studied soil profile, a free drainage boundary was specified at the bottom of the subsurface domain (Verbist et al., 2012).

To avoid influence of initial conditions at the start of the rainy season, simulations each year started on the first of January, five months before the season onset and proceeded until 31 December. Global water balance and simulation data, such as hydraulic heads could be extracted from HGS at requested time steps, as it continuously writes detailed numerical information.

Validation and soil water balance

The model was validated by comparing soil-water content simulations with observations of 2011, 2012 and 2013. P amounted to 417 mm in 2011, 687 in 2012 and 615 in 2013, rainfall amounts which respectively have a probability of exceedence of 88%, 11% and 14%. Soil-water content was monitored using a neutron probe (CPN-503DR hydroprobe) with two aluminum access tubes per plot as described in Chapter 4. Measurements were taken at 15-cm increments at depths of 15, 30, 45, 60, 75, 90 and 105 cm, providing each year 14 observation time series per treatment.

Residual mean squared error (RMSE) was computed to evaluate the goodness of fit between observed and simulated θ values for CF and DL:

$$RMSE = \sqrt{\frac{\sum_{i=N}^{N}[X_i - O_i]}{n}} \tag{7.11}$$

where, n is the number of observations, X_i and O_i are the observed and simulated values.

Subsequently, simulations enabled calculation of the rainfall partitioning as influenced by WSC design, i.e. for C, DL, DL+ and DL++. The water balance components included rainfall (P), run-off (R), actual transpiration (T), surface water evaporation (E_{sw}), open water evaporation (E_{ow}) and deep drainage (D) (below 1.05 m). Except for P which was obtained from measurements, all components were extracted from the model hydrographs and water balance output files. The overall change in water storage within the 0-1.05 m soil layer was then obtained by solving the soil water balance equation:

$$\Delta S = P - T - E_{sw} - E_{ow} - R - D \tag{7.12}$$

7.3 Results

7.3.1 Model performance

Fig. 7.2 shows observed and simulated soil moisture content values θ at 15 cm depth for CF and DL, both within the cropping area (θ_{in}) and in between cropping areas (θ_{out}). Additionally, HGS model performance is reflected by corresponding RMSE values as summarized in Table 7.2. Except for a consistent overestimation in August ($\simeq$ DOY 210 - 240), there was a relatively good agreement between simulated and observed θ_{in} and θ_{out} values of CF, and θ_{out} values of DL. However, HGS performed poor in simulating θ_{in} values of DL. Simulations substantially overestimated θ_{in} peaks for DL which resulted in elevated RMSE values indicating poor model performance.

7.3.2 Effect of design optimization on rainfall partitioning

In Table 7.3 water balance components are given for simulations of the conventional practice (CF), and the original (DL) and optimized (DL+ and DL++) demi-lunes designs. Most rainfall water is lost as Run-off R and surface water evaporation E_{sw}. Simulated E_{sw} did not vary much among treatments, but simulated R significantly reduced when

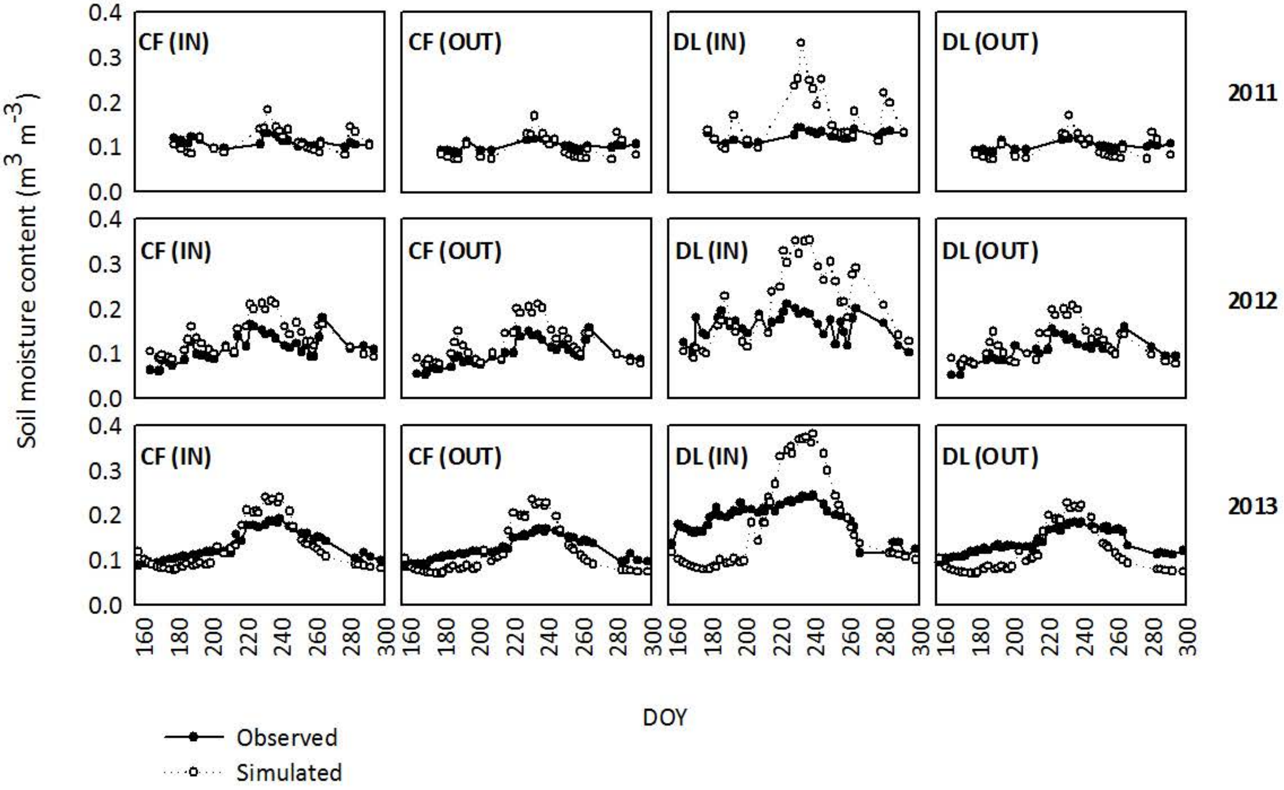

Figure 7.2: Observed and simulated soil moisture contents at 15 cm for CF(IN) (next to the plant), CF(OUT)(in between plants), DL(IN) (inside the DL cropping area) and DL(OUT) (in between DL bunds or in the catchment) for 2011, 2012 and 2013

Table 7.2: Residual Mean Squared Error (RMSE) for simulated moisture contents of CF(IN), CF(OUT), DL(IN) and DL(OUT) for 2011, 2012 and 2013

RMSE (θ_s, m^3 m^{-3})	CF(IN)	C(OUT)	DL(IN)	DL(OUT)
2011	0.02	0.02	0.10	0.05
2012	0.04	0.04	0.11	0.05
2013	0.03	0.04	0.10	0.05

DL bund density per surface area increased. R decreased from $\simeq$ 37-50% of the total rainfall amount P for CF to $\simeq$ 28-42% for DL, to $\simeq$ 25-40% for DL+ and to $\simeq$ 23-37% for DL++. No rainfall was lost as deep drainage D and the amount of rainfall going to actual transpiration T was overall low. T increased with higher number of DL bund density. In 2011, soil-water depleted for all treatments over the 0-1.05 m soil layer, but in other years only CF resulted in soil-water depletion.

Fig. 7.3 illustrates the development of surface flow in time as affected by treatment. Two-dimensional illustrations of surface water depth are given for different time steps following the rain event on DOY 220 (40 mm) in 2011 (see Fig. 4.7, in Chapter 4). Under CF, surface water runs off at the downslope side of the field, whereas for DL, DL+ and DL++, surface water is collected inside the DL cropping areas, resulting in increasing water depths. Moreover, surface flow was redistributed from one DL cropping area to the other until surface flow stopped and water remained stagnated in the cropping area.

Fig. 7.4 illustrates the evolution of soil moisture contents in the subsurface as affected by treatment. Cross-sections along the slope clearly show higher soil moisture contents in the soil profile for DL, DL+ and DL++ than for C.

7.4 Discussion

7.4.1 Potential of HGS to simulate water dynamics of demi-lunes

Poor agreement between observed and simulated θ_{in} values for DL suggests poor model performance. This can either be explained by the large sphere of influence of the neutron probe or by the simplified rectangular form of the DL bunds in the model. The neutron probe used for measuring soil moisture contents in this study had a sphere of influence of $\simeq$ 20 cm on average (Kristensen, 1972).

Table 7.3: Simulated water balance components (mm) over the 0-0.105 cm soil layer (as presented in Eq. 7.12) for 2011, 2012 and 2013 for the control treatment (CF) and the original (DL) and optimized (DL+ and DL++) demi-lunes designs. P is the precipitation, R is the run-off, T is the actual transpiration, E_{sw} is the surface water evaporation, E_{ow} is the open water evaporation, D is the drainage and ΔS is the soil-water storage when positive and the soil-water depletion when negative

year	treatment	P	R	T	E_{sw}	E_{ow}	D	ΔS
2011	CF	417	154	6	265	15	0	-23
	DL	417	117	45	252	14	0	-11
	DL+	417	106	55	248	15	0	-7
	DL++	417	96	68	241	15	0	-3
2012	CF	687	338	8	333	22	0	-13
	DL	687	288	54	312	22	0	11
	DL+	687	270	67	320	22	0	7
	DL++	687	253	84	310	22	0	19
2013	CF	615	309	3	303	23	0	-23
	DL	615	262	22	300	26	0	4
	DL+	615	245	28	302	28	0	12
	DL++	615	230	35	299	29	0	22

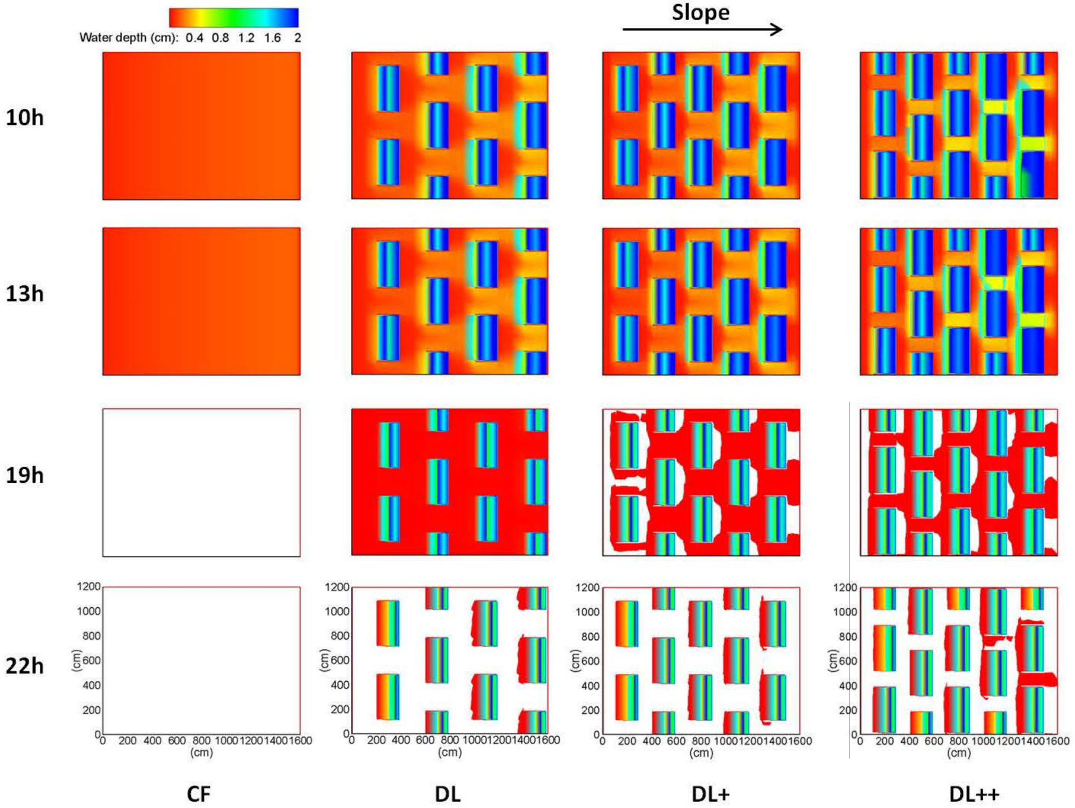

Figure 7.3: Effect of DL design on surface flow. Simulated water depth at the surface are represented for CF (control), DL (original DL design), DL+ and DL++ (optimized designs) for different timesteps following the rainfall event initiated at 07h on DOY 220 (40 mm) in 2011 (see Fig. 4.7, in Chapter 4). Note that the color scale starts at a water depth of 1×10^{-2} cm. A white color thus means zero water depth and no overland flow

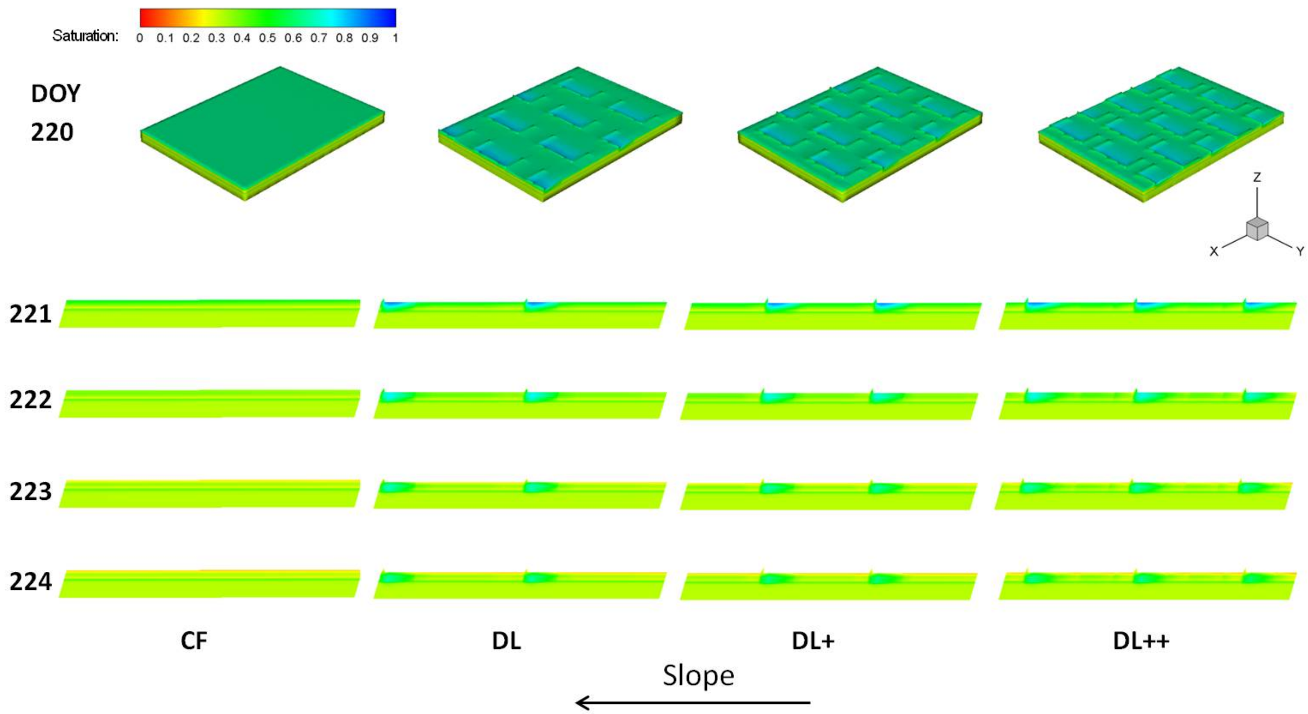

Figure 7.4: Effect of DL design on subsurface soil moisture contents. Saturation degree is represented three-dimensionally for CF (control), DL (original design), DL+ and DL++ (optimized designs) following the rainfall event initiated at 10h on DOY 220 (40 mm initiated at 07h) in 2011 (see Fig. 4.7, in Chapter 4). The lower part shows vertical two-dimensional slices of the soil domain at $y = 6$ m for CF, DL and DL+ and at $y = 7$ m for DL++ for different timesteps

Although the probe was calibrated separately for the 0-15 cm, 15-30 cm and 30-105 cm soil layers, observed θ_{in} at 15 cm reflects the average over the top $\simeq$ 40 cm soil layer, while simulated θ_{in} reflects a point measurement at 15 cm. Given the presence of petroplinthtite at 35-40 cm and the expected higher soil moisture content in the top layer, observed θ_{in} might underestimate actual θ_{in} values at 15 cm. In addition, representing DL bunds as rectangular instead of circular presumably overestimates simulated θ_{in} values for DL. Generating circular DL bunds in Gridbuilder is not possible without exponentially increasing the number of nodes and computing time. Representing the DL bunds as rectangular on the other hand restricts the number of nodes, but increases the total volume within the bund from $\simeq$ 0.45 m ^{3} to $\simeq$ 0.65 m ^{3}. Simulations with rectangular DL bunds hence overestimate the volume of 'harvested' water and most likely result in elevated θ_{in} values.

Although discrepancies between observed and simulated θ_{in} are partly clarified, water balance components as calculated from simulations also differ greatly with the results reported in Chapter 6. Both simulated R and E_{sw} exceed observed values for C and DL. Whereas simulations indicate an absence of water loss by D for DL, in contrast to what was observed in the field experiment (see Chapter 6). Simulated T values are very low when compared to observed crop yields (see Chapter 4). These over and underestimations of water balance components indicate that simulating the rootzone water balance of a small-scale WSC technique is not straightforward.

To our knowledge, this is the first HGS-study that separates a zone with bare soil where only evaporation occurs, from a vegetated zone where both evaporation and transpiration take place. Although this separation of zones is essential to simulate the water balance under Nigerien conditions with sparse vegetation, the model might process this incorrectly and underestimate T. Overall, the baseline requirements for this study are more complex than for previous HGS studies. Besides two zones with different evapotranspiration properties, the model also has to simulate two layers with different hydraulic properties (rootzone and petroplinthite). On top of that the model also needs to compute the effect of WSC structures, resulting in overall complex model simulations.

Inaccurate simulated θ_{in} values might also be attributed to incorrect estimates of input parameters. Given the underestimation of D and the overestimation of R and θ_{in} at 15 cm, K_{sat1} and K_{sat2} seem to be underestimated. Verbist et al. (2012) reported that, besides λ_c, K_{sat} was the most sensitive parameter when simulating hydraulic behaviour of infiltration trenches in a semi-arid environment. This indicates that instead of one calibration parameter (λ_c) an automatic calibration of a set of three or more parameters is needed to obtain an accurate model. However, this could not be accomplished within this dissertation because of practical reasons.

Our results indicate that HGS seems a powerful tool to simplify design optimization of ancient WSC techniques, but its complexity has a downside. Multiple parameters need to be determined in the field or calibrated, but this demands advanced computational power and detailed observations of θ_S throughout the growing season (Brunner and Simmons, 2012). The model's complexity might therefore restrict the number of practical applications. nevertheless, HGS does show potential to successfully simulate WSC upscaling. Evaluating upstream/downstream effects of WSC on watershed scale is one of the major issues in need of analysis and should be tackled in future research (Wani et al., 2009). HGS seems a suitable tool for this, as it was already successfully applied by Pérez et al. (2011) to evaluate water management changes on watershed scale.

7.4.2 Demi-lunes design optimization

Although simulations of water dynamics of the DL microcatchment system needs improvement, model results did follow logical trends (e.g. R increases with higher P). Simulated water balance components hence give an indication of the water harvesting capacity DL, DL+ and DL++. For the same amount of P, T increases significantly with DL density, due to elevated soil-water storage in the rootzone. Our results indicate that DL++ is the most promising design, as it retains the same volume of water per bund as DL and DL+, while total transpiration and thus crop production increased. Note, however, that labour and manure requirement increase proportional with the increase in DL bund density.

The same LAI values were used for the DL+ and DL++ simulations as for the DL simulations. Nevertheless it is recommended to apply lower planting densities within the DL+ and DL++ cropping areas. Our results in Chapter 4 indicated that lower planting densities did not result in lower grain yields.

7.5 Conclusion

When only λ_c is taken into account for parameter optimization, HGS does not succeed in simulating very accurately the water dynamics of the complex system in this study. Simulating the combination of DL-bunds with the requirements of two soil layers and two zones of which one is representing bare soil without automated calibration of an extended parameter set is currently not straightforward.

However, the model did produce logical outputs. According to these results, current spacing of demi-lunes can be optimized by decreasing the distance between bunds on the contour level from 2 m to 1 m and by decreasing the distance between two successive DL bund lines from 4 m to 3 m. If then only 16 plants ha^{-1} are sown instead of 24, millet crop yield will be higher for the typical planting density of 10000 plants ha^{-1}.

8

Assessing the constraints to adopt water and soil conservation techniques in Tillaberí, Niger[1]

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[1] This chapter is based on the eponymous paper published in Land Degradation & Development. DOI:10.1002/ldr.2252.

8.1 Introduction

Nigerien farmers increasingly rely on marginal, severely degraded lands that generally produce little or no yields (0-100 kg ha^{-1}) (Fatondji et al., 2006; Roose, 1999; Sawadogo et al., 2008). These poor yields can be attributed to recurrent droughts, which are, as explained in Chapter 4, related to frequent dry spells and inefficient use of rainfall. A large part of rainfall is lost as run-off ($\approx 25\%$) and soil evaporation ($\approx 12\%$) (see Chapter 6) and only a small fraction is used by crops for biomass-producing transpiration.

Higher yields and more efficient use of rainwater can be achieved by water and soil conservation techniques (WSC) which harvest run-off and positively modify the distribution of rainfall over the rootzone. In Niger, zaï and demi-lunes are the most-promising WSC techniques (see Chapters 4 and 6)(Fig. 8.1). They both result in substantial yield increases and are applicable by small-scale, subsistence farmers since they only require locally available materials like manure and a hand-hoe (Roose, 1999). Despite much effort to disseminate these WSC techniques on a larger scale in Niger, their adoption has had limited success.

Figure 8.1: The two most-promising WSC techniques in Niger are zaï (left) and demi-lunes (right). Zaï are pits of ± 0.3 m diameter and 0.15 m depth in which millet is sown. Demi-lunes are earth bunds parallel to the contour line. For this WSC technique millet is sown inside the basin of the bund. In general manure is applied within the pit for zaï and within the basin for demi-lunes

Throughout the world, widespread WSC dissemination has, similarly, seen limited success (Falkenmark et al., 2001). In an effort to address this problem, the approach to disseminate WSC techniques has been evolving. Before the 1980s, WSC-dissemination projects applied a top-down approach and excluded farmers from the decision making process. This made farmers reluctant to adopt WSC techniques and hampered their ability to innovate and adjust the techniques to their local biophysical and socioeconomic conditions (Reij et al., 1996). To prevent the incompatibility between WSC techniques and local farm management, WSC-dissemination projects shifted towards a participative approach in which farmers took a more central part in the design of WSC techniques (Van Damme, 1989; Ouédraogo and Bertelsen, 1997; Sendzimir et al., 2011). Despite current effort for farmer participation, widespread WSC adoption still remains limited (Shiferaw et al., 2009).

A number of studies have been investigating the factors that influence a farmer's adoption of WSC techniques. Most of these studies investigated the adoption constraints related to the resource availability of farmers. The most influencing adoption factors were found to be the limited availability of labour capacity (Anley et al., 2007; Ouédraogo and Bertelsen, 1997; Slingerland and Stork, 2000; Wedum et al., 1996), manure or fertilizer (Slingerland and Stork, 2000) and agricultural equipment or transport means (Hassan, 1996; Slingerland and Stork, 2000; Wedum et al., 1996).

However, de Graaff et al. (2008) and Tenge et al. (2007) pointed out that resource availability only explains the adoption constraints related to the actual adoption phase and that several other factors hamper WSC adoption. They came to this conclusion by outlining the WSC-adoption process of farmers. In this process, there is an acceptance phase before the actual adoption phase. In order to accept WSC techniques, a farmer has to become aware of the soil erosion problem. He has to recognize the symptoms of soil erosion, understand its effects and perceive it as serious before he is willing to undertake action against it. When a farmer is aware of erosion, he subsequently has to become aware of adequate WSC measures. This means that WSC measures should be successfully applied in his neighbourhood or that an institution is present that provides adequate WSC-dissemination. If a farmer is concerned about soil erosion and knows which WSC measures to adopt, adoption can finally still be obstructed if he does not have the resources to do so (actual adoption phase). Until now, research on WSC-adoption constraints mainly focused on a farmer's resource availability and paid little attention to the vital adoption factors related to the acceptance phase.

This study investigates the adoption constraints of WSC techniques in the Tillaberí region of Niger. We hypothesized that WSC adoption is not only hampered by limited resource availability (i.e. actual adoption), but also by a lack of soil erosion awareness and knowledge of WSC techniques (i.e. acceptance). To test these hypotheses, we carried out a survey in three villages (Nikoye, Panoma and Bogoudjotou), which inquired the erosion perception of farmers, their knowledge of WSC techniques and their resource availability. The importance of erosion awareness and WSC knowledge for WSC adoption was analyzed by comparing adopters and non-adopters. While the importance of resource availability for WSC adoption was evaluated by comparing the resource availibility of farmers with the resources requiremed for WSC implementation. An analysis of how the presence of WSC-dissemination projects interfered with these adoption factors furthermore resulted in several recommendations for extension.

8.2 Materials and methods

8.2.1 Description of the study area

The Tillaberí region in Niger has a Sudano-Sahelian climate with a long, hot dry season and a short rainy season (June-October). This rainy season is essential for the inhabitants who mainly live on small-scale, subsistence farms ($\leq$ 2 ha), where primarily millet (*Pennisetum glaucum* (L.) R. Br.) is grown with or without cowpea (*Vigna unguiculata* (L.) Walp.) or groundnut (*Arachis hypogaea* L.) as intercrop.

The region is subjected to recurrent droughts. An increasing amount of soils is affected by serious degradation due to overgrazing, firewood cutting and intensification of farming (Tabor, 1995; Visser et al., 2003). The Torodi district (13°07' N 1°48' E) is located in the Say department (16 people km^{-2}) of the Tillaberí region (Fig. 8.2). It includes 112 villages, hosts a large weekly market and is inhabited by Zarma, Songhai, Gourmantche and Fulani communities, which were the original inhabitants, and Tuareg, Tamajeq, Mossi and Hausa communities, who migrated into the region, largely during the second part of the 21st century (Guengant et al., 2003).

The district has a surface area of 696, 029 ha of which approximately 43% is under cultivation and 44% is forested. Each year 4000 ha of forest is destroyed to expand the cultivable area. These newly exploited lands are poorly managed, which results in severe land degradation and poor crop yields (Rinaudo and Yaou, 2009). Although WSC techniques have been promoted to combat land degradation and increase crop yields, they are not widely adopted in the district.

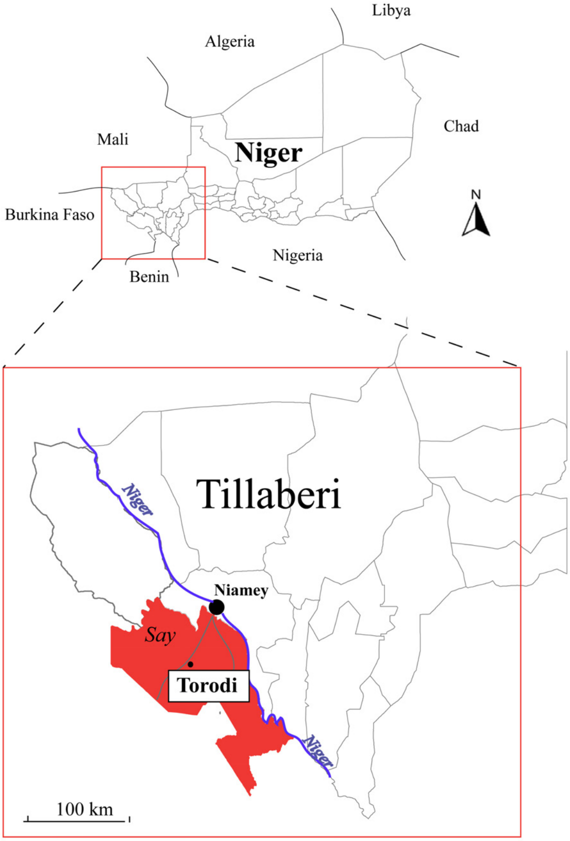

Figure 8.2: Map of Niger and the Tillaberí region (enlarged section). The study site is located in the Torodi district (13°15' N 1°48' E, 50 km south-west of Niamey and 50 km east of the border with Burkina Faso) in the Say departement (shaded area) of the Tillaberí region

Together with local environmental and agricultural district officers of the Torodi district, we selected three villages (Panoma, Nikoye and Bogoudjotou) in order to study WSC adoption. The villages were selected from the topographical positions associated with shallow Plinthosols (see Chapter 2, section 3.1.2) where WSC techniques can be implemented. Furthermore, the villages were selected based on their difference in WSC-project presence. Interviews with district officers and village chiefs made clear that Panoma village was never in contact with a project promoting or demonstrating WSC techniques, whereas in Nikoye a short-term project promoted WSC techniques during one cropping season. Bogoudjotou, on the other hand, has been hosting a long-term-WSC field trial (more than 5 years). This difference in WSC-project presence enabled the evaluation of the influence of a project's presence on WSC adoption.

8.2.2 Survey design

A survey was designed with the help of seven key informants who provided insight in the specifics of WSC techniques and their adoption in the Tillaberí region. Key informants were selected by means of a snowball sampling method, in which each key informant recruits new key informants from his or her network (Bernard, 1994). The sampling chain started with WSC specialist Dr. Fatondji, who was introduced to us by WOCAT (World Overview of Conservation Approaches and Technologies) as their local representative and researcher at ICRISAT. Together with these key informants several adoption factors were discussed, specific for the Tillaberí region and related to the different WSC adoption steps as described by de Graaff et al. (2008).

Based on the information the key informants provided, a questionnaire was designed with open, half-open and closed questions. To control whether our research population was representative, several general questions regarding household characteristics (e.g. ethnicity, age of household head, education, market orientation) were included in the survey. Furthermore also questions concerning the farmer's land availability and food security situation were included to ensure the relevance of WSC techniques for the research population. The questions concerning the constraints for adoption looked into the farmer's awareness of erosion, his WSC knowledge and his resource availability, and will be discussed in following sections.

Erosion awareness

Farmers will only adopt new techniques if they want to solve a problem they perceive themselves (Kiome and Stocking, 1995; Sidibé, 2005; Tenge et al., 2007). According to de Graaff et al. (2008), a good understanding of the soil erosion problem is hence a prerequisite to adopt WSC techniques. The lack of WSC adoption in the region is therefore possibly a result of a lack of erosion awareness. To assess erosion awareness among farmers in the region, three erosion awareness indicators with five levels (no, slight, mediocre, good, perfect) were composed. These indicators evaluate the awareness of farmers of the concept of erosion (1), its causes (2) and its effects (3). For the indicator dealing with the concept of erosion (1), questions on a farmer's notion of changing soil conditions over time were included in the survey. These questions investigated whether they understand that fertile land can degrade and vice versa, that degraded land can be rehabilitated. For the indicator looking into the causes of erosion (2), questions were included that analysed the connection a farmer makes between soil damage or soil loss and its causes (deforestation and wind and water erosion). These questions evaluated their understanding of how gullies and degraded land are formed and the interaction of WSC techniques with erosion processes. Finally, for the indicator dealing with the effects of erosion (3), several questions were included that analysed a farmer's perception of drought and soil-water household and their understanding of the positive effect of WSC techniques on the soil resource. The three indicators were composed by assembling and scoring the answers of farmers to these questions.

WSC knowledge

Another possible constraint for WSC adoption is the unawareness of WSC techniques. Farmers not only have to know WSC techniques, they also have to understand why the techniques are adequate to combat soil erosion and improve crop productivity, and they need to know how to implement them correctly. To study this constraint, the knowledge of farmers about the two most promising WSC techniques in the region, zaï and demi-lunes, was analysed qualitatively with open ended questions. The survey included questions dealing with the farmer's knowledge of the practical implementation of the techniques, their advantages and disadvantages and the acquisition of this knowledge.

Resource availability

Even when a farmer is aware of soil erosion and knows which WSC techniques to implement, adoption is not assured, as he needs resources to implement the techniques. Both zaï and demi-lunes are fairly easy techniques to implement, but a minimum of labour, manure or fertilizer and agricultural equipment (implements and transport facilities) is

required.
Access to labour was analysed qualitatively and quantitatively by questions dealing with the number and availability of workmen for all field activities. The availability of manure and fertilizer was analysed qualitatively by inquiring about current nutrient management practices and was quantified by questions regarding the surface area of land to which nutrient management was applied, questions regarding livestock and questions regarding manure price. Finally, the access to agricultural equipment was assessed quantitatively through questions regarding the implements needed for WSC installation and the transport facilities used for manure and harvest transport.

8.2.3 Data collection and processing

The questionnaire was piloted to evaluate both formulation and effectiveness of the questions to evaluate WSC adoption constraints in the region. This pilot study was conducted with five farmers who were randomly selected on the weekly market of Torodi. They answered the complete questionnaire, after which their answers and the questionnaire were elaborately discussed. Subsequently, a total of 100 (to obtain a confidence interval $\geq$90%) household heads were randomly selected from the population register of the three villages. We chose to select household to avoid interviewing family members working in the same farm. The number of respondents per village was proportional to the total number of household heads per village. As such, 44 from the 112 household heads were interviewed in Nikoye, 23 from the 60 in Panoma and 33 from the 85 in Bogoudjotou. Eventually, due to two drop-outs, 98 were interviewed between 3 and 25 October 2011. One interpreter was trained to conduct the interviews in Zarma, the local language. Several 'control' questions were included in the survey (i.e. similar questions with different formulation) to verify the accuracy of the answers. Reported results are therefore never based on an answer to only one question, but are deducted from information provided to a set of questions and their control questions. Collected data was processed and analysed with SPSS. Pearson correlation was used to test the dependency of adoption on household characteristics, project participation, erosion awareness, WSC knowledge and resource availability. Further qualitative analysis of erosion awareness, WSC knowledge and resource availability in the region involved descriptive statistics including frequency distribution and cross-tabulations. A cost-benefit analysis was added to evaluate resource availability in the region.

8.3 Results and discussion

8.3.1 Household characteristics and agricultural context

The average age of the household heads was 49.8 (SD = 16.1) of which the oldest and youngest were respectively 90 and 16 years old. Households, on average, counted 9.2 persons (min. 2; max. 26, SD = 4.9) with a mean number of 6.9 children (min. 0; max. 22, SD = 4.4) and 1.3 wives (min. 0; max. 4, SD = 0.7). The level of formal education was very low, as the majority of the respondents (59%) was illiterate. Only a few household heads completed primary education, took literacy training or went to the Arabic school. The multi ethnicity of the area was represented by our respondents of which 28% are Fulani, 19% Songhai, 17% Mossi, 14% Tamajeq, 11% Tuareg, 5% Zarma, 5% Gourmantche and 1% Hausa.

Ninety-six percent (96 %) of the household heads declared that they do not produce enough food to sustain their family year-round. Most families overcome this production shortage by buying food, but 35% are not financially capable to do so, which means they yearly cope with food shortage, rely on food aid or on donations from farmers with a harvest surplus. Forty four percent (44 %) of the respondents declared that they had a harvest surplus in the past, but these are now non-existing, suggesting that food security is an increasing problem.

Fertile land proves to be scarce in the study area. Respondents on average own only two large parcels (± 1 ha) and either a medium (± 0.5 ha) or small (± 0.25 ha) sized parcel, of which the majority (67%) is located nearby the family house. Seventy-two percent (72%) of the respondents declared not to have enough fertile land and merely 17% could extend their agricultural activities with fertile land if necessary. Land shortage is mainly attributed to fast population growth (2.5-3.5% year^{-1}), ongoing severe land degradation and land acquisition through inheritance. An exponential family growth with consecutive large numbers of sons results in land fragmentation, leading to declining land availability per capita. This makes land availability a key constraint for food production and suggests that targeting degraded land is a rational approach to increase food production and should trigger the investment in WCS techniques (Reij et al., 1996). Although markets are accessible, market orientation is relatively low. Only 40% of the farmers would sell their harvest surplus if they gained one, whereas 34% would store it for future consumption and almost a quarter of the farmers would give it away.

Fourteen (14) farmers stated that they currently apply one of both WSC techniques (zaï or demi-lunes) and are referred to as 'adopters' throughout this manuscript. Although several studies report a relation between household features and adoption (Anley et al. (2007) in Ethiopia; de Graaff et al. (2008) in Tanzania), this relation was absent in our study which does accord with the results of Baidu-Forson (1999) in Niger and Slingerland and Stork (2000) in Burkina Faso. The latter moreover prove the insignificance of formal education on adoption, but stress the importance of specified extension education, which will be discussed further on.

8.3.2 Erosion awareness

Table 8.1 shows the results of the erosion awareness indicators. Most farmers in the Tillaberí region of Niger (68%) are aware of the concept of erosion, but they lack knowledge regarding the causes and effects of erosion. Several farmers mentioned deforestation (26%) or wind or water as erosion causes and many respondents pointed to intangible and uncontrollable causes for erosion such as, overpopulation, God or superstitions (Fig. 8.3). Zarafshani et al. (2007) reported a similar phenomenon in Iran. According to them the more extreme yield losses due to drought are, the more emotional farmers act, which for example results in praying for rain instead of trying to mitigate drought threats.

Just like the causes of erosion, the effects of erosion are not well understood in the region either. Many farmers only mentioned indirect effects of erosion such as food insecurity (34%) or 'suffering' (47%) and those who did attribute direct effects mostly noticed a decline in soil fertility and yield (51%). Thirty-nine percent (39%) of the farmers however, did connect erosion with reduced water retention or infiltration.

Although it is not surprising that uneducated farmers do not deduct natural processes in a scientific reductionist way, it seems worrying that farmers do not observe the direct causes and effects of one of the most threatening processes to their livelihood. They do relate the decrease in production potential with land degradation, which was also reported by Taylor Powell (1991), but they do not link land degradation with plant water

Table 8.1: Awareness of farmers of erosion, its causes and effects in Torodi, Niger. The percentage of farmers (n=98) per awareness level is given

Knowledge of	Awareness level				
	No	Slight	Moderate	Good	Excellent
(1) Erosion concept	0	31	5	50	14
(2) Erosion effects	0	51	39	6	4
(3) Erosion causes	17	26	30	21	6

availability. As such, it is difficult for them to grasp the rationale of increasing plant water availability by the implementation of WSC techniques. In contrast, Bielders et al. (2001) and Sterk and Haigis (1998) found that most Nigerien farmers are aware of the damage wind-blown particles cause to their crops and also Visser et al. (2003) report good wind erosion knowledge in Burkina Faso. They also reported however, that farmers understand far less of water erosion and drought than of wind erosion.

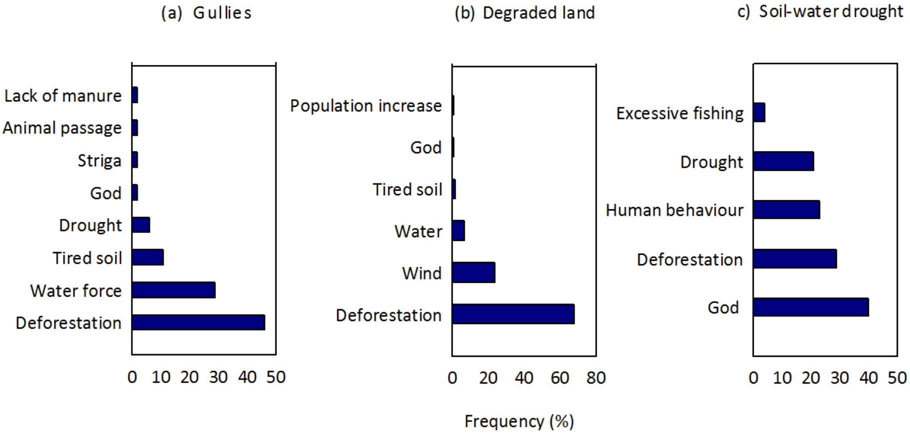

Figure 8.3: Farmer perceived reasons for gullies (a), degraded land (b) and decreased soil water content (c) in Torodi, Niger. Percentage of farmers (n=98) per answer is shown

The migrated population (20%) is less aware of erosion than the native population (Fig. 8.4). This might be explained by recent demands to the nomadic population to become sedentary. Likely, previously nomadic inhabitants do not link erosion problems to its effects and causes, because they did not cultivate fields long enough to notice gradually developing processes such as soil erosion.

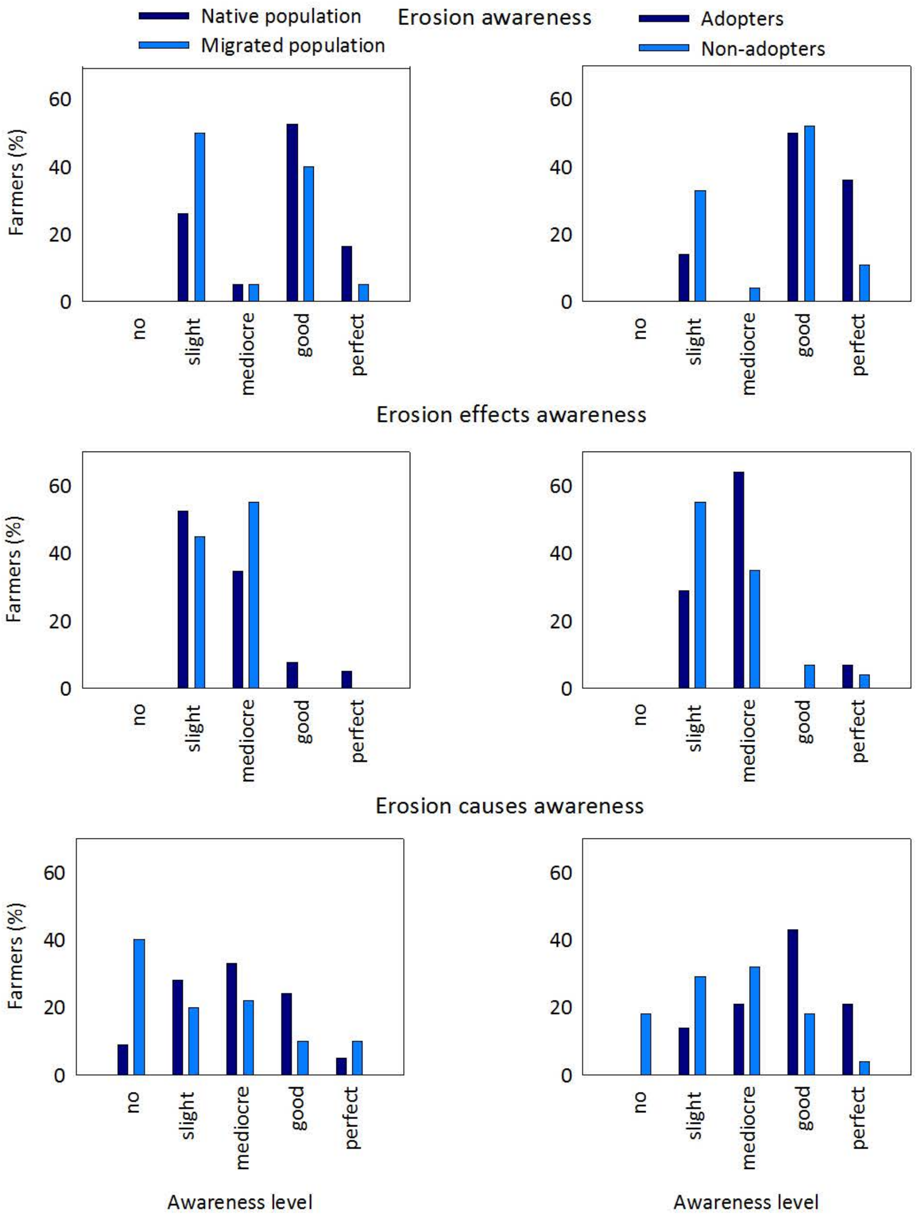

Figure 8.4: Awareness of farmers of erosion, its effects and causes in Torodi, Niger, considering native and migrated population (left) and adopters and non-adopters (right). Percentage of farmers (n=98) per level is shown

Farmers often seemed to confuse the effects of drought with the effects of soil erosion. For them, it is difficult to distinguish soil-water drought, caused by soil erosion, from meteorological drought, caused by unfavourable rainfall distribution, when they both result in a lack of water availability for the plant (Slegers and Stroosnijder, 2008) (see Chapter 4). As a matter of fact, all respondents believe that climate is changing in the region. They believe that their climate is becoming warmer and dryer. However, until now, there is no meteorological evidence that the total amount of annual rainfall is decreasing (see Chapter 4) and only few farmers (9%) explicitly mentioned less rain. Hence, most farmers understand that the increasing drought problem is not related to a decrease of annual rainfall amount, but they do not link drought with the degrading soil resource.

Figure 8.4 shows that adopters of WSC techniques have an overall higher awareness of the erosion concept and its processes, which confirms the importance of erosion awareness for WSC adoption.

8.3.3 Knowledge of WSC techniques

Profound knowledge of WSC techniques often lacks among farmers in the Tillaberí region. The majority of farmers are acquainted with zaï (76%), which are better known than demi-lunes (36%), but more than one fifth (22%) of the population is not familiar with any of the WSC techniques. Figure 8.5 shows that 15% of the farmers have no idea of why WSC techniques are implemented, while 64% understand that WSC techniques improve harvest. A higher yield is, however, an evident and direct advantage of WSC. The knowledge of farmers of indirect and less obvious advantages (e.g. increased plant water availability and run-off reduction) on the other hand appears to be rather poor and is associated with their limited awareness of the effects and causes of erosion. Yet, farmers will be more motivated to adopt WSC techniques when they understand their multiple indirect advantages, as is reflected by the better WSC knowledge of adopters compared to non-adopters (Fig. 8.5).

This lack of profound WSC knowledge is remarkable, as zaï is indigenous to the Sahelian region and the demi-lunes technique was already introduced in the 1950s. Possibly some of the WSC knowledge was lost during the ‘wet’ period between the 1950s and 1970s, when both methods were abandoned (Roose, 1999; Sawadogo et al., 2008). Most farmers in the research population (43%) got reacquainted with WSC techniques through extension projects as opposed to one third which state to have 'heard about it from another farmer'.

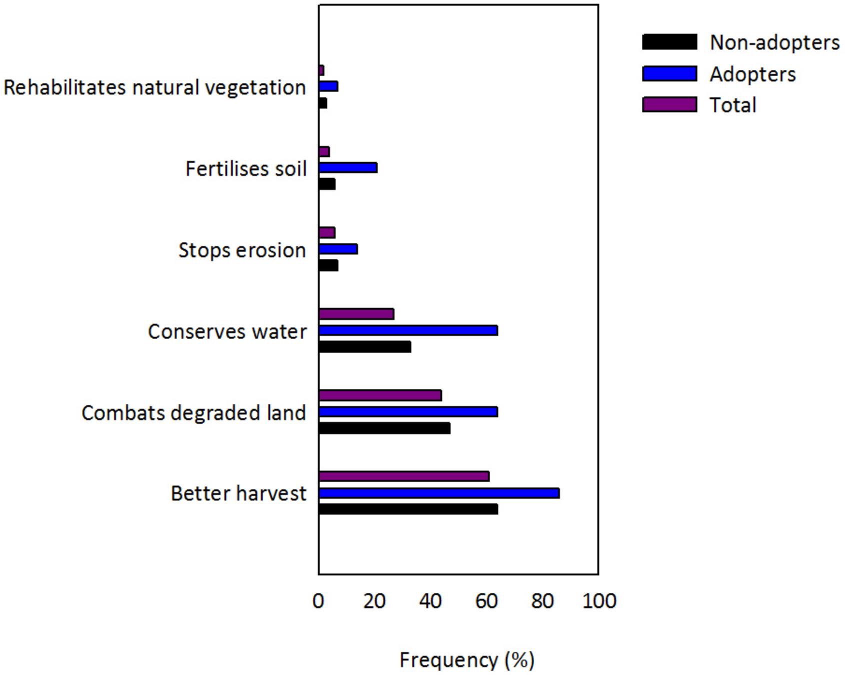

Figure 8.5: The knowledge of farmers of the advantages of WSC techniques in Torodi, Niger, comparing non-adopters with adopters. The percentage of farmers (n=98) per advantage is given

8.3.4 Resource availability

Both zaï and demi-lunes are labour consuming techniques, but labour availability does not appear to be a constraint for WSC adoption. Digging zaï pits, which has to be redone once every 3 years, requires approximately 400 man-hours ha^{-1}, equivalent to 75 000 to 105 000 CFA ha^{-1} of labour (Communauté Financière Africaine) (115 to 160 EUR) (Slingerland and Stork, 2000). This is best done during the dry season, when there are no other field activities. The majority of the household heads declared that they have plenty of labour available during the dry season (86%) and that they have easy access to additional labour force of 1 to 2 (29%), 3 to 5 (33%), 6 to 10 (20%) or even more (7%) persons. Besides help from family and relatives, 26% of the population also annually pay for labour and 11% do this occasionally.

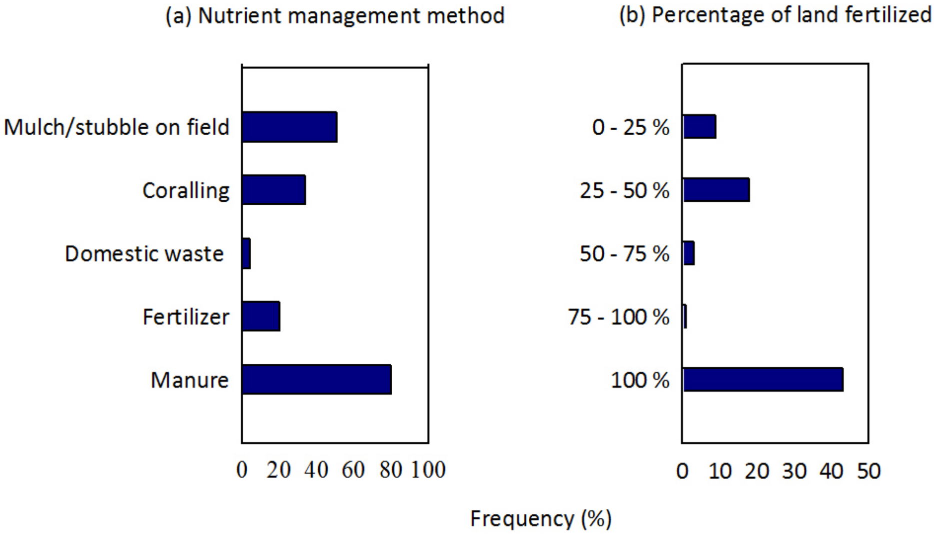

Figure 8.6: Percentage of farmers (n=98) in Torodi, Niger carrying out different nutrient management techniques (a) and the percentage of land they are able to fertilize (b)

Unlike labour availability, shortage in resources for nutrient management does prove to be a constraint for WSC adoption. Almost all farmers (91%) apply some form of nutrient management, but Figure 8.6b demonstrates that more than half of the farmers who do so, apply it to less than 50% of their land. Those who do apply nutrients to all their fields (43%) moreover apply rates far beneath the recommended rate. Furthermore, common nutrient management methods, such as corralling or mulching (Fig. 8.6a), are not compatible with WSC techniques. WSC requires the creation of an isolated environment with favourable growing conditions, for which farmers intentionally have to collect manure and apply it to the plant. Only 80% of the farmers do this. The implementation of WSC techniques in the region cannot succeed without substantial nutrient application (Hassan, 1996). For optimal yields, 3 ton of manure ha^{-1} or 300 g per zaï pit should be applied (Fatondji et al., 2006).

Manure generally originates from domestic livestock and is seldom purchased (7%), but can be bought at 750 CFA per barrow or for 30 000 to 50 000 CFA (45 to 75 EUR) ha^{-1}. Manure shortage in the region is largely related to livestock shortage (Table 8.2). Cattle ownership is remarkably low, despite its indigenous symbol of social standing. Ten percent (10%) of the farmers have neither cattle nor small ruminants and 21% have less than five of both, which means that one third of the population is remarkably poor in livestock. However, farmers do not only gather manure from their own animals, but contract other animals or collect manure on common land. Currently, collecting manure on common land seems to be a viable practice for adopters without livestock. However, when WSC would be adopted on a large scale, present number of livestock is not likely to sustain the overall manure demand. Compost could be a feasible alternative, but up until now none of the farmers appears to use it or is even aware of it.

Table 8.2: Number of cattle and small ruminants farmers owned by farmers in Torodi, Niger. Percentage of farmers (n=98) is given per level

	Number of cattle and small ruminants						
	0	1-5	6-10	11-20	21-30	31-40	40+
Cattle	39	32	14	7	5	4	1
Small ruminants	12	30	17	21	12	5	4
Poultry	12	28	16	18	9	7	11
Donkey	43	55	1	0	1	0	0
Dromedary	89	10	1	0	0	0	0

Besides labour and manure, agricultural equipment and transport facilities to carry manure are needed to implement WSC techniques. Although zaï and demi-lunes are fairly easy to implement, zaï requires a pickaxe or a daba (hand hoe) and demi-lunes a spade and daba (Sidibé, 2005; Wedum et al., 1996). Most farmers, however, do not own these materials (Table 8.3). To solve this, equipment is often shared within the community, enabling farmers who do not own implements to apply the techniques anyway. As such, it is possible for adopters to implement WSC even though respectively 21%, 50% and 43% of them do not own a daba, spade or hand hoe. If WSC is to be applied on a larger scale, more equipment should be available within the community. In addition to agricultural equipment, there is a general lack of transport facilities, especially wheel barrows and carts, which are most appropriate for manure transport. Unlike agricultural equipment, ownership of transport facilities is more individual and less shared. All adopters own some kind of transport facility, while only 70% of the non-adopters owns this.

Table 8.3: Number of implements and vehicles owned by farmers in Torodi, Niger. Percentage of farmers (n=98) is given per level

	Number of implements and vehicles					
	0	1	2	3	4	≥5
Daba	31	19	16	12	11	9
Spade	65	25	3	3	1	1
Hand-hoe	65	11	10	4	5	3
Wheelbarrow	92	6	0	0	0	0
Cart	55	38	5	0	0	0
Bike	38	55	3	1	1	0
Motorcycle	83	14	1	0	0	0

Despite the shortage of manure and agricultural equipment, all resources necessary for WSC implementation are currently available in the region. The question is whether it is economically viable to apply those resources for WSC implementation. The annual costs to implement zaï to one hectare of degraded land in the region (annual application of 3 ton manure ha^{-1} and 3-yearly digging of zaï pits), range from 105 000 to 155 000 CFA (160 to 230 EUR). Taking the average price of millet grain into account (500 CFA or 0.75 EUR per 'tiya' or 2.5 kg), an annual grain yield of 525 kg to 775 kg ha^{-1} is required to merely cover the costs. Scientific literature reports millet grain yields for zaï range between 130 and 1500 kg ha^{-1}, depending on the amount of rainfall (Fatondji et al., 2006; Roose, 1999; Slingerland and Stork, 2000). Investing in WSC techniques hence bears considerable risks. Note moreover that, even if farmers have sufficient resources, they may not be willing to adopt WSC techniques because other investments are more urgent or because retirement or migration in the near future do not make them eager to invest.

Given the high cost of manure and fertilizers and the lack of agricultural equipment external support by the government or NGOs might be required to improve WSC adoption. The region largely consists of subsistence farmers who depend on soil resources for their livelihoods and yearly rely on government funded food aid. However, food aid might hamper the adoption of WSC. Why investing in WSC to only gain little grain, while it is also donated for free.

8.3.5 Influence of a WSC project on adoption

The presence of a WSC project not only encourages adoption, as almost all adopters (91%) got acquainted with WSC techniques through a project, but it also results in better erosion knowledge and nutrient management among farmers. Being in contact with a WSC project increases the number of farmers who have a good awareness level of erosion, its effects and its causes respectively from 48% to 56%, 0% to 13% and 14% to 29% and also increases the number of farmers who fertilise their fields from 85% to 95%. Two thirds of the farmers who relate WSC techniques (Fig. 8.5) with water conservation know this through a WSC project, but also more than half of those who were part of a project do not realize the benefits of WSC for water conservation.

However, participating in a WSC project does not assure adoption. Only 30% of the farmers who participated in a project are still implementing WSC techniques. Active participation (i.e. the actual executing of WSC techniques), increases the adoption rate from 30% to 43% . Besides active participation, also long-term project presence promotes a higher WSC adoption rate. Farmers in Bogoudjotou were in contact with a long-term field trial of Niamey University, whereas farmers in Nikoye only had contact with a WSC project during one cropping season. A similar percentage of farmers got acquainted with WSC techniques through a WSC project (i.e. 63% in Bogoudjotou and 61% in Nikoye), but 33% of the population in Bogoudjotou actually practice WSC techniques in contrast to only 5% of the population in Nikoye.

Former research largely attributes low WSC-adoption rates despite project participation to a project's incentives (e.g. fertilizer, manure and equipment) in exchange for cooperation (de Graaff et al., 2008; Bizoza, 2012). When the project ends and support stops, farmers often revert to their former practices because they believe implementation without help and incentives is impossible. Another reason for the relatively low adoption rate among farmers who participated in a WSC project might be an incomplete transfer of WSC knowledge. During the project farmers often do not absorb all information concerning the indirect benefits of WSC techniques. According to Perkins et al. (2011) and Tesfaye et al. (2014) it is essential to focus on more than yield alone when promoting WSC techniques. Also the environmental awareness of farmers needs to be stimulated which is according to Bewket (2007) and Bodnár et al. (2006) the most important determinant of

WSC adoption. This awareness is best generated when farmers actively participate in a WSC project and when interest in experimentation is promoted (Corbeels et al., 2000).

8.4 Conclusion

Several constraints limit the adoption of WSC techniques in the Tillaberí region. Currently, the erosion awareness of farmers is not profound enough to fully understand the physical intervention of WSC to the eroding processes degrading their lands. Farmers furthermore lack certain key resources like manure and agricultural equipment, but do seem to dispose of the necessary labour to implement WSC techniques.

When assessing WSC adoption constraints, studies generally overlook the erosion awareness of farmers or their knowledge of WSC and its benefits. Our findings show that these are critical factors influencing adoption. Farmers in the Tillaberí region need to recognize their ability to interfere with soil erosion to safeguard their food supply, but this will require a boost of the collective environmental awareness. Widespread institutional engagement in agricultural extension of WSC techniques is therefore much needed (whether from NGOs, the government or a cooperative).

WSC-dissemination projects should not solely focus on the yield benefits of WSC techniques, but also on their indirect benefits. These projects should moreover aim at long-term presence and active participation to reduce the risk of temporary WSC adoption and should take local socio-economic factors into account. When dealing with soil erosion, it is for example advisable to pay special attention to former migratory populations, who are less acquainted with slowly evolving natural processes such as soil erosion.

Since the investment for WSC often surpasses a farmer's resources, a form of material support to enable adoption, is recommendable. However, mere access to programs in exchange of 'incentives' such as 'food for work' should be avoided, as this creates the idea of dependency on external aid to implement WSC. WSC-dissemination projects should therefore combine material support with intensive attention for the wide spectrum of benefits of WSC. With respect to material support, more efficient use of manure or alternative soil butrient management sources such as compost could be introduced and farmers could be assisted in acquiring agricultural equipment through loan systems or investment.

Besides the effect of micro-level constraints on WSC adoption, which is discussed in this chapter, a remaining question is the effect and importance of macro-level factors, such as food aid, governmental efforts for re-greening, market development, migration and decentralisation on the adoption of WSC. This should be tackled in future research.

9

General conclusion

The overall objective of this dissertation was to evaluate the biophysical and socioeconomical viability of small-scale water and soil conservation (WSC) techniques in the Tillaberí region of Niger. The evaluated WSC techniques are zaï (Z), demi-lunes (DL) and scarification (SCAR), three common WSC techniques in the region. They are compared with two conventional practices in the region, one with and one without manure application (CF and C respectively). The data presented in previous chapters provides insight into the processes of agricultural drought in the region and reveals the potential and constraints of several WSC techniques to mitigate this. Furthermore, several solutions are presented to tackle constraints related to design optimization, farmer adoption and land rehabilitation. This chapter summarizes the main conclusions and presents several recommendations for extension and future research.

9.1 Agricultural drought stress

Agricultural drought is defined as the shortage of available water for plant growth in the rootzone (Mishra and Singh, 2010; Wilhite and Glantz, 1985). It is a much-debated issue whether agricultural drought in Niger (and the Sahel) is related to meteorological drought (i.e. deficit of rainfall or unfavourable rainfall distribution) or to soil-water drought (i.e. decreased water infiltration and water-holding capacity). Worsening drought in the region is often attributed to climate-change-induced meteorological drought, whereas several rootzone water balance studies point to ongoing land degradation as a main cause for increasing soil-water drought (Mahé and Paturel, 2009; Rockström et al., 1998; Slegers and Stroosnijder, 2008). Our findings show that both meteorological and soil-water drought cause drought stress for millet production in the Tillaberí region in Niger.

9.1.1 Dry-spell-induced meteorological drought

Our long-term rainfall analysis demonstrated that total rainfall amount did not decrease in time (see Chapter 4). Worsening drought stress is hence not related to declining annual rainfall amount. However, meteorological drought stress in the region does appear to worsen due to an increasing prevalence of dry spells in the region. Currently, millet production in the study area averagely suffers three dry spells of seven consecutive days without rain each growing season. The probability to face a dry spell is moreover elevated during flowering and grain filling, when millet is most sensitive to drought stress.

9.1.2 Soil-water drought on Plinthosols

Our results showed that there is not enough water available in the rootzone for sustainable millet crop production under the conventional practices (C and CF), even if there is sufficient rainfall. Soil-water storage in the rootzone for C and CF never significantly exceeded the critical soil-water storage for drought stress in the rootzone (defined by Allen et al. (1998)). As such, the soil did not contain enough water to sustain considerable crop production and millet plants suffered soil-water drought.

Previous research in Niger contrastingly stated that soil water was not a major limiting factor for crop growth. Payne (1999) for example reported that millet did not make optimal use of the available soil water because plant growth was restrained by soil-nutrient shortage. If soil nutrients were the most limiting production factor, simply providing soil nutrients would increase millet crop production. Notwithstanding the essential contribution of nutrients for optimal plant production, our results indicate that providing manure alone does not ascertain crop production, as CF did not attain desirable grain yields (see Chapter 4).

Soil-water drought in the Tillaberí region is caused by an imbalanced partitioning of rainfall over the rootzone. For the conventional practices (C and CF) at least 25% of the rainfall amount was lost as run-off and 12% as soil evaporation (see Chapter 6). The crop water requirement is estimated at 450 mm and the long-term average total rainfall amount is 550 mm. Hence if 37% of the total rainfall amount is lost as run-off or evaporation under C and CF, water availability in the rootzone does not attain the millet crop water requirement.

The excessive run-off rate is mainly attributed to high intensity rainfall and to a poor soil structure. The soil has a structure stability index of only 3.3% as designed by Pieri (1992), a high bulk density, a low plant available water capacity (according to the critical levels proposed by Reynolds et al. (2009)) and very low hydraulic conductivities (see Chapter 5). Poor soil-structural quality also hinders root development, resulting in very shallow root depths for C (± 10 cm) (see Chapter 4). This worsens soil-water drought, as soil-water availability for plant growth not only depends on water availability in the rootzone, but also on rootzone depth.

9.2 Mitigation of agricultural drought stress by WSC

Millet suffers from increasing drought stress under the conventional practices (C and CF). Although WSC techniques are widely proclaimed to mitigate both meteorological and soil-water drought stress, this has never been scientifically verified. WSC techniques are designed to tackle drought stress in two ways, by positively altering rainfall partitioning over the rootzone and by improving physical soil properties (Liniger et al., 2011).

9.2.1 WSC effect on physical soil properties

Descriptive studies on WSC techniques attribute several improved physical soil properties to WSC techniques. According to these studies, WSC techniques improve water retention and increase water infiltration as a result of macropores formation (Fatondji et al., 2009; Roose, 1999), but these statements are based on qualitative appreciation and quantitative assessment is often lacking. None of the WSC studies in the Sahelian region have quantitatively investigated the effect of WSC on physical soil properties.

Our study demonstrates that WSC techniques did not beneficially affect physical soil properties in the short term (see Chapter 5). Although bulk density tended to decrease in the top soil (0-10 cm), there were no significant changes in hydraulic conductivity and soil porosity parameters derived from the SWRC. Given the close-to-single-grain condition of the studied soil with loamy sand texture and its very low SOC content, substantially enhancing soil structure is not straightforward. Even so, it is remarkable that the physical soil properties within the cropping areas of both Z and DL did not significantly change due to manure application. The difficulty to induce structural changes on the studied Plinthosol is largely related to the difficult SOC sequestration (see section 9.4).

Note however, that processes inducing change in soil structure are slow and beneficial effects of WSC on physical soil properties in the long term should not be excluded. The slightly higher values of θ_s for SCAR, for example, might indicate that crop residue management induced the formation of structural pores, as a consequence of termite activity.

9.2.2 WSC effect on rainfall partitioning

WSC techniques did positively alter rainfall partitioning over the rootzone. Although WSC practices did not improve the infiltration capacity of the soil, they did promote water infiltration by prolonging infiltration time by collecting run-off water. As such, run-off water losses decreased significantly, from 25% (C and CF) to less than 5% for DL and Z, and to less than 10% for SCAR (see Chapter 6).

WSC techniques also reduced water loss by evaporation, from 12% (C and CF) to 8-11% (SCAR, DL and Z), with DL having the greatest effect, followed by Z. Variation in soil evaporation between treatments only originated from variation in canopy cover. The crop residue that was left for SCAR, was expected to reduce soil evaporation by covering the soil surface, but the residue was largely blown away by the harmattan wind and those few wilted stalks that remained did not seem to cover the soil significantly (see Chapter 6).

Soil evaporation was overall lower than expected due to the self-mulching capacity of the studied soil. The topsoil was sandy and hydraulic conductivity of sandy topsoil drops drastically when it dries out, which obstructs water transmission from deeper soil layers to the soil surface, thereby preventing soil evaporation. Notwithstanding its inefficiency for evaporation reduction, crop residue management should not be discarded completely, as it slowed down run-off water (see Chapter 6), protected the soil from raindrop impact and might induce pore creation and SOC build-up in the long term (see section 9.4).

By reducing the amount of water lost as run-off and soil evaporation, WSC techniques mitigate agricultural drought stress. DL induced remarkable increases in soil-water storage throughout all growing seasons. Likewise, soil-water storage inside the zaï pits increased, though short periods of low soil-water storage prevailed in all years towards the end of the growing season (when millet is sensitive to drought stress) (see Chapter 4).

9.3 WSC effect on crop response

By promoting plant water availability in the rootzone, WSC techniques increase biomass-producing crop transpiration and enable improved crop yields. Grain yield was zero or very poor for the conventional practices (C and CF), whereas WSC techniques produced significant grain yields. Zaï pits (Z) produced the highest grain yield (up to 651 kg ha^{-1}), which was two to three times higher than grain yield produced by demi-lunes (DL) (up to 249 kg ha^{-1}) for all years and of by scarification (up to 246 kg ha^{-1}) treatment (SCAR) for 2012 and 2013.

Due to high plant densities within the DL basins, millet grain yields were surprisingly low given the remarkable increase of soil-water storage under DL. Two optimized designs (DL and DL++), with lower planting density but with higher bund density, showed great potential to increase crop yields with DL significantly (see Chapter 7). Note that millet production with these optimized DL designs might be more cost-effective than zaï pits as the installation of DL requires less labour (see Chapter 8).

Even though WSC techniques enable millet yields on Plinthosols comparable to the millet yields produced on Arenosols, which are the most fertile soils in Niger, millet yields remained overall low ($\leq$ 1 ton ha^{-1})(see Chapter 4). Moreover, grain yields showed large variation between growing seasons, while risk avoidance is of major importance to farmers. This indicates that even though WSC techniques mitigate drought stress on Plinthosols, several other production factors besides water need to be tackled in the region. On the experimental field for example, just like on the neighbouring farmer fields, millet underwent several stem borer and locust infestations. Furthermore, the growing cycle of the local variety is too long for the short rainy season (see Chapter 4) and although short duration millet cultivars exist (and made available by INRAN and ICRISAT), farmers do not seem to purchase them.

9.4 Soil rehabilitation of Plinthosols

Sustainable biomass productivity in Niger is impeded by the deterioration of the soil resource and the incessant decline in soil organic matter content (Lahmar et al., 2012; Kintché et al., 2010). Several WSC techniques have therefore been developed to rehabilitate degraded lands (Tittonell et al., 2012), but research investigating their effect on soil quality is to our knowledge, often lacking.

WSC techniques only slightly improved soil quality. In general, soil-quality monitoring involves the assessment of chemical, physical and biological soil-quality indicators. In section 9.2.1, we reported that WSC techniques did not affect the physical soil quality. The effect of WSC techniques on chemical (SOC, pH) and biological (nematode abundance) soil quality indicators will be explained in this section.

SOC content significantly increased for treatments with manure application (CF, SCAR, DL and Z), but still resulted in only suboptimal SOC levels. Soil pH was very low (pH ± 4.0) for C, but raised (to 4.2-5), following the application of manure (CF, SCAR, DL and Z), which presumably improved plant availability of essential nutrients.

The combination of considerable SOC sequestration with biomass production seems difficult. The nutrients supplied by manure lead to an improved crop production rather than to lifting SOC. In this respect, the intrinsic manure shortage in the region seems problematic (see Chapter 8). Alternative nutrient management strategies are therefore to be considered (Lahmar et al., 2012), but several authors question whether organic recourses can reverse SOC losses under continuous cultivation (Kintché et al., 2010; Rusinamhodzi et al., 2013).

WSC techniques significantly increased nematode abundance. An activated soil life is important for nutrient cycling and organic matter decomposition and could induce the formation and preservation of important biopores in the long term.

9.5 Optimizing WSC techniques

The rootzone water balance study in Sadoré, revealed several possibilities to further optimize crop water management of zaï and demi-lunes, the two most-promising WSC techniques in the Tillaberí region of Niger.

9.5.1 Zaï

Millet plants produced in zaï pits seem to encounter drought stress near the end of the growing season during flowering and grain filling. Since millet plants are very sensitive to drought stress, grain yields for zaï can most likely be increased by applying only little supplemental irrigation when rain events fail at the end of the growing season. Water for supplemental irrigation could either be collected from nearby ponds (if these are not overexploited for animal and domestic use) or from water harvested from rooftops (this demands installation of corrugated roofs). Supplemental irrigation can also be applied throughout the growing season when long-lasting dry spells prevail and soil-water storage in the rootzone drops below the critical level for drought stress. The impact of supplemental irrigation on millet yield production with zaï should be further investigated.

9.5.2 Demi-lunes

The demi-lunes at the experimental field were installed according to the design of Zougmoré and Ouattara (2004), but the planting density within the DL appeared to high. Grain yields for DL were relatively low despite the remarkable increase of soil-water storage due to the high planting density within the DL basin. In addition, a ponding effect induced water loss to drainage beyond the rootzone. An optimization of the DL design was hence warranted.

According to the results obtained with a coupled surface/subsurface hydrological model (see Chapter 7), the original spacing of demi-lunes can be improved by decreasing the distance between bunds on the contour level from 2 m to 1 m and by decreasing the distance between two successive DL bund lines from 4 m to 3 m. Higher DL bund density reduced run-off water loss and increased soil-water storage.

Crop response results in Chapter 4 moreover demonstrated that decreasing the number of plants within one DL basin from 24 to 18 and 12 plants did not affect grain yield per bund. Hence, if for the optimized DL design only 16 plants ha^{-1} are sown within the cropping area of one bund instead of 24, millet crop yield is expected to increase significantly for the typical planting density of 10000 plant pockets ha^{-1}, given the higher number of DL bunds per surface area.

9.5.3 Improving physical soil properties

Physical soil properties did not improve under current WSC techniques and structural changes related to elevated SOC contents seem difficult (at least in the short-term), not only because organic resources are scarce, but also because SOC accumulation in a loamy sand soil remains limited. Hence, in order to improve water household of Plinthosols, soil structural enhancement needs to be stimulated differently. This can possibly be achieved by increased soil organism activity and by the gradual decomposition of roots, as this creates important macropores. Root decomposition and increased soil life can be attained by combining WSC techniques with regenerated shrubs (NEWS). The roots of these shrubs create macropores, while leaves and twigs can be used as mulch. The impact of the combination of WSC with NEWS on soil quality, water household and crop response should be further investigated.

9.6 Adoption constraints

WSC techniques have been widely promoted, but their dissemination encounters difficulties. A number of studies investigated the factors that influence their adoption (Ouédraogo and Bertelsen, 1997; Slingerland and Stork, 2000; Sidibé, 2005). Most of these studies focus on the resource availability of farmers to explain adoption constraints and pay only little attention to vital adoption factors concerning erosion awareness and knowledge of WSC techniques.

According to our findings, the erosion awareness of farmers in the Tillaberí region is not profound enough to fully understand why and how soil erosion should be tackled. Furthermore farmers are aware that WSC techniques exist an that they result in yield increase, but they are not aware of the indirect benefits related to WSC techniques (see Chapter 8).

In addition, farmers lack certain key resources like manure, agricultural equipment and transport facilities to implement WSC techniques. Although crop production in the region has a subsistence nature, a simplified cost-benefit analysis showed that investing in WSC bears considerable investment risks when only millet grain yield is taken as a benefit (see Chapter 8).

Even if farmers would perceive soil rehabilitation as a benefit in addition to increased grain yield, the findings in Chapter 5 suggest that they should sustain their efforts in the long term in order to improve soil quality of a Plinthosol. It is known that farmers do not easily adopt strategies that demand long-term sustained efforts of resources, labor requirement and knowledge acquisition, if they only generate little revenues on the short term (Tittonell et al., 2012). Institutional engagement in education and resource support to disseminate WSC techniques, whether from the state or from NGOs, seems in this respect inevitable.

9.7 Recommendations for WSC extension

Since 96% of the farmers in our study area do not produce enough food to sustain their family year-round (see Chapter 8), our study supports the pledges of the main food security reports (Cockburn, 2012; De Schutter, 2010) to concentrate on increased productivity of small-scale, subsistence farmers in Niger to tackle food insecurity. According to our findings, restoring degraded land, as recommended by 'World Vision' (Rinaudo and Yaou, 2009) (see Chapter 3) is a rational approach to do this. As a result of the fast population growth, fertile land has become a key constraint for food production in the region and the great majority of farmers do not have access to sufficient fertile land (see Chapter 8). We moreover demonstrated that WSC techniques successfully tackle the water constraint on Plinthosols and produce millet yields comparable to the ones obtained on 'fertile' Arenosols in the region. In addition, WSC tackles communal consequences of land degradation by averting excessive run-off that causes inundations and damage to roads and other infrastructure (see Chapter 6).

Our findings have shown that successful WSC dissemination without external intervention will be difficult due to the considerable investment risk. The presence of a WSC project encourages WSC adoption and also results in a general better understanding of interaction between natural resource management and agricultural production (see Chapter 8). Based on the findings in this dissertation, we recommend to consider the following issues when organizing dissemination:

- **Planting density inside the cropping area of demi-lunes (or any other WSC technique) should remain limited.**
  Earlier studies on demi-lunes (Zougmoré et al., 2003), as well as technical information distributed by INERA (Zougmoré, 2000), recommend a planting density of approximately 25 plant pockets within the DL cropping area. This planting density is, according to our findings, to high. High planting density induces competition for light and nutrients between plants and suppresses the tillering capacity of millet. Tillering is one of the attributes of millet that allows 'natural' mitigation of drought stress (see Chapter 3). Since millet suffers less from competition and tillers more at lower planting density, similar yields per DL basin are achieved when only 12-18 plants in stead of 25 plant pocket per DL basin are sown (see Chapter 4).
- **A higher number of demi-lunes per surface area than suggested by Zougmoré and Ouattara (2004) should be applied.**
  According to our results obtained with the coupled surface/subsurface hydrological model, the original spacing of demi-lunes, as suggested by Zougmoré and Ouattara (2004) can be improved by decreasing the distance between bunds on the contour level from 2 m to 1 m and by decreasing the distance between two successive DL

bund lines from 4 m to 3 m. Increasing DL bund density reduces run-off and increases soil-water storage in the rootzone. The higher DL bund density moreover allows a lower planting density (16 plants ha^{-1}), while containing the typical planting density of 10000 plant pockets ha^{-1}.

- **Supplemental irrigation might secure grain yields of millet plants in zaï pits towards the end of the growing season and during severe dry spells.**
  Grain yields of millet for zaï might be optimized by applying small amounts of water when soil-water storage drops beneath the critical level for drought stress towards flowering (see Chapter 4). In view of the increasing prevalence of dry spells (see Chapter 4), supplemental irrigation during dry spells can improve the technique's resilience to more frequent meteorological droughts.
- **Combine WSC techniques with other soil rehabilitating measures like the regeneration of shrubs or crop rotation with leguminous crops.**
  A higher dose of manure than the optimal annual application rate of 3 ton ha^{-1}, as suggested by Fatondji et al. (2006), is needed if one wishes to attain accumulation of soil organic matter in combination with high crop productivity. However, manure and organic resources are limited in the Tillaberí region and it is not straightforward to significantly uplift the soil organic matter content of Plinthosols. Land rehabilitation might be facilitated by crop rotation and intercropping with shrubs and leguminous crops are applied (see Chapter 5). Since crop rotation is one of the three key principles of Conservation Agriculture (CA), the recommendation of 'World Vision' to 'include aspects of CA in hard pan rehabilitation' is hence justified (Rinaudo and Yaou, 2009) (see Chapter 3).
- **WSC projects should not only provide resource incentives. They should include specific education on soil management.**
  Some material support might be necessary to tackle the adoption constraints related to resource availability. However, merely exchanging incentives like fertilizer, manure and equipment (or food, like 'food for work') for participation in WSC projects often results in temporary adoption, as farmers believe that continuing WSC implementation without external support is impossible. WSC projects should therefore combine material or financial support with intensive motivation of the wide spec-

trum of benefits of WSC techniques through specific education on soil management. It is essential that farmers recognize their ability to interfere with soil erosion in order to safeguard their subsistence food (see Chapter 8).

- **WSC dissemination should include hands-on implementation to ensure long-term adoption.**

  Active participation triggers a detailed follow up of the feasibility and multiple benefits of WSC (see Chapter 8). Chances of long-term adoption moreover increase when farmers' interest in experimentation is stimulated (Corbeels et al., 2000).

9.8 Future perspectives

This dissertation provides new insights into the processes causing agricultural drought in the Tillaberí region of Niger. Additionally, the effect of several WSC techniques (SCAR, DL, Z) on crop yields, rainfall partitioning over the rootzone and soil quality was assessed and the main constraints for adoption were identified. While studying this, many issues in need of further clarification were revealed. A general concern that arose, was the issue of family planning. The enormous growth of a resource-poor population, together with the severe land scarcity and the limited availability of organic residues makes sustainable crop production in combination of land rehabilitation difficult. Any effort to improve food security will therefore only attain limited success if population pressure is not tackled. Furthermore, following specific aspects need further investigation.

- **Investigating the possibility and effects of the integration of WSC techniques with other agricultural technologies.**

  WSC techniques are integrated strategies to upgrade the farming system in Niger. This dissertation focused on the effect of WSC on water and nutrient management, but we found that including several other research fields with their own specific research questions would be beneficial. In our opinion WSC is best evaluated by research that integrates a.o. socio-economics, phytopathology, plant science, hydrology, land evaluation and soil management. For example, the effect of changing soil quality on soil pests or the influence of large scale WSC application on river hydrology should be assessed in a similar study, and more productive varieties with higher crop water requirements should be tested in combination with WSC techniques.

- **Assessing the effect of WSC techniques on the crop response of other crops and trees than pearl millet.**

  When aiming at profit, millet production with WSC techniques contains a significant investment risk for an independent farmer (see the simple cost-benefit analysis in Chapter 8). The risk for crop failure or poor production due to severe drought remains, while market prices for millet are very low. Other crops with higher market prices, could justify the investment cost and generate a higher profit. Crops like groundnut or cowpea, e.g. could be tested in rotation with pearl millet (see Chapter 5).

- **Assessing the impact of upscaling WSC techniques on watershed level.**

  Our results have shown that run-off is significantly reduced under WSC techniques. This replenishes green water resources by limiting flows to blue water resources and creates, depending on the watershed, positive or negative downstream effects (see Chapter 6). Upscaling of WSC to assess impacts on watershed hence remains a major research need.

- **Estimating the transferability of WSC techniques to changing biophysical and meteorological conditions.**

  A remaining question is whether WSC techniques will continue to mitigate drought stress if both meteorological drought (increasing occurrence of dry spells) and soil-water drought (ongoing land degradation) worsen. With the aid of hydrological modelling, the impact of WSC techniques under different meteorological conditions with varying soil properties could be simulated. A significant constraint for such study is the lack of extensive soil and meteorological databases in the region. In this respect it is also valuable to investigate the added value of combining WSC techniques with supplemental irrigation.

- **Quantifying the effect of alternative soil rehabilitation strategies on chemical, physical and biological soil quality parameters.**

  Just like WSC techniques, many alternative land management practices are proclaimed to rehabilitate degraded land. However, the effect of these techniques on soil-quality indicators has never been scientifically quantified. Specifically for soil rehabilitation of Plinthosols, soil-quality assessments of the regenerated shrub system (NEWS) and crop rotation are needed. Furthermore the feasibility of generating compost as organic residue source should be investigated. When assessing system effects on soil quality, soil crust evaluation should moreover be included.

- **Understanding the effect and importance of macro-level factors on WSC adoption.**

  With respect to adoption constraints, an important remaining question is the effect and importance of macro-level factors, such as food aid, governmental efforts for re-greening, market development, migration and decentralization on the dissemination of WSC.

Summary

Rainfed agriculture is the dominant source of food in dryland Africa countries and is practiced on approximately 95% of the agricultural land. Due to growing population pressure, Nigerien subsistence farmers increasingly rely on marginal lands (Plinthosols), locally called 'gangani' or laterite soils, but these generally produce little or no yields. The two major limiting factors for crop production on these soils are an imbalanced partitioning rainfall over the rootzone and a very poor soil quality with limited soil fertility.

Increasing food production to match growing demands therefore calls for innovative practices that improve crop production, while rehabilitating the Nigerien water and soil resources. This can be achieved with the aid of water and soil conservation (WSC) techniques which combine improved soil fertility management with the optimization of the rootzone water balance.

Many studies revealed promising results on yield increases with WSC techniques, but little is known about the overall impact of WSC. There is a lack of scientific verification of the impact of WSC on the rootzone water balance, the impact of WSC on soil quality and the adoption constraints that prevent farmers from implementing WSC techniques.

The overall objective of this dissertation is to evaluate the biophysical and socio-economic viability of small-scale water and soil conservation (WSC) techniques in the Tillaberí region of Niger.

Following specific objectives were therefore investigated:

- gain insight into the mechanisms behind the occurrence of drought by characterizing; agricultural, meteorological and soil-water drought;
- evaluate the potential of small-scale WSC techniques (Z, DL and SCAR) in mitigating drought stress by evaluating crop response and monitoring soil-water content during the cropping season;
- evaluate the soil rehabilitating capacity of small-scale WSC techniques (Z, DL and SCAR) by monitoring their impact on physical, chemical and biological soil quality parameters;
- quantify water loss caused by imbalanced rainfall partitioning over the rootzone and evaluate the effect of WSC techniques (Z, DL and SCAR) through assessment of surface run-off, evaporation, transpiration, deep percolation and storage of water in

the rootzone;

- optimize WSC design with a coupled surface/subsurface hydrological model that simulates the hydrological behaviour of a small-scale WSC technique; and
- better understand why farmers in the study area do not adopt small-scale WSC techniques on a larger scale.

In order to monitor the WSC techniques a Plinthosol in Sadoré village, Niger, in cooperation with the department of Natural Resource Management, INRAN (Niger National Institute for Agronomic Research). The field experiment was laid out according to a randomized block design with five treatments and three replicates. The treatments include:

- control (C): this is a conventional practice in the Tillaberí region. No manure was added and no land preparation was applied;
- control with manure, which is locally referred to as 'fumier' (CF): this is a conventional practice in the Tillaberí region, but with cattle manure application (described below). No land preparation was applied;
- scarification (SCAR): Furrows of 0.05 to 0.07 m depth and 0.10 m width were made parallel to the slope with a distance of 1 m. Cattle manure (similar to CF) was mixed within the furrow with the loosened top soil. Stubble was not harvested and left on the field after harvest to cover the soil year round;
- demi-Lunes (DL): this WSC technique consists of installing earth bunds parallel to the contour line. The earth bunds, also known as half moon-shaped bunds, were installed according to the design of Zougmoré et al. (2003). Manure was mixed with the top soil (similar to CF); and
- zaï (Z): this is an indigenous Sahelian WSC technique which consisted of digging pits of ± 0.3 m diameter and 0.15 m depth during the dry season, in which the same amount of manure as for CF was applied.

This field experiment was monitored during three rainy season (2011-2013). The rainy season of 2011 was characterized by a low total rainfall amount (417 mm), whereas total rainfall amount in 2012 (687 mm) and 2013 (615 mm) was above average (550 mm).

A long-term rainfall study showed that millet does not suffer increasing drought stress due to decreasing annual rainfall amount. However, other daily rainfall parameters more important for crop biomass productivity than total rainfall amount, such as number of dry spells, do cause increasing drought stress for millet production. Besides Meteorological drought, the region also suffers soil-water drought. Grain yields for the conventional practices (C and CF) are extremely low and soil-water storage in the rootzone remains below the critical value for drought stress, even if there is sufficient rainfall.

WSC techniques, on the other hand, successfully mitigate drought stress. WSC increases grain yields to 700 kg ha^{-1} for Z and to 250 kg ha^{-1} for DL and SCAR. By applying WSC, soil-water storage increases above the critical value for drought stress. This is mainly a result of significant run-off reduction under WSC (i.e. from approximately 25% for C to 5-10%). WSC techniques were, on the other hand, found to have only little impact on soil evaporation, which was limited (i.e. 12%) due to the self mulching capacity of Plinthosols.

Soil quality analysis showed that, SOC increased significantly after three growing seasons for the treatments provided with manure (CF,SCAR, DL and Z), from ± 2.5 to ± 5 g kg^{-1}, but the increase was lowest for Z, which produced highest yields. Combination of optimized plant production with SOC sequestration seemed difficult. Alternative integrated management strategies which combine WSC with other biomass producing practices should therefore be investigated. WSC techniques do not improve physical soil quality on the short term, but did significantly improve biological soil quality.

Soil-water storage was highest for DL, but the spacing of DL bunds was not water use efficient and high planting density within the cropping area of the basin seemed to restrain good yield production. To solve this, the optimization of DL design was tested with a three-dimensional coupled surface-subsurface soil hydrological model. Two optimized designs with higher DL density were tested (DL + and DL ++). Although the model did not succeed in very accurately simulating the water dynamics of the WSC system, the model did produce logical outputs. According to the results, the optimized designs improved rainfall partitioning over the rootzone, resulting in higher biomass production.

A socio-economic study showed that WSC adoption in the study area is mainly hampered by manure shortage and a lack of erosion knowledge. Most farmers have little awareness of erosion, its causes and effects.

Samenvatting

Voedselproductie in de Afrikaanse ‘drylands’ is grotendeels afkomstig van kleinschalige en regenafhankelijke landbouw. Door terugkerende droogtes en de degradatie van de land- en waterreserves, produceren de huidige landbouwsystemen onvoldoende voor de snel groeiende bevolking. In Niger lanceerde de overheid daarom in 2011 het 3N-initiatief (Nigeriens Nourishing Nigeriens), een programma dat de groei van de nationale voedselproductie ondersteunt en voor Nigerese voedselsoevereiniteit moet zorgen.

Innovatief land- en waterbeheer is essentieel om een adequate voedselproductie te verzekeren in Niger. Een groot deel van de boeren is aangewezen op marginale landbouwgronden (Plinthosols) die lokaal lateriet of gangani worden genoemd. Deze gedegradeerde gronden produceren weinig tot geen graan omdat ze kwetsbaar zijn voor droogtes. Door de beperkte bodemkwaliteit wordt het regenwater slecht verdeeld over de wortelzone en is er een nutriëntentekort voor plantgroei. Verschillende studies toonden reeds aan dat water- en bodemconserveringstechnieken (WSC) hogere graanopbrengsten mogelijk maken. De technieken creëren optimale omstandigheden voor plantgroei in de wortelzone door verhoogde bodemvruchtbaarheid te combineren met regenwatercaptatie. Voor een grootschalige implementatie is er momenteel nog te weinig bekend over de precieze impact van WSC technieken. Zo is er nog onvoldoende informatie over hun hydrologische impact, hun impact op de bodemkwaliteit en de socio-economische factoren die de adoptie van de technieken beïnvloeden.

Deze studie heeft daarom als hoofddoel de bio-fysische en socio-economische haalbaarheid te evalueren van verschillende WSC technieken in Niger. De specifieke doelstellingen zijn daarbij:

- de oorzaken van droogtestress bij parelgierst (*Pennisetum glaucum* (L.) R. Br.) identificeren en het potentieel evalueren van verschillende WSC technieken om droogtestress te verhindren;
- het effect bestuderen van WSC technieken op de verdeling van regenwater over de

wortelzone;

- de impact bestuderen van WSC technieken op de fysische, chemische en biologische bodemkwaliteit;
- de werking van WSC technieken optimaliseren met behulp van een hydrologisch model; en
- de socio-economische factoren bepalen die de adoptie van WSC technieken beïnvloeden.

Om de impact van de verschillende WSC technieken op de waterbalans en de bodemkwaliteit te bestuderen, werd samen met het INRAN (Nationaal onderzoeksinstituut voor landbouw in Niger) een veldproef opgezet in het dorp Sadoré in Niger. Hiervoor werd een waterbalans experiment geïnstalleerd volgens een gerandomiseerde blokkenproef met vijf behandelingen en drie herhalingen. Volgende vijf behandelingen werden bestudeerd:

- controle (C): deze behandeling reflecteerde de lokale gangbare praktijk. Voor deze behandeling werd geen stalmest toegediend en de bodem werd niet bewerkt. Tijdens het zaaien werden enkel kleine putjes gegraven die na de toediening van de zaden terug toegemaakt werden;
- controle met mest (CF): deze behandeling verschilde enkel van C door een jaarlijkse toediening van mest (3 ton stalmest ha^{-1}) enkele weken voor het zaaien. De mest werd telkens toegediend in een cirkel met een diameter van 0.3 m rond de plaats waar later gezaaid zou worden;
- scarification (SCAR): voor deze behandeling werden twee van de drie hoofdprincipes van conserveringslandbouw toegepast, permanente bodembedekking en minimale bodemverstoring. Gedurende elk droogseizoen werden smalle (0.1 m) en ondiepe (0.05 - 0.07 m) geulen gegraven waarin net als bij CF elk jaar enkele weken voor het zaaien mest werd aangebracht. Verder werd na de oogst het graanstoppel op het veld achtergelaten, waardoor de bodem gedurende het verdere jaar gedeeltelijk bedekt bleef;
- demi-Lunes (DL): de halfmaanvormige dijken werden bij de aanleg van het proefveld geïnstalleerd. Hiervoor volgden we de richtlijnen van Zougmoré et al. (2003). De dijken hadden een diameter van 4 m en werden op de contourlijn 2 m uiteen geplaatst terwijl de afstand tussen twee opeenvolgende rijen dijken 4 m bedroeg. In het bassin waar elk jaar parelgierst gezaaid werd, werd net als bij SCAR en CF jaarlijks mest toegediend; en
- zaï (Z): voor deze behandeling werden bij aanleg van het proefveld zogenaamde zaï-

putten gegraven. Hiervoor volgden we de richtlijnen van Fatondji et al. (2006). De putten hadden een diameter van 0.25 m en een diepte van 0.15 m. Elk jaar werd net als voor CF, SCAR en DL mest in de putten toegediend waarin later de zaden konden geplaatst worden.

Deze veldproef werd gedurende drie regenseizoenen (2011-2013) opgevolgd. De totale hoeveelheid neerslag in 2011 lag lager (417 mm) dan het jaarlijkse gemiddelde (550 mm), terwijl het in 2012 (687 mm) en 2013 (615 mm) hoger lag. De neerslagverdeling werd in 2011 en 2013 gekenmerkt door verschillende droogteperiodes.

Aan de hand van een studie van de regenval op lange termijn, toonden we aan dat de totale jaarlijkse neerslaghoeveelheid niet vermindert. Toenemende droogtestress in het studiegebied is dus niet gerelateerd met een dalende totale neerslaghoeveelheid. De verdeling van de neerslag over het seizoen, echter, verandert volgens onze resultaten wel in de tijd. Het aantal droogteperiodes per regenseizoen stijgt, waardoor parelgierst gedurende korte of lange periodes ernstige droogtestress ondervindt en weinig tot geen graan produceert. Naast meteorologische droogte, veroorzaakt door droogteperiodes, is er volgens de resultaten van onze waterbalans studie, ook sprake van bodemwater droogte. Voor C en CF, de gangbare behandelingen, ligt het volume bodemvocht in de wortelzone niet enkel tijdens de droogteperiodes, maar gedurende het grootste deel van het jaar onder de kritische waarde voor droogtestress bij parelgierst. Dit wil zeggen dat de parelgierst onder C en CF droogtestress ervaart, zelf als er voldoende regen valt. Hierdoor was de graanopbrengst voor zowel C als CF voor de drie regenseizoenen nagenoeg onbestaande.

Door de toepassing van WSC technieken werd parelgierst voor een groot deel van droogtestress gevrijwaard, het bodemvocht steeg significant boven de kritische waarde doorheen het regenseizoen. Hierdoor namen graanopbrengsten toe tot 700 kg ha^{-1} voor Z en tot 250 kg ha^{-1} voor DL en SCAR. Het hogere gehalte aan bodemvocht voor WSC is vooral het resultaat van minder waterverlies via run-off. Het volume water dat verloren ging als run-off werd gereduceerd van 25% voor C tot 11 % voor SCAR en tot 5% voor DL en Z. WSC technieken hadden geen groot effect op evaporatie (bodemverdamping). Vooral omdat de verliezen door evaporatie onder C en CF minder groot waren dan verwacht door de ‘zelf-mulchende’ eigenschap van de bodem.

Uit de analyse van de bodemkwaliteit bleek dat na drie regenseizoenen de hydraulische eigenschappen van de bodem niet verbeterden onder WSC. De reductie van run-off was dus niet het gevolg van betere waterretentie en betere infiltratiecapaciteit zoals eerder vermeld werd in de literatuur. De chemische bodemkwaliteit daarentegen, verbeterde wel door de toepassing van stalmest bij CF, SCAR, DL en Z. Het gehalte aan organisch materiaal steeg significant voor alle behandelingen met mest. De stijging bleek echter miniem voor Z. Mogelijks induceerde de hogere biomassaproductie onder Z een hogere activiteit van bodemorganismen die het organisch materiaal afbraken. De cominatie van een hoge biomassaproductie met een hoger SOC gehalte blijkt dus niet vanzelfsprekend op deze gedegradeerde gronden. Om deze combinatie toch mogelijk te maken, zou de toediening van stalmest in de toekomst aangevuld moeten worden met alternatieve technieken.

Hoewel Z de hoogste opbrengst produceerde, resulteerde DL in de hoogste bodemvochtgehaltes. Hieruit werd afgeleid dat het aantal DL per oppervlakte eenheid vermoedelijk te laag was en dat de plantdichtheid in het bassin van een DL te hoog was. Om dit op te lossen werd met behulp van het hydrologisch model Hydrogeosphere onderzocht hoe het DL-design geoptimaliseerd kon worden. Op basis van de veldmetingen kon het hydrologisch model gekalibreerd worden, waarna simulaties het effect van design optimalisaties op de waterbalans konden voorspellen. De resultaten van de voorspellende simulaties tonen aan dat een hoger aantal DL per oppervlakte eenheid de verdeling van regenval over de wortelzone en de biomassaproduction kunnen verbeteren.

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2012 Advanced academic English writing skills, UCT Gent, certified
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