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Hydrologic Relations Between Native Woody Shrubs and Food Crops in the Peanut Basin, Senegal

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Hydrologic Relations Between Native Woody Shrubs and Food Crops in the Peanut Basin, Senegal

A Dissertation submitted in partial satisfaction of the requirements
for the degree of Doctor of Philosophy

in

Environmental Systems
(Soil Physics)

by

Nathaniel Alexander Bogie

Committee in charge:

Professor Teamrat Afewerki Ghezzehei, Chair
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2016

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2016

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University of California, Merced, 2016
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Hydrologic Relations Between Native Woody Shrubs and Food Crops in the Peanut Basin, Senegal

Abstract

The Sudano-Sahel is prone to frequent shortages of food supply. Agricultural productivity in this region is severely limited by soil degradation, desertification, and highly erratic rainfall patterns. The single most limiting factor for agricultural production in the Sudano-Sahel is water supply to the crop rooting zone. As the population increases, so too does pressure on the already marginal farmlands, and drought can have devastating effects. Agricultural practices that provide adequate nutrient and water supplies while maintaining crop yields and land conservation are urgently needed in the region. Local knowledge and prior research indicate that intercropping with the native woody shrubs *Guiera senegalensis* and *Piliostigma reticulatum* can increase crop yields by over 250% and avert drought induced crop failure. An important feature of these native shrubs is their ability to lift water from deep moist soil and redistribute it into shallow, dry soil. The goal of this study is to provide quantitative and mechanistic understanding of the effect of the native shrubs on water and nutrient availability to crops, and how the crops respond physiologically to being grown near shrubs. Prior work in the Peanut Basin has shown that planting food crops within the rooting zone of native woody shrubs has the potential to provide increased nutrients, water resources, and harvest yields compared to crops planted on bare soil. These shrubs are among the few plants in the region able to maintain photosynthesis even during periods of extreme drought. The specific research questions addressed here are how shrubs can affect the growth and vigor of crops during the growing season, how the presence of shrubs and their biomass have affected soil physical properties over ten years, and whether shrubs performing hydraulic redistribution provide water to nearby crops under drought stress conditions. The sites of Keur Matar Arame and Nioro Du Rip in the Central and Southern

Peanut Basin in Senegal have been under management since 2003 with a rotation of peanut (*Arachis hypogea*) and pearl millet (*Penisetum glaucum*) intercropped with native shrubs. In order to investigate the effect of ten years of biomass addition on soil properties, surface infiltration rate, hydraulic conductivity and water retention were measured on samples from the two fields. At a site with *G. senegalensis* the surface infiltration rate was 75% higher in the absence of shrubs than in plots with shrubs. At the Southern site crops planted alone had surface infiltration rates that were 28% higher than plots with intercropped *P. reticulatum* shrubs. Additionally soil moisture, transpiration rate, crop growth and physiological data were collected in the field during the growing seasons of 2012 and 2013 peanut and millet were grown, respectively. This dissertation shows that shrubs help protect shallow soil layers early in the season from potentially deadly drought and heat and despite lower soil moisture content at the end of the season, crops grown in association with shrubs have increased biomass production and a faster development cycle. At Keur Matar the presence of shrubs can increase plant available water in the shallow zones in the early season by up to 14%. Additionally, at Keur Matar the shrubs moderate the temperature in the early part of the season by keeping daily maximum temperature 5°C cooler in the crop+shrub treatment. At Nioro the results showed decreased moisture content in the crop+shrub treatment compared to the crop only treatment at 10 cm depth, but an increase of moisture of 18-20% of plant available water at 20 cm depth in the crop+shrub plot compared to the crop only. The temperature differences were less pronounced at Nioro with the daily maximums were 0-5°C cooler in the crop+shrub plot than in the crop only. Under irrigation in 2014 an isotopic tracer study investigating hydraulic redistribution was carried out by injecting deuterium-enriched water into the roots of three shrubs at one-meter depth and sampling shrubs and nearby crops for isotopic analysis of plant water. Deuterium enriched water was found in the crops of all three plots with δD in the crop tissue over 300‰. This provides strong support of the idea that water is lifted from >1 m by the shrubs and that the crops take advantage of some of this water. By keeping the rhizosphere hydrated hydraulic redistribution by the shrubs may be one way that shrubs can help crop roots avoid mortal desiccation under drought conditions. Using even the limited resources that farmers possess, this agroforestry technique can be expanded over wide swaths of the Sahel.

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My UCM colleagues Ammar Albalasmeh, Chelsea Arnold, Thomas Gebrenegus, Mathew Jian, Samuel Araya, Rebecca Abney, Ryan Lucas, Alisa Keyser, Melissa Thaw, and Lixia Jin were always around to share a cup of coffee, answer a question, or help with a favor. None of the field work would have been possible without the amazing PIRE team of Senegalese colleagues and mentors: Roger Bayala, Ibrahima Diedhiou, Bassirou Sine, Moussa Dione. I also want to thank Roger and Ibrahima for being such gracious hosts to me and all of the visiting students while we were in Senegal. Additionally, though I never met him, I want to thank Dr. Modou Sene of ISRA for his pioneering work in soil physics in the Peanut Basin. I also want to thank the farmers Saliou Diouf and the Diouf family, and Biram Bessane, and the Bessane family, as well as farmers in the villages around Nioro du Rip and Keur Matar who worked hard in the fields and graciously shared their knowledge and expertise. There are many people to thank who toiled under difficult field circumstances to support the success of the project including the field technicians at ISRA. I also want to thank all of the students who helped on the project: Ashia Burns, David Bethel, Thaddeus McCants, Mame Balla Ndiaye, and Boubacar Badji for all of their help and support. Additionally I would like to thank the PIRE students, Matt Bright, Chelsea DeLay, Sidi Diakhate and Spencer Debenport for their good company and help in Senegal.

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2015	First Place, UC Merced GradSlam Three minute dissertation competition	$2000
2015	UC Merced Representative, UC Office of the President GradSlam Finals three minute dissertation competition	
2015	Bobcat Fellowship, UC Merced	$6000
2011-2014	NSF Partnership for International Research and Education (PIRE) Ph.D. Fellowship in Tropical Rhizosphere Hydrology	Three years of graduate tuition, salary, and research support.
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Professional Experience:

2010-2011 **Geologist**. Characterized rock cuttings, prepared engineering borehole logs, ran rig IT and realtime data acquisition during geothermal drilling activities. *ThermaSource. Healdsburg, California.*

2009 **Hydrologic Technician.** Collected quantitative geomorphic data on forest road features and entered them into a GIS land stability and stream sediment load model. *US Forest Service. Emmett Ranger District, Idaho.*

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Subsurface Hydrology (UCM)
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Publications:

List of Published abstracts:

1. Bogie, N.A., Bayala, R., Diedhiou, I., Ghezzehei, T.A., Dick, R.P., Fogel, M. Isotopic Tracer Study of Hydraulic Transfer Between Native Woody Shrubs and Associated Annual Crops Under Dry Conditions in the Sahel. European Geosciences Union General Assembly, Vienna, 2015. *(Oral)*

2. Ghezzehei, T.A., Albalasmeh, A.A., Bogie, N.A. Plant roots can actively regulate hydraulic redistribution by modifying the hydraulic properties of the rhizosphere using exudates, European Geosciences Union General Assembly, 2015.

3. Ghezzehei, T.A., Albalasmeh, A.A., Bogie, N.A. Hydrodynamics of the Rhizosphere: How Roots Modulate Flow and Transport Properties in their Immediate Environment, SIAM Conference on Mathematical & Computational Issues in the Geosciences, Stanford CA, 2015.

List of Manuscripts in preparation:

1. Bogie, N.A., Bayala, R., Diedhiou, I., Ghezzehei, T.A., Dick, R.P., Fogel, M. Effect of Intercropping With Native Shrubs on Soil Physical Properties in the Peanut Basin, Senegal.

2. Bogie, N.A., Bayala, R., Diedhiou, I., Ghezzehei, T.A., Dick, R.P., Fogel, M. Hydraulic Redistribution and Transfer from Native Woody Species to Annual Crops Using an Isotope Tracer in the Peanut Basin, Senegal.

3. Bogie, N.A., Bayala, R., Diedhiou, I., Ghezzehei, T.A., Dick, R.P. Field Measurements of Soil Moisture and Evapotranspiration Dynamics Under an Intercropped System of Native Woody Shrubs and Annual Crops in the Sahel.

Non-Referreed Publications:

1. Bogie, NA, Native Shrubs: a Simple Fix for Drought-Stricken Crops in Sub-Saharan Africa, The Conversation, September 17, 2015.

2. Bogie, NA, Setting yourself up for Success: Planning and Executing Field Campaigns far from Home, CSA News Magazine, 60:36-37, 2015. doi:10.2134/csa2015-60-11-14

Conference Abstracts:

1. Bogie, N.A., Bayala, R., Diedhiou, I., Dick, R.P., Ghezzehei, T.A. Lateral Hydraulic Redistribution by Native Woody Shrubs in a Sahelian Agro-Ecosystem. AGU Fall Meeting, 2014: *(Poster)*

2. Bogie, N.A., Bayala, R., Diedhiou, I., Dick, R.P., Ghezzehei, T.A. Scaling Up the Effect of Intercropping with Native Woody Shrubs From Plot Region in the Peanut Basin Senegal. SSSA Annual Meetings, 2014. *(Poster)*

3. Bogie, N.A., Bayala, R., Badji, B., Diedhiou, I., Dick, R.P., Ghezzehei, T.A. Increased Crop Yields and Differing Soil Properties as a Result of Two Native Shrubs in the Peanut Basin, Senegal. LBNL Complex Soil Systems Conference, 2014. *(Poster)*

4. Bogie, N.A., Bayala, R., Badji, B., Diedhiou, I., Dick, R.P., Ghezzehei, T.A. Effects of Native Woody Shrubs on Crop Growth In the Peanut Basin, Senegal. W-2188 Project meeting: Characterizing Mass and Energy Transport at Different Vadose Zone Scales, 2014. *(Oral)*

5. Bogie, N.A., Bayala, R., Burns, A., Diedhiou, I., Dick, R.P.,Ghezzehei, T.A. Crop Water Stress Reduction Due to The Effects of Native Woody Shrubs in the Peanut Basin, Senegal. AGU Fall Meeting, 2013. *(Poster)*

6. Bogie, N.A., Bayala, R., McCants, T., Bethel, D., Diedhiou, I., Dick, R.P.,Ghezzehei, T.A. Beneficial Hydrologic Relations Between Evergreen Woody Shrubs and Food Crops in the Peanut Basin, Senegal. AGU FallMeeting, 2012. *(Poster)*

7. Bayala, R., Diedhiou, I., Bogie, N.A., Dick, R.P., Ghezzehei, T.A. Influence of Two Native Shrubs and Fertilizer on Crop Growth and Yield in Peanut Basin of Senegal. SSSA Annual Meetings, 2014. *(Poster)*

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CHAPTER 1

General Introduction

1.1. Background

The word Sahel derives from the Arabic *Sahil* which means sea shore or border and represents the zone of transition between the arid Sahara Desert in the North and the more humid Sudanian Zone in the South. If one could consider the Sahel a coastline of sorts, then the hot, dry Harmattan winds that blow from the Sahara would be the low tide, and the humid monsoon bringing the rains from the South would be the high. As with the tides, the arrival time and magnitude of the monsoon in the Sahel varies widely. This change in timing and quantity of precipitation can have a large impact on rain-fed agriculture throughout the region. Variability in climate, along with population pressure and decreasing fallow land have led to high levels of land degradation and low crop yields (FAO, 2015; Lal, 2008; Vågen et al., 2005). Agricultural yield per hectare in many places has not improved since the 1960s despite massive global advances in agricultural technology (Pingali, 2012). Because the Sahel is a water-limited environment that is of inherently low fertility, farming systems that can maximize the efficient use of water and nutrient resources are greatly needed in the region (Walker et al., 1981).

Agroforestry is one approach that holds such a promise. Variations of agroforestry have been in practice in the Sahel for many years (Cook and Grut, 1989). Generally, the agroforestry approach, also referred to as parkland agriculture, involves planting crops in proximity to scattered woody vegetation such as trees and shrubs that that are dispersed throughout agricultural fields. Agroforestry requires minimal resource input and has proven to benefit staple food crop production in many instances (Sinare and Gordon, 2015). When benefits exist in agroforestry systems, they are attributed to shading by tree canopy (Jackson and Wallace, 1999; Armas and Pugnaire, 2005), increased nutrient availability and cycling (Lufafa et al., 2008), suppression of evaporative losses (Lal, 1989), and increased soil moisture as a result of hydraulic redistribution by shrubs (Kizito et al., 2006, 2007). However, agroforestry systems can also put crops at a disadvantage when their roots compete for scarce resources with trees and shrubs in water limited environments.

This study focuses on the effects of two native woody shrubs, *Guiera senegalensis* (DC.) Hochst and *Piliostigma reticulatum* J.F. Gmel on the soil hydrologic environment and the near-surface microclimate where peanut and millet crops are inter-planted with shrubs at two sites in Senegal (Appendix A, Fig. A.1). Even during times of heat and water stress crops are able to survive and produce more yield in the presence of these two shrubs. Farming with native shrubs is a traditional practice and different shrub densities and management techniques exist throughout the Sahel (Wezel and Böcker, 1999; Dossa et al., 2012). The dominant management technique in the Peanut Basin involves coppicing the aboveground biomass and burning it in the fields just before planting where the ash is left to blow away or be incorporated into the soil. In this study, the biomass is chopped into 5 cm pieces, spread over the fields, and turned in to the soil with a shallow plow drawn by a horse (Appendix A, Fig. A.2). The research project, ongoing since 2003, has studied the water balance (Kizito et al., 2007), crop production (Dossa et al., 2012), quantity of aboveground shrub biomass and decomposition of shrub material in soils (Lufafa et al., 2008; Dossa et al., 2010), mesofauna (Diakhaté et al., 2013), and microfauna (Debenport et al., 2015). This study rests on the work of Dr. Modou Sene, Dr. Fred Kizito, and their colleagues who studied various hydrological aspects of the shrub-crop system in 2003-2004.

1.2. Scope

This study was an integral component of an interdisciplinary and international collaborative project titled: *Hydrologic Redistribution and Rhizosphere Biology of Resource Islands in Degraded Agroecosystems of the Sahel: A PIRE in Tropical Microbial Ecology*. It brought together plant physiologists, agronomists, soil physicists, plant pathologists, and microbial ecologists from Ohio State University, University of California-Merced, Institut Sénégalais de Recherches Agricoles (ISRA), l'Institut de recherche pour le développement (IRD), and the École Nationale Superieur d'Agriculture (ENSA) at the University of Thiès. The field research was conducted at two research plots in the villages of Keur Matar Arame and Nioro du Rip, in Senegal. The sites were established in a previous study (2003-2004) to investigate beneficial association between shrubs and staple crops. The plots have been under the same management since 2003. The study demonstrated that inter-cropping with native shrubs is effective and manageable. The collaborative effort of Senegalese and American scientists, postdoctoral trainees and African graduate students has established that two dominant local shrubs *G. senegalensis* and *P. reticulatum*, even at their native of 200-400 plants ha^{-1}, have much greater potential to sequester carbon and improve soils than manure, composts or planting other trees (Lufafa et al., 2008). The earlier study further established that with 1200-1500 shrubs ha^{-1} intercropping can increase millet yields by >250% (Dossa et al., 2012). The shrubs did not appear to compete with crops for water (Kizito et al., 2006) and when conditions were favorable showed signs of ability to transfer water by hydraulic lift (HL) from wet sub-surface soil to dry near-surface regions (Kizito et al., 2012; Dawson and Ehleringer, 1993).

The current study was designed to further advance the mechanistic understanding of the hydrology and microbiology that results in native shrub stimulation of crop growth. The primary goals of the project was to establish the HL capacity of the native shrubs, the microbial composition of shrub rhizospheres, and to identify and isolate potentially growth promoting microorganisms (PGPM) from shrub rhizospheres. Ultimately, the study was intended to propose agricultural procedures that will restore currently degraded landscapes and help develop effective and sustainable agricultural systems in the Sahel.

This dissertation focuses on the physical aspects of the study, particularly on how water and energy dynamics are impacted by presence of shrubs, along with physiological responses of crops to microclimatic conditions in the field. This study is a mix of agronomic and physiological monitoring of crop growth system as well as basic research into the process of HL of soil moisture and the physical mechanisms by which crops and shrubs are able to thrive while occupying the same soil profile.

1.3. Objectives of the dissertation

(1) Objective 1: To establish what, if any, role ten years of biomass additions and shrub growth has had on the ability of the soils to retain water, and what, if any, effect has there been on hydraulic conductivity as a result of these biomass additions.
(2) Objective 2: To explore the seasonal patterns responsible for increased soil moisture below shrubs at certain times, and a lack of apparent competition for water resources during times of low water availability between the crops and shrubs. Part of this study is to investigate the effects of the shrub treatment on the vigor and water status of crop growth using physiological measurements.
(3) Objective 3: To determine, under experimentally imposed extreme drought conditions (cessation of irrigation), whether the shrubs perform upward HL through their roots and provide some of this redistributed water to crops growing nearby.

1.4. Organization of the dissertation

This dissertation consists of five chapters. The three stand-alone chapters that follow this introduction contain the core parts of this study and address the specific objectives of this dissertation. They are structured in a format that meets the requirements of peer-reviewed publication. The last chapter summarizes the key findings from the entire study and identifies remaining knowledge gaps and outlook for future studies. Brief descriptions of the chapters follows.

Chapter 1: A general introduction to the site, the history of farming in the region, and the previous work performed in this agro-ecological system.

Chapter 2: An investigation of the physical properties of the soil and how they are affected by the presence of shrubs and the addition of above and below ground shrub biomass since 2003.

Chapter 3: A reporting of two years of field soil moisture and meteorological data which was collected continuously in 2012 and 2013 in order to investigate the dynamics of crop physiology and water use of crops and shrubs.

Chapter 4: A manuscript detailing an isotope tracer study, one of the few of its kind successfully carried out, to investigate the presence of hydraulic lift in *G. senegalensis* and the transfer of water from deep in the profile, through the shrubs, and into the crops.

Chapter 5: A general conclusion summarizing how this work fits into the larger picture of agroforestry research, agricultural research in the Sahel, and the advancement of knowledge of root and rhizosphere function under low-moisture conditions.

CHAPTER 2

Soil Physical Properties After Ten Years of Intercropping With Native Shrubs in the Sahel

Prepared for submission to: Soil and Tillage Research

N. Bogie, R. Bayala, I. Diedhiou, R.P. Dick, T.A. Ghezzehei

Abstract

In Senegal the native woody shrubs *Piliostigma reticulatum* (DC.) Hochst and *Guiera senegalensis* J.F. Gmel grow interspersed in farmers' fields at two sites in Central and Southern Senegal, Keur Matar Arame and Nioro du Rip, respectively. Previous studies have found large benefits to crop yield by interplanting crops with shrubs and incorporating all of the aboveground shrub biomass into the soil. These biomass additions have occurred 3-4 times annually over a period of ten years for total additions on the order of 5 Mg ha^{-1} year^{-1}. The presence of the shrubs has resulted in increased soil moisture near the shrub canopies during the growing season. This study investigates the effect of shrub presence and biomass additions on soil water retention, unsaturated hydraulic conductivity, surface evaporation, and surface infiltration at the two sites. At Keur Matar samples were collected in crop+shrub plots near (< 0.5 m) from the canopy (CSn), crop+shrub plots far (>1 m) from the canopy (CSf) and in crop only plots (CO). At Nioro samples were taken in CSn CSf, CO, and also from bare soil (BS) with no crops or shrubs. At Keur Matar the surface infiltration rate measured 75% higher in the in the CO than in the CSn treatment. At Nioro the surface infiltration rate measured 28% higher in the in the CO than in the CSn treatment. At Keur Matar water retention was significantly higher at wilting point in the CSn treatment than in the CSf treatment with values of at 0.030 and 0.016 m^3 m $^{-3}$, respectively ($P < 0.10$). At Nioro there was no significant difference in wilting point water content with 0.031 and 0.035 m^3 m $^{-3}$ in the BS and CSn treatments, respectively ($P > 0.10$). At 100 cm of suction unsaturated hydraulic conductivity was 3.37×10^{-3} cm hr^{-1} in the CSn plot and 6.75×10^{-3} cm hr^{-1} in the CO plot at Keur Matar. At Nioro unsaturated hydraulic conductivity at 100 cm suction was 4.96×10^{-3} cm hr^{-1} in the CSn treatment and 5.88×10^{-3} cm hr^{-1} in the BS treatment. Unsaturated hydraulic conductivity was reduced by shrub as compared to areas with only crops (at Keur Matar) or an area of bare soil with no crops or shrubs (Nioro). These results suggest that shrubs slow down soil water as it infiltrates in the the sandy soils at both sites, likely allowing for more water availability to crops nearby, particularly in the early part of the growing season. The findings in this study highlight the role that shrub presence and biomass additions play in altering centimeter-scale soil properties. This unique agroforestry

practice capitalizes on the evolutionary adaptation of native shrubs to mitigate detrimental effects of frequent extreme drought events in Sahelian climate.

2.1. Introduction

The harsh climate of the Sahel and lack of agricultural inputs has resulted in intense degradation of soils in the region (Lassaletta et al., 2014). It is generally reported that additions of carbon to soils in the form of plant litter and mulch can help to build the soil quality (Liu et al., 2016; Rawls et al., 2003; Lahmar et al., 2011), which, in turn correlates with higher crop yields (Woomer et al., 2004; Dossa et al., 2012). There are clear benefits to physical properties of degraded soils achieved by the addition of biochar (Glaser et al., 2002), crop residue (Michels et al., 1995), and low C:N ratio material such as animal or green manure (Snapp et al., 1998). Addition of C from plant biomass can lead to changes in the physical properties of the soil matrix through increased specific surface area (Pennell et al., 1984), increased cation exchange capacity (CEC), increased aggregation (Kong et al., 2005), and increased porosity as a result of micro faunal activity (Mando et al., 1996).

What is less clear, however, is how the carbon is physically incorporated into soils, and whether it stays in place over time. Surface biomass additions also affect surface energy and water fluxes compared to areas with no added biomass. Field-scale studies to investigate how carbon additions affect physical soil quality over time require sustained management and sampling efforts over a period of years and are limited in number, particularly in the semi-arid Sahel (Ouattara et al., 2006). Thus, there is a challenge in determining whether biomass additions affect soil moisture as a result of *in situ* microclimatic effects, or whether they change the soil structure itself.

The main goal of this study is to investigate the effect of of two native evergreen woody shrubs *G. senegalensis* and *P. reticulatum* on soil physical properties over a period of ten years. Specifically, this study focuses on alterations of soil properties due to the presence of the shrub rhizosphere and the surface application of shrub biomass throughout the cropping season. At the sites of Keur Matar Arame and Nioro du Rip, a yearly rotation of pearl millet (*Penisetum glaucum*) and peanut (*Arachis hypogea*) are intercropped with the aforementioned shrubs, and all of the aboveground shrub biomass is turned into mulch and spread on the fields. Shrub biomass at both sites has been added 3-4 times per year at a rate of approximately 5 Mg ha^{-1} year^{-1} since 2003 (Dossa et al. 2012; personal comm., M. Bright, 2016). A previous study at the site in carried out in the first two years of biomass additions revealed increased surface infiltration, and reduced soil evaporation as a result of the shrubs at both sites (Kizito et al., 2006).

However, no net increase in soil C was observed between 2003 and 2013 (Table 2.1). In contrast, there was a clear difference in C content in the soils under the shrub canopy as compared to those outside of the shrub canopy (Table 2.1). There were also statistically significant differences in POM between shrub amended and non-shrub amended plots, and higher POM also correlated with higher crop yield (Dossa et al., 2012). Increases in POM have been linked to increased water-holding capacity as a result of increased aggregation, and total carbon has been linked to higher water capacity and higher infiltration rates (Rawls et al., 2003; Kizito et al., 2006). The temperature and moisture regime at both field sites supports high levels of biomass decomposition. A study in 2005 at both sites investigated the rate of shrub biomass decomposition, and exponential decay constants were developed. The maximum decay constants reported in Diedhiou-Sall et al. (2013) were 0.46 and 0.49 year^{-1} for *G. senegalensis* and *P. reticulatum*, respectively. Based on these decay constants, there is potential for a significant aggradation of shrub biomass at the land surface.

The specific objectives of this study were to investigate how native shrubs, planted at higher-than-native density, and the incorporation of all of their aboveground biomass into the surface soil of agricultural fields have affected the soil physical properties over ten years. Specifically, addressed here are the questions of how the biomass additions have affected the water retention, unsaturated hydraulic conductivity, and in turn, the surface evaporation and infiltration at these two sites. This study is part of a multi-year research effort to understand the complete effects of intercropping with native woody shrubs on crop productivity.

2.2. Materials and Methods

2.2.1. Site description. The study consists of two sites, Keur Matar Arame (14° 46’N, 16°51’W), and Nioro Du Rip (13°45N 15°47’W) located in the Central and Southern Peanut Basin of Senegal, respectively. The soil at Keur Matar, is characterized as a Rubic Arenosol

(Michéli et al., 2006) (USDA Psamments) (USDA, 2016), it is known locally by the name Dior (Badiane et al., 2000). The majority of the material originates from aeolian deposits emplaced by the Harmattan winds (Renaud, 1961). There is a faint crust at a depth ranging from 3-7 cm that is found intermittently throughout the plots, except directly beneath the shrub canopy, but otherwise there is no distinct horizonation this crust appears to weaken after it becomes wet with the first rains, and shallow ploughing appears to break parts of it up. The texture measured near Keur Matar at Bambey is 3% clay 6% silt 91% sand 0.15-0.35% total C, 0.02% total N, and a P content of 95 mg kg^{-1} (Table 2.1) (Nicou, 1986). The area receives a mean annual rainfall of 450 mm but has large fluctuations in the quantity and timing of rain. The water table lies at 11 m depth at the start of the rainy season in June as measured by the authors. At Keur Matar the mean annual temperature is 26 °C the annual minimum and maximum temperatures are 11 °C and 43 °C, respectively. Relative humidity at the site is between from 50-100% during the rainy season. The site is located at 54 m above sea level (Google Inc., 2016). The dominant native shrub in the area is *G. Senegalensis*.

The second site at Nioro is predominantly occupied by *P. reticulatum* shrubs on a sandy, lateritic area classified as a fine-sandy, mixed Haplic Ferric Lixisol (USDA Alfisol), which is locally known as Deck-Dior (Badiane et al., 2000; USDA, 2016). The texture is 5% clay 16% silt 77% sand (Nicou, 1986) with a total C content of 0.25 - 0.35% (Table 2.1). There is no distinct horizonation. The area has unimodal rainfall, 750 mm per annum and a mean annual temperature of 32 °C. The water table lies at approximately 18 m, and the field site is 18 m above sea level (Google Inc., 2016). At Nioro the mean annual temperature is 28 °C and the annual minimum and maximum temperatures are 9 °C, and 44 °C, respectively. During the rainy season relative humidity ranges from 50 -100%.

2.2.2. Design and management of experimental plots. The measurements were performed in research plots that have been in existence since 2003. Prior to 2003, for at least 50 years the area was in a crop rotation between peanuts and millet under local farmer management. *G. senegalensis* and *P. reticulatum* existed at Keur Matar, and Nioro at densities of 239±74.6 and 185 shrubs ha^{-1}, respectively, prior to 2003 (Kizito et al., 2006; Lufafa et al., 2008). In 2003 additional shrubs were planted in crop and shrub plots to bring their density to 1500 to 1833 shrubs ha^{-1} at Keur Matar and 1000 to 1300 shrubs ha^{-1} at Nioro (Dossa et al., 2012). The research plots at each site were subdivided into four randomized complete blocks each with 8 subplots (6 m × 10 m at Keur Matar, 4.5 m × 10 m at Nioro) randomly assigned to two levels of shrub treatments (crop only (CO) and crop+shrub (CS)) and four levels of fertilizer treatments (0 ×, 0.5 ×, 1 ×, 1.5 × recommended rate). All of the results reported in this study are from the 0 × fertilizer CO and and CS plots. Also, for the purposes of this study, samples in the shrub amended plots within 50 cm of shrub center referred to as crop+shrub "near" (CSn), and $>$ 1 m from shrub center crop+shrub "far" (CSf). The shrub plots were split into "near" and "far" to investigate soil properties beneath the shrub canopy, which includes both the shrub rooting zone as well as biomass additions vs. soils outside the shrub canopy that are only influenced by the surface biomass additions, with no direct influence from the shrub canopy.

The management strategy at both sites involves preparing the field by cutting all of the shrub material at the ground surface before the arrival of the rainy season late May, the largest diameter of the shrub branches are 2 cm, which are regrowth since the last shrub cutting of the previous rainy season. Once the aboveground material is cut, the shoots and leaves are chopped manually into approximately 5 cm pieces and spread over the shrub plots. Following the spreading of biomass a horse and plow pass over the area ploughing to a depth of approximately 6 cm and turning some of the shrub material in with the soil. Shrub material is cut and turned back into the soil with the 6 cm depth plow 3 to 4 times during the growing season: before planting, after crop emergence, at flowering (depending on year and shrub growth), and once after harvest. The surface coverage of the shrub mulch in the CSn and CSf plots after the first cutting before sowing was estimated visually at 40-60%, depending on the plot. Subsequent cuttings produce less biomass and less surface coverage. The practice of coppicing the shrubs, except mulching and spreading of biomass, are standard procedures employed by the local farmers. Farmers typically burn the shrub biomass collected at the beginning of the growing season and leave the ash in the fields, partially because of lack of adequate labor or equipment to chop and spread the biomass. Annual biomass additions vary widely with a minimum from 2011-2015 of 2824 kg ha^{-1}

and a maximum of 8651 kg ha^{-1} in the zero fertilizer plots at Keur Matar (Personal comm., M. Bright).

2.2.3. Automated mini disc infiltrometer. Tension infiltrometers were used to measure surface infiltration rates in the plots. At each site, three of four blocks were chosen, and 4-8 measurements were made per subplot of the CO, CSf, and CSn treatments for a total of n = 12-22 per treatment. Infiltration measurements were performed at a tension of -2 cm of water suction. The mini disc infiltrometers (MDI) (Decagon Devices, Pullman, WA) were outfitted with differential pressure transducers (SCX01DN, Honeywell, Freeport, IL), excited with 3.00 volts and read every second using a datalogger (CR800, Campbell Scientific, Logan, UT) and a PC (Madsen and Chandler, 2007). Up to the second data was displayed using a field computer (Panasonic, Osaka, Japan) and datalogger software (PC400, Campbell Scientific, Logan, UT). A field calibration was used due to the fluctuating nature of the battery voltage which corrected for differences throughout the day.

$$V(t) = V_{tot}\left[1 - \frac{v_o(t) - v_{min}}{v_{max} - v_{min}}\right] \tag{2.1}$$

Where $V(t)$ is volume of water discharged at time t and is calculated using the scaled voltage and total water discharged during the measurement, V_{tot}. Where $v_o(t)$ is the voltage output v in the infiltrometer at time t, v_{max} and v_{min} are the maximum and minimum voltages for each infiltrometer repetition.

For each measurement the maximum and minimum voltages and volumes were recorded as well as the time of day to the nearest second. In order to record all of this information a team of two was deployed. One person held the tensiometer steady just above the ground and read the initial volume. The tensiometer was then placed on the ground for the duration of the infiltration just before the infiltrometer drained the operator lifted it off of the ground surface to read the final volume. The second person read the voltages from the computer and recorded all of the data. At each group of four to six infiltrations per treatment, triplicate samples of gravimetric soil moisture were collected for the 0-10 cm depth.

2.2.4. Dual tensiometer constant evaporation. The evaporation method of Schindler and Müller (2006) was used to measure the evaporative flux of water from a soil core

(HYPROP, UMS/Decagon, Pullman, WA). This technique allows simultaneous calculation of the unsaturated hydraulic conductivity, soil water potential, and volumetric water content. Samples were collected using a sample ring of 80 mm inside diameter by 50 mm height a photo and schematic of the system is pictured in Appendix (B). The sample rings were carefully inserted vertically into the soil then excavated and the excess soil material carefully trimmed off with a sharp knife flush at both ends and sealed. The samples were brought to the lab for analysis.

Samples were saturated by laying a cloth over one end of the sample ring and placing a perforated plastic plate over the cloth, then inverted into a container of tap water filled so that the water was 1 cm below the rim of the soil core. The samples were then left for 24 hours to saturate by capillary action before being removed from the water. While the sample saturated, two mini tensiometers presoaked in de-ionized and de-aired water were saturated under a vacuum of 90 kPa until two internal volumes of water had been drawn through the tensiometer from the outside up the shaft. The transducer base of the apparatus was also de-aired with a vacuum pump using a special attachment included in the HYPROP kit. Tensiometers were then checked for air bubbles, if none were found they were placed on the apparatus base and tested for proper function by drying the porous ceramic with a dry paper towel. If the tension rose above 600 hPa within seconds of drying the ceramic, the tensiometer fill was considered adequate and the tips were kept moist and set aside for loading the sample. Once the sample was saturated, two holes for the tensiometer shafts were drilled using the auger and auger guide included in the HYPROP. The saturated sample was carefully loaded onto the transducer apparatus and both placed on a balance with 0.01 g precision. Samples were left on the balance, and the mass, tension, and soil temperature were logged every minute, for 5-10 days or until the tensiometers underwent air entry and the suction was zero. The data were then downloaded from the HYPROP software to a computer for analysis using R (R Core Team, 2016).

The range of measurements was extended from the cavitation values of the tensiometers, typically 800 - 1500 hPa, to 8800 hPa by using the air entry value of the ceramic tensiometers, which is documented as 8800 hPa (UMS, 2012). Suction values between cavitation and tensiometer air entry were interpolated using hermite splines in this range, the interpolated data were then used for calculation of water retention and hydraulic conductivity (Schindler et al., 2010).

$$q^i = \frac{1}{2}\left(\frac{\Delta V^i}{\Delta t^i A}\right) \tag{2.2}$$

The volumetric flux between the tensiometers q^i was calculated using Eq. 2.2. Where ΔV^i is the change in water volume in the sample measured by the balance and converted to volume, Δt^i is the time interval between measurements, and A is the cross-sectional area of the evaporating soil column.

$$\overline{\overline{h}}^{\,i} = \frac{h_1^{i-1} + h_2^{i-1} + h_1^i + h_2^i}{4} \tag{2.3}$$

In Eq. 2.3 $\overline{\overline{h}}^{\,i}$ is the medial water tension between the two tensiometers h_1 and h_2 at the time steps i and $i-1$. The difference Δh^i between between the tensiometer readings at time i and time $i-1$, was calculated by taking the mean difference in tension between tensiometers at the two time steps. The distance between the tensiometers Δz^i (2.5 cm) was used to calculate the hydraulic gradient $\Delta h^i/\Delta z^i$.

$$K^i(h^i) = -\frac{q^i}{\Delta h^i/\Delta z^i + 1} \tag{2.4}$$

Unsaturated hydraulic conductivity, $K^i(h^i)$ was calculated using Eq. 2.4 (Darcy, 1856). For the water retention curve, the suction was calculated using the geometric mean of the two tensiometers, as this interpolation of the suction profile better matches the true profile during stage II evaporation (Schelle et al., 2013).

2.2.5. Chilled mirror dewpoint potentiometer. For the dry range of soil moisture retention a chilled mirror dewpoint potentiometer was used (WP-4, Decagon Devices, Pullman, WA). Samples were collected in situ at depths of 10 cm in plastic sample cuvettes and trimmed of excess soil with a sharp knife. The samples were then sealed and brought back to the lab for analysis. In order to increase the precision of the dew point potentiometer it was placed inside of a box where temperature fluctuations in the room were dampened.

This allowed for an accuracy of ±0.03 MPa. Samples were measured in continuous mode using the instrument attached to a Windows computer with a serial cable and read with a serial port emulator. Data was then read directly by an R script to check for constant measurements (R Core Team, 2016). Dewpoint potentiometer was calibrated or checked for calibration after every 2-3 samples to ensure accurate readings using 0.5 molal KCl supplied by the manufacturer (Decagon Devices, Pullman, WA). The mass of the sample cuvette was measured before and after each water potential reading and the average of these two masses was used for each measurement step.

$$\Theta_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \tag{2.5}$$

$$\Theta_e = \sum_{i=1}^{2} w_{Di}(1 + (-\alpha_i h)^{n_i})^{m_i} \tag{2.6}$$

Once the suction in each sample surpassed 5.00 MPa the masses and water potentials were compiled and inserted into a non-linear fitting routine using the parameters from equation (2.5) to fit equation (2.6) (Appendix B.3) (R Core Team, 2016; Van Genuchten, 1980; Zurmühl and Durner, 1998). Where Θ_e is the effective saturation, θ is the measured volumetric moisture content, θ_r is the residual moisture content set to 0.001, and θ_s is the saturated moisture content as measured at the beginning of the dual tensiometer measurement for each sample. A weighting factor w_{Di} is assigned to each mode i, α is the Van-Genuchten α which corresponds to the inverse of the air-entry value for the mode i, the matric suction is h, n represents the pore-size distribution for the mode i and m is equal to $1 - 1/n$. The bimodal equation allows for a more accurate depiction of the moisture content in the dry range. This equation was used to interpolate values of water content at various suctions.

2.2.6. Potential for water retention in the rhizosphere. Water retention may differ considerably in the rhizosphere compared to the bulk soil due to the presence of root exudates an aggregates (Kroener et al., 2014; Ghezzehei and Albalasmeh, 2015). Thus an attempt was made to quantify the potential for the rhizosphere to harbor increased moisture based on the known root architecture of *G. senegalensis*. A calculation was performed using the root length density (cm cm^{-3}) and root radius (cm) by depth from Kizito et al. (2006). The aforementioned article also shows a graphical depiction of the rooting system of both *G. senegalensis* and *P. reticulatum*. The range of rhizosphere soil between 0 mm and 2 mm which is the extent of the "exudation zone" as reported in York et al. (2016). The value for "rhizosphere" soil water content at 80 kPa reported in Kroener et al. (2014) is 0.04 $\mathrm{cm}^3\ \mathrm{cm}^{-3}$ and the moisture content of Keur Matar soils at 80 kPa, as measured in this study, is 0.023 $\mathrm{cm}^3\ \mathrm{cm}^{-3}$. Calculations were made of the difference in water retention of a *G. senegalensis* root zone with and without rhizosphere compared to the bulk soil at the same water potential. The rhizosphere influenced soil could be visualized as "rhizosphere" cylinders of radii 0 - 2 mm surrounding all of the shrub roots in the rooting zone. The calculated soil moisture retention is the total of moisture retention of this cylinder shaped rhizosphere and any non=rhizosphere influenced soil in the profile at calculated for each of the radii. The necessary assumptions for this calculation are that exudate-influenced soil water retention is similar in *G. senegalensis* as the chia *Salvia hispanica* seed mucilage used in Kroener et al. (2014). Additionally it was assumed that soil was influenced by exudation along the entire length of the root. Another assumption is that the rhizosphere soil is in equilibrium with the surrounding soil, and this is not necessarily the case due to a hysteretic effect. Kroener et al. (2014) also showed that rhizosphere soils may retain more moisture under drying conditions, and significantly less under re-wetting conditions. The last assumption would lead to larger differences in moisture content if the soil was drying and smaller differences if it was re-wetting.

2.2.7. Dye infiltration. A short trial was performed to investigate bulk infiltration into the soils using water with brilliant blue dye in it (Food Blue 2, C.I. 42090). Two hundred liters of water were applied to a plot 7.5 m long and 0.5 m wide over a period of 111 minutes for a total application of 53 mm at a rate of 28.6 mm hr^{-1}. The water was left for 24 hours to infiltrate, then a transect trench along the length of the infiltration zone was dug up and the depth of the wetting front was measured every 0.20 m. It was noted in the wetting front measurement where roots were located while digging out the trench.

2.2.8. Surface evaporation with microlysimeters. Soil microlysimeters made of grey PVC tubes measuring 12.5 cm tall with an inside diameter of 10.3 cm and a wall thickness of 0.2 cm were installed to measure soil evaporation during times of no rain (Daamen et al., 1993). The PVC tubes were carefully inserted into the soil until the rim of the lysimeter was 0.5 cm above the soil surface, then excavated. The bottom of the lysimeter was carefully cut to be flush with the bottom of the PVC and then sealed with heat conductive foil tape (Appendix B, Fig. B.2). The bottom of the hole was filled back in so that it had a flat bottom and such that the bottom of the lysimeter when placed back in the hole was in complete contact with the soil below and the surface soil inside the lysimeter was flush with the surrounding surface soil. A 4 cm plastic barrier was inserted around the outside of each lysimeter to keep wind from blowing the soil away (Appendix B, Fig. B.3). The lysimeters were removed from their holes and weighed every 3-4 hours during the day over a period of 24 hours with a field balance of accuracy ± 0.1 g. Lysimeters were installed a minimum of 24 hours after the last rain so that no water would flow out the bottom of the lysimeter and the moisture content would be at field capacity or less. Data shown represent mass loss over 24 hour periods.

The late season measurements in 2012 (Sept. 19-21) at Keur Matar were taken with a sparse shrub and crop canopy. The June 25, 2013 measurements at Keur Matar were taken before any significant rain had fallen or crop or shrub growth had occurred. The August 2013 values were taken under a sparse millet crop at both sites. The measurements taken on Sept. 26, 2012 at Nioro were taken under a full peanut canopy and when there was significant shrub growth as it had been one month since shrubs were cut.

2.2.9. Statistics. For the surface evaporation data a log transformation brought the samples under the normality assumption and an two way ANOVA with date as the blocking factor was performed. For the bulk density at Nioro, the infiltration, the gravimetric moisture content, and the wilting point data, the normality and homogeneity assumptions did not hold so a Kruskal-Wallis ranked sum test was carried out to find any significant differences and Dunn's test was used for pairwise comparisons of treatments using a Bonferroni correction for the P threshold for multiple comparisons. For the Keur Matar bulk density a Dunn test was used since there were only two groups. Due to small sample sizes, statistical significance was considered at $P < 0.1$. Statistical analysis was carried out using base R, and the dunn.test package (R Core Team, 2016; Dinno, 2016).

2.3. Results

2.3.1. Field infiltration.

2.3.1.1. *Surface infiltration.* Surface infiltration measurements revealed significant differences between treatments at both sites and are presented in (Fig. 2.1). Overall, infiltration rates near the shrubs were lower at both sites. At Keur Matar the surface infiltration rate was 75% higher in crop only (CO) treatment than in the crop+shrub near the canopy (CSn) treatment and at Nioro the rate in the CO treatment was 28% higher than the CSn treatment. At Keur Matar the infiltration rates were 244±24, 370±17, and 420±15 cm hr^{-1} in CSn, CSf, and CO plots, respectively. At Nioro the values were 115±13, 157±9, and 147±6 cm hr^{-1} for CSn, CSf, and CO plots, respectively. At Keur Matar all treatments were significantly different from each other ($P < 0.001$). At Nioro there were significant differences between CSn and CO and CSn and CSf ($P < 0.001$), but but not between CO and CSf ($P = 0.56$). The CSn treatment at both sites showed the highest variability ranging from 72 to 480 cm hr^{-1} at Keur Matar and 34 to 267 cm hr^{-1} at Nioro. Overall the mean infiltration rate was 147% higher at Keur Matar than at Nioro.

In addition to the infiltrometer measurements moisture content at each infiltration measurement point was measured. There were significant differences at both sites in soil moisture ($P < 0.05$). A post-hoc Dunn test revealed that CSn had significantly more moisture than both CSf and CO treatments ($P < 0.05$) but there was no significant difference between CSf and CO at Keur Matar. At Nioro there was statistically significant higher moisture content in the CSf as compared to both the CSn and CO plots, but no significant difference between CSn and CO.

2.3.1.2. *Dye infiltration.* The dye infiltration study revealed that the wetting front moved more slowly in a 30 cm radius centered on the middle of the coppiced shrub canopy. The infiltration depth in this area was 10-15 cm after 24 hours whereas away from the shrub infiltration depths ranged from 20-30 cm. The deepest depths of the wetting front were 25-30 cm depth were between the 500-700 cm horizontal distances, 200 cm away from the shrub canopy (Fig. 2.2).

2.3.2. Laboratory analysis of water retention and hydraulic conductivity.

2.3.2.1. *Water retention.* At Keur Matar small but statistically significant differences in water content at wilting point were found ($P < 0.10$), (Fig. 2.3 Table 2.2). The CSn samples had a wilting point water content 0.02 cm ^{3} cm^{-3} higher than CSf and was statistically significant ($P = 0.04$), but there was no difference between CO and any other treatments. For the tensiometer-based volumetric water content measures at Keur Matar, the CSf plot had the highest 100 cm suction water content at 0.10 cm^3 cm^{-3}. The lowest value at 100 cm suction was in the 100 cm soil pit sample (SP100) at 0.05 cm^3 cm^{-3}. At field capacity the sample with the most moisture was also CSf with 0.05 cm^3 cm^{-3} and the lowest was in SP100 at 0.02 cm^3 cm^{-3}.

The wilting point water content values at Nioro were not statistically different. Tensiometer measurements at 100 cm suction at Nioro were highest in the bare soil (BS) sample at 0.18 cm^3 cm^{-3}and the lowest in the CSf at 0.12 cm^3 cm^{-3}. At field capacity the maximum water content was in the SP100 sample at 0.12 cm^3 cm^{-3} CSn and CSf samples had the lowest water contents, both at 0.06 cm^3 cm^{-3}.

2.3.2.2. *Unsaturated hydraulic conductivity.* Overall the unsaturated hydraulic conductivity was lower at Keur Matar than Nioro. The CSn and CSf samples had lower hydraulic conductivities than the CO plots, and the soil pit had intermediate values. A comparison of unsaturated hydraulic conductivityis given in (Fig. 2.4) and the data at 100 cm suction and field capacity (333 cm suction) are presented in (Table 2.3). Note that raw conductivity curves from the SP100 samples and the UNSODA Dior data are not shown (Vachaud et al., 1978; Nemes et al., 2001). At Keur Matar the hydraulic conductivity increased with increasing distance from the shrub at both 100 cm suction and field capacity. At a tension of 100 cm, hydraulic conductivity values at Keur Matar were within one order of magnitude of each other. The minimum was in the CSn plot at 3.37×10^{-3} cm hr^{-1} and the maximum at 6.75×10^{-3} cm hr^{-1} in the CO plot. At field capacity all of the values at Keur Matar were within one order of magnitude of each other with the minimum in the CSn plot at 9.06×10^{-6} cm hr^{-1} and the maximum at 4.85×10^{-5} cm hr^{-1} in the crop only plot.

At Nioro the 100 cm suction hydraulic conductivity was the lowest in the CSf plot at 4.72×10^{-3} cm hr^{-1} and highest in SP100 at 9.30×10^{-3} cm hr^{-1}. At field capacity the highest conductivity was in the 100 cm soil pit at 2.70×10^{-3} cm hr^{-1} and the lowest was in the CSn plot at 8.88×10^{-5} cm hr^{-1} (Table 2.2).

2.3.2.3. *Potential for rhizosphere influence on water retention.* A comparison of potential rhizosphere influence on water content in the Keur Matar soil is presented in Fig. 2.5. The calculation shows that a 2 mm radius rhizosphere could increase the total soil water content in a shrub plot by 0.001-0.003 cm^3 cm^{-3} at 80 kPa of suction. The near-surface soils at Keur Matar routinely reach this water potential during the growing season.

2.3.2.4. *Bulk density.* At Keur Matar the bulk density near the shrubs was small but significantly lower than the crop only plot (Table 2.4). At Nioro there was no significant difference in bulk density between the CSn, CSf, and CO plots. The bulk density was 0.01 g cm^{-3} higher in the CSn than in the CO plots at Keur Matar and significantly different ($P < 0.1$). There was no CSf measured at Keur Matar. At Nioro both CSn and CSf were measured and had no difference between treatments (Kruskal-Wallis H = 20.3, df = 2, P = 0.36). At Keur Matar the lowest bulk density was at 40 cm in the soil pit at 1.531 g cm^{-3}. At Nioro the lowest bulk density in the measured profile was at 20 cm in the soil pit at 1.397 g cm^{-3}

2.3.3. Soil surface evaporation. Surface evaporation measured on multiple dates showed no significant differences between shrub treatments at either site. At Nioro, there was more surface evaporation in all treatments one day after rain than two or more days after rain. Raw evaporation data from soil microlysimeters as well as days since the last rain and PET are presented in (Fig. 2.6). At Keur Matar all surface evaporation values on all days were less than 35% of PET. At Nioro surface evaporation values were higher overall and ranged from a minimum of 8% of PET 13 days after rain to a maximum of 66% of PET one day after rain. There were no statistically significant differences at Keur Matar between dates or treatments at ($p < 0.10$) (Table 2.5). At Nioro there were statistically significant differences between all dates ($P < 0.02$) but none between treatments (Fig. 2.6, Table 2.5).

2.4. Discussion

2.4.1. Water retention, hydraulic conductivity, and carbon inputs. In this study minimal to no differences in water retention between samples, except at Keur Matar at the wilting point were observed. Unsaturated hydraulic conductivity was only measured on one sample per treatment, but the lowest conductivity was measured in the in the crop+shrub near treatment (CSn) at both sites. The effect often associated with trees and shrubs in agroforestry systems is an increase in macroporosity, which in turn increases infiltration into the soil profile (Kizito et al., 2007). One of the ways an increase in macroporosity can occur is through addition of biomass and subsequent termite activity. Mando (1997) cited increased infiltration as a result of termite activity in mulched plots of *Penisetum pedicellatum* and *Pterocarpus lucens* based on a field soil water balance. Root channels can also create macroporosity (Devitt and Smith, 2002) and have been linked to much higher microbial activity than matrix soil in a temperate forest (Bundt et al., 2001). The small, but significant decrease in 10 cm depth bulk density at Keur Matar in the CSn plots compared to the CO plots may reflect this increased porosity. While increased macroporosity was observed by the authors under *G. senegalensis* as well as *P. reticulatum* in the field, this did not manifest in faster movement of the wetting front near the shrubs. On the contrary, infiltration under a cut shrub was reduced when measured with dye and no indication of fingered or preferential flow was observed in this trial (Fig. 2.1).

At Keur Matar surface infiltration under 2 cm of tension increases with increasing distance from the shrub. This indicates an effect not only of the shrub canopy and rooting zone near the shrub base (CSn), but of the additional biomass applied (CSf). Lower infiltration rates likely contribute to increased soil moisture at 10 and 20 cm depths in the critical early season at Keur Matar (Chapter 3.4.4). At Nioro, there was a shrub and biomass effect (CSn), but not a biomass-addition-only (CSf) effect. The lack of CSf treatment effect at Nioro may be due to the fact that there is more silt and clay in the soils there and organic matter amendments have a smaller effect in fine-grained soils than in coarse ones, such as those at Keur Matar (Table 2.1). Studies in coarse soil tend to show a larger effect of C additions on the dry end, near 15 000 cm water, and fine-textured soils tend to see diminished benefits at low water content (Petersen et al., 1968). The reasons for this may be twofold. First of all, in fine-grained soils C additions can increase aggregation and stabilize aggregates (Oades, 1984), increase of aggregation, particularly microaggregates, can lead to increased water-holding through their behavior as soil particles. Since microaggregates are often the same size as sand-sized particles, they can behave as such, but will only hold moisture at low suctions due to their large size, at higher suctions water will quickly drain from the coarse pores. Coarse soils, on the other hand, do not necessarily undergo aggregation when C is added. Increased water holding capacity and hydraulic connectivity in coarse soils may relate to changes in surface characteristics of the bulk soil due to organic material which has a much larger CEC by mass than soil particles (Hillel, 1998).

Additionally, at Keur Matar, fields sat for only two months after shrub coppicing before infiltration measurements were taken. At Nioro seven months elapsed between shrub coppicing and infiltration measurements. Therefore measurements at the two sites could reflect two different stages of litter decomposition (Budelman, 1989). De Jong et al. (1983) found that leaf-amended soils underwent an increase in water holding capacity of 55% as compared to the mulch-free control. Budelman found, however, that the effect of mulch on soil moisture retention in the upper zones followed a negative linear trend with mulch age from 0-60 days where moisture excess as a result of mulch reduced from a maximum of 6% to a minimum of 1%. Budelman (1989) credits this reduction of moisture excess to the fact that as time progresses the mulch material is mineralized and incorporated into the shallow soil. This could be a similar pattern seen at Keur Matar and Nioro where early application of shrub biomass creates large benefits to soil water holding capacity and nutrient status that diminishes throughout the growing season as the C is mineralized. If the above mentioned litter-decomposition hypothesis is true, than one would see larger differences in infiltration and water holding capacity at Nioro in early months after cutting and spreading biomass than were observed in this study. Additionally, one would see larger differences in surface infiltration and water retention in the critical early part of the season when germinating seeds are the most vulnerable to heat and moisture stress at shallow depths. The beginning and end of season soil C data reflect this trend of diminishing quantity at both sites in 2012 under a peanut crop, but the trend is not as clear in 2013 under a millet crop (Table 2.1).

2.4.2. Scale and sampling considerations. The size of the samples collected for these studies, 12 cm^3 for the dewpoint potentiometer, and 250 cm^3 for bulk density and water retention measurements, may fail to capture one important scale that is present in these systems: the macropore. In the field increased macroporosity was observed below the shrubs. This is a result of root channels as well as burrows by micro and meso-fauna. These channels are extremely important for the exploration of roots, and the infiltration of water. Macropore and root channel surfaces can exhibit significantly different water relations as a result of decaying flora and fauna. Kizito et al. (2006) observed increased surface infiltration as a result of shrubs. Other authors have cited similar results as a result of surface biomass amendments (Barzegar et al., 2002). The results in this study do not rule out increased infiltration as a result of shrubs or their biomass, but instead represent a smaller scale that may not capture the macropores. The soil matrix has lower unsaturated hydraulic conductivity in the CSn and CSf treatments than the CO treatment at the cm scale, which can help retain moisture near the surface at critical times when there are smaller rain events and capillarity (sorption) dominates the movement of moisture in unsaturated conditions. However, when the soil passes a moisture threshold where where capillary forces give way to gravitational forces, macropore flow can dominate, bringing higher infiltration rates beneath areas of shrub and biomass amendments, as observed at the field scale at this and other sites (Kizito et al., 2006).

Another structure that may not be well captured in the sampling of this study is soil influenced by the rhizosphere. The reason it may not be well represented is because these samples were taken at 10 cm depth, and at this depth, at both sites, there were minimal roots observed. Roots and the rhizosphere, however, likely have a greater effect in deeper parts of the profile beneath shrubs where their density is highest (Kizito et al., 2006). A calculation using the shrub root density measured by Kizito et al. (2006) and rhizosphere properties based on Kroener et al. (2014) and York et al. (2016) indicate that at 80 kPa of suction there could be differences in water content between a shrub root zone soil and a soil with no shrub roots. This calculation neglects the presence of millet or peanut roots. Recent research suggests that rhizosphere soil undergoes hydrodynamics which differ considerably from the bulk soil (Carminati et al., 2009; Ghezzehei and Albalasmeh, 2015). Additionally, sampling at 10 cm depth may neglect to capture the surface, where particulate organic matter likely influences infiltration, as well as the 15-20 cm region where shrub roots are the most abundant (Kizito et al., 2006). In the field very few shrub roots were observed between 0 and 15 cm depth. The processes facilitated by macropores such as increased water movement and channels for root growth and decay may not be captured well by the size and location of the samples taken. These samples show influence of both the shrub biomass and the shrub rooting zone but the differences are not constant throughout the types of measurements. Capturing the scale of the macropore may lead to larger differences than seen in this study.

2.4.3. Surface evaporation. The rates of soil surface evaporation measured in this study were comparable to rates measured in an agroforestry system in Kenya with a partial tree canopy (LAI = 0.1) where surface evaporation was 5 mm day^{-1} the first day after rain, and then quickly dropped to just over 3 mm day^{-1} on day two after rain (Jackson and Wallace, 1999). The fact that beginning two days after rain the evaporation rate at Keur Matar does not significantly change indicates that capillary contact between the surface and subsurface is broken and it is likely the maximum vapor diffusion rate in the soil, not atmospheric demand, that that controls evaporation. This can be considered a shift from stage-I (atmospheric limited) to stage-II (diffusion limited) evaporation. The shift from stage-I to stage-II evaporation happens fastest in material with low air-entry suction (Lehmann et al., 2008). All of the data, except the 1 day post-rain data from Nioro, are below 2 mm day^{-1} and fall into the range of stage II evaporative losses reported in Shokri and Or (2011) as between 0.75 and 3.25 mm day^{-1}. The range reported therein is consistent in empirical studies across soil types and differing potential evaporation conditions. Kizito et al. (2007) reported differences surface evaporation rates that were 44-60% higher in the CO compared to the CS treatments though it was not clear how many days had elapsed since the last rain when lysimeters were installed and measurements were started. These data indicate that two days or more after rain, the shrubs have no effect on surface evaporation. This implies that surface evaporative losses, and any potential shrub effects, are likely important for one to two days after a rain. If the rain events are large and infrequent, the effect of the stage-II evaporation transition could decrease the importance of the surface evaporation component of evapotranspiration as compared to small, frequent storms. However, if the rain events are frequent and small then shrub effects such as shading and increasing the boundary layer thickness with the addition of surface biomass mulch could have a larger effect on the surface evaporation component of the water balance. Kizito et al. (2007) attribute the differences they saw in surface evaporation to these shrub effects.

2.4.4. Perspectives.

When it did create a difference, overall, the presence of shrubs and their biomass led to slightly lower unsaturated hydraulic conductivity, and lower surface infiltration rates. Further study of water retention and infiltration within different parts of the rooting zone at short time intervals throughout the season would add insight to the effects of shrub management on soil properties, as well as more in-depth dye infiltration studies in the field which could help to quantify the impact of shrubs on preferential flow and field-scale water infiltration. Overall the shrubs appear to help the moisture regime of crops growing nearby, at least in the early part of the season. The soil factors influencing higher moisture content near shrubs shown here are reduced surface infiltration rates and potentially the presence of a shrub rhizosphere. Additionally, hydraulic redistribution likely plays a role in in increased root zone water content, at least in the dry and early wet seasons.

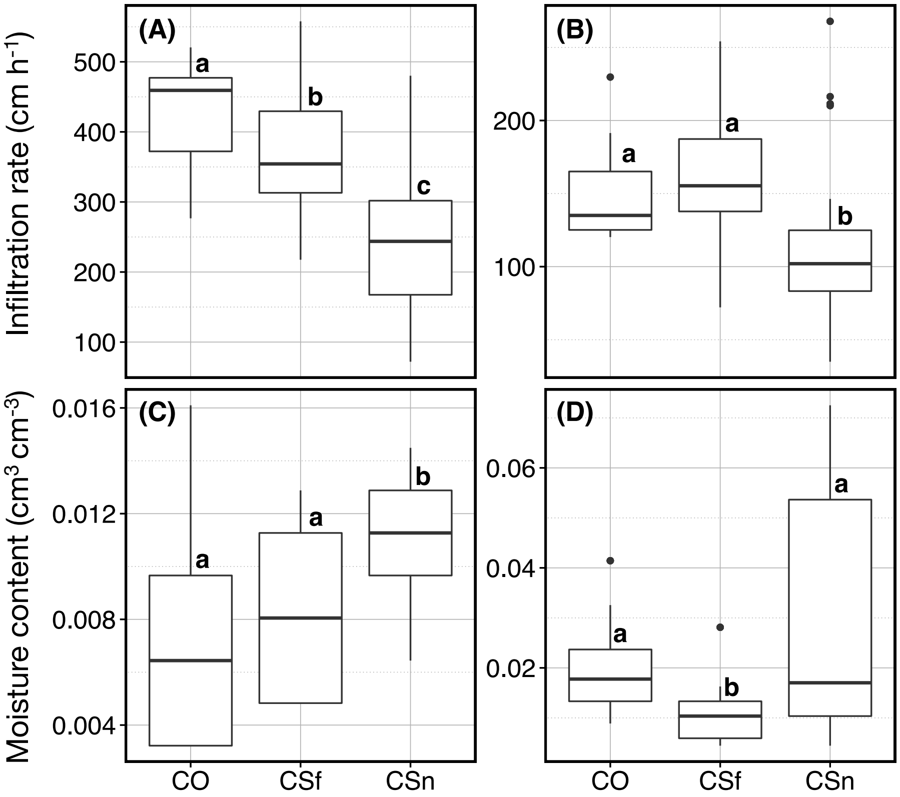

FIGURE 2.1. Field infiltration rates from mini-disc infiltrometers at -2 cm suction comparing crop only (CO), crop+shrub near the canopy (CSn), and crop+shrub far from the canopy (CSf) plots at (A) Keur Matar and (B) Nioro. Lower plots are the moisture content measured at each infiltration location at (C) Keur Matar and (D) Nioro. Boxes outline the 25th and 75th percentiles, the solid lines are medians, the whiskers are the box boundaries ±1.5 times the inter-quartile range, and outliers are points outside of the whisker extents. Boxes within the figure followed by the same lowercase letter are not significantly different at $P < 0.05$.

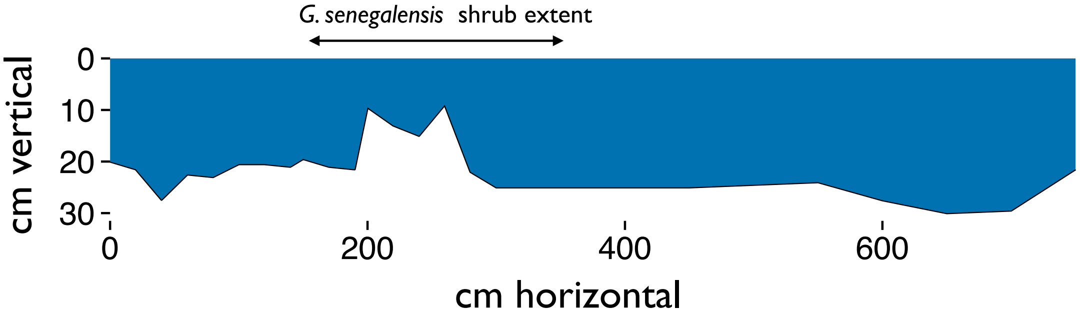

FIGURE 2.2. Wetting depth of blue dye 24 hours after application to soil surface measured every 20 cm along a 7 m transect during the dry season at Keur Matar.

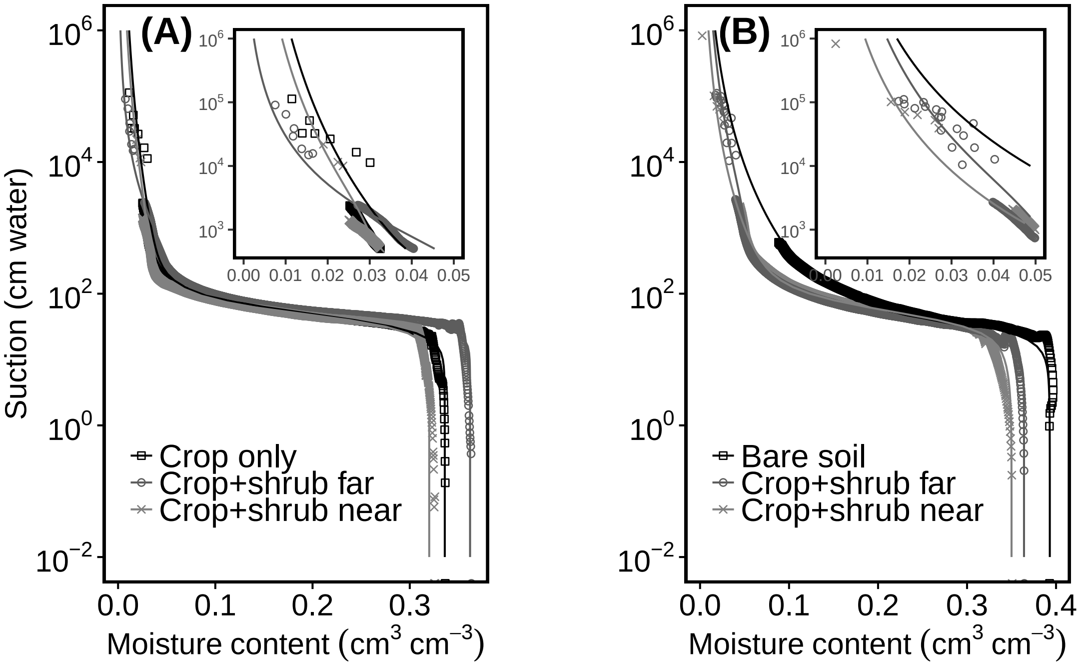

FIGURE 2.3. Comparison of soil water retention and fitted Durner-Van Genuchten model using WP4 and extended tensiometer data at (A) Keur Matar and (B) Nioro.

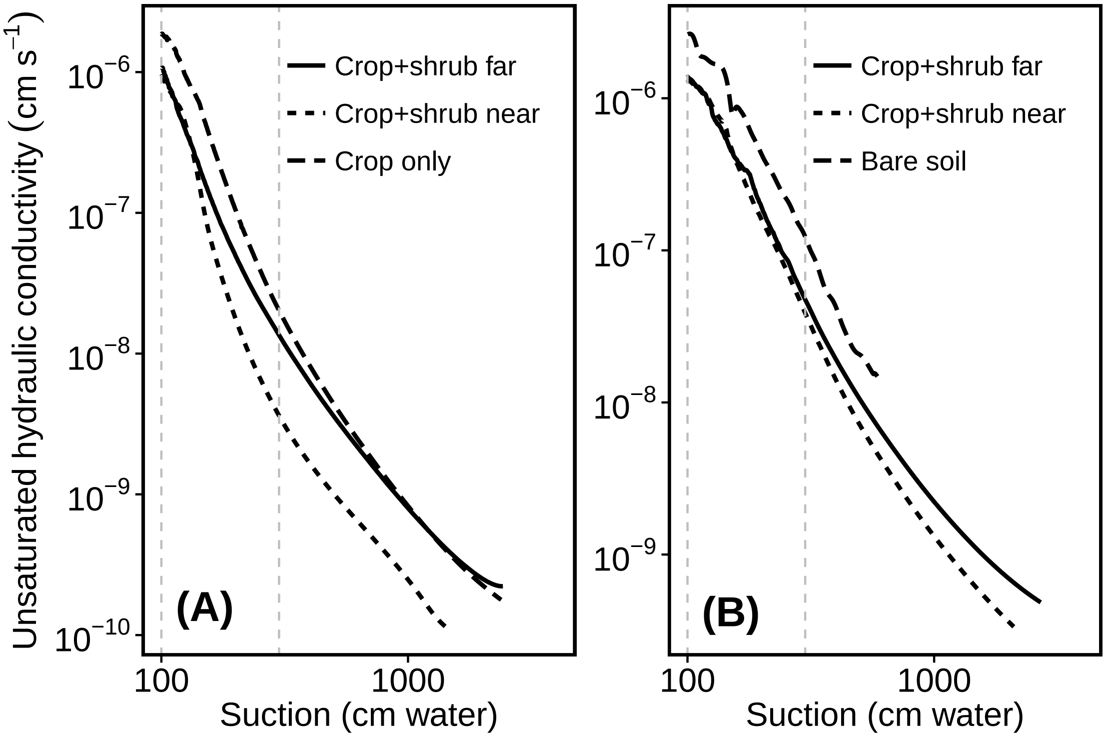

FIGURE 2.4. Comparison of unsaturated hydraulic conductivity measured with extended tensiometer technique from (A) Keur Matar in crop+shrub far (CSf), crop+shrub near (CSn), crop only (CO). (B) Nioro in the CSf, CSn, and bare soil (BS) plots. Dashed grey lines drawn at 100 cm and 333 cm of suction (field capacity) of tension for reference.

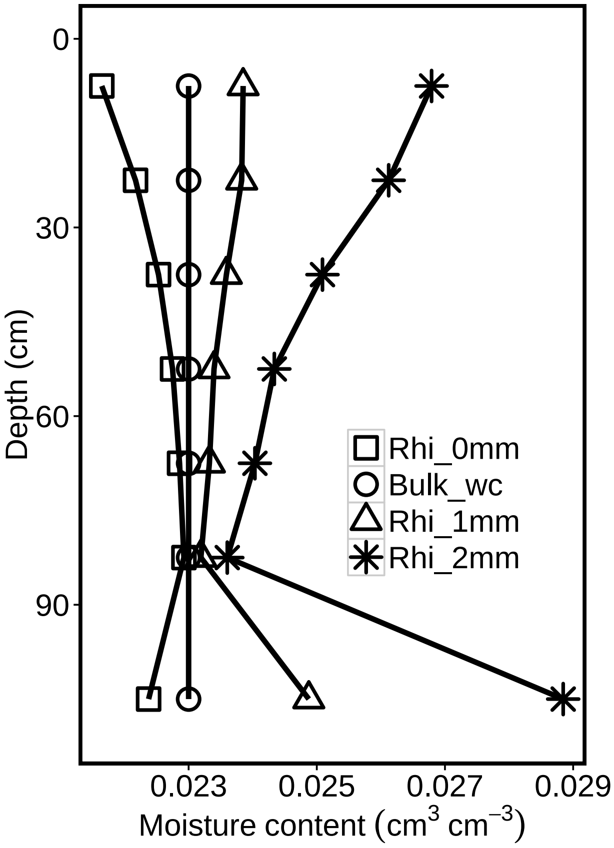

FIGURE 2.5. Simulated range of moisture contents in profile at 80 kPa in bulk soil as compared to a profile with alteration of soil by shrub roots. This takes into account the volume of the *G. senegalensis* root system surrounded by a 0-2 mm thickness of "rhizosphere influenced soil". Rhi_0mm indicates root presence with no rhizosphere, bulk_wc indicates soil with no roots or rhizosphere, Rhi_2mm is soil with roots and a 2 mm rhizosphere. Soil with mucilage exudate in the rhizosphere holds more water under drying conditions than pure mineral soil.

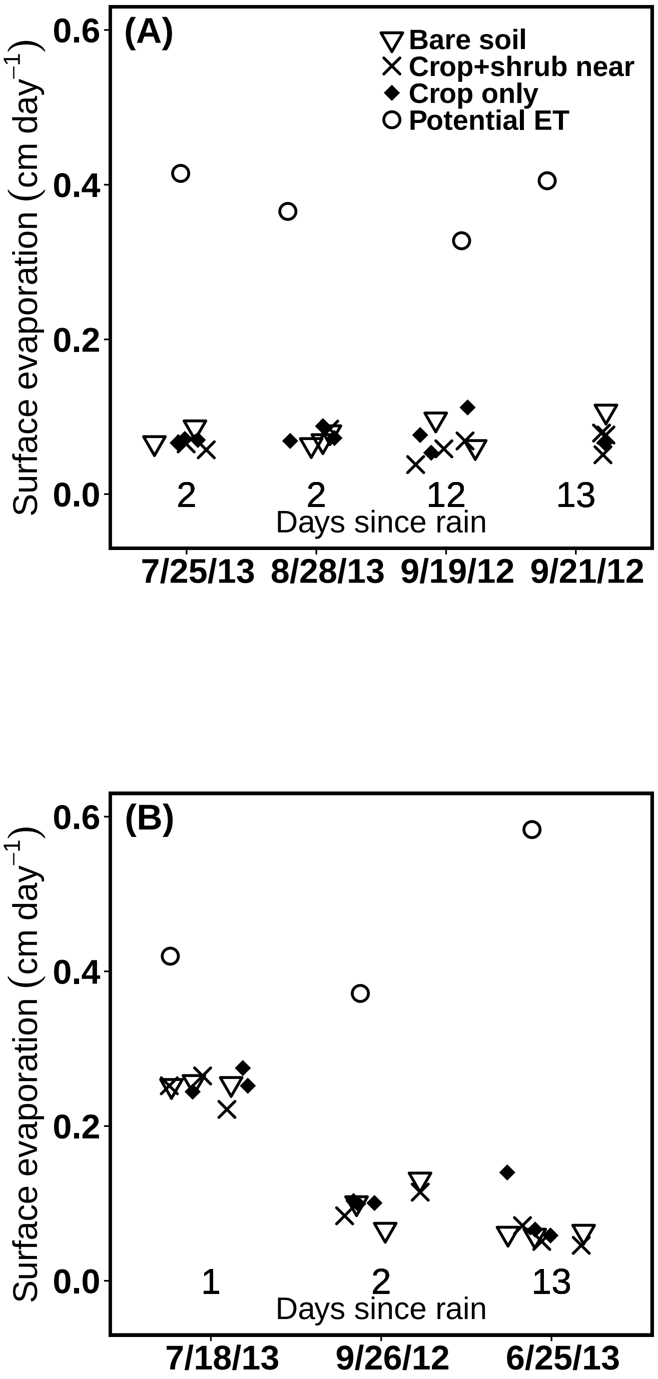

FIGURE 2.6. Field evaporation rates measured with microlysimeters on multiple dates at both sites. All raw data is presented. (A) Keur Matar, (B) Nioro. Potential evapotranspiration (PET) for the same 24 hour period as lysimeter measurements is shown by circles. Measurements taken in bare soil (BS), crop+shrub near the canopy (CSn) and crop only (CO) plots. Days since rain are days that have elapsed since the last rainfall event before lysimeters were installed in the field and measured.

TABLE 2.1. Selected soil physical and chemical properties from Keur Matar and Nioro.

Site & Measurement	Units	Year	Crop+shrub	Crop only	Unspecified	Location sampled	Ref.
Keur Matar							
pH	-	2003	5.2	5.4	-	Farmers' fields with fertilization	3
pH	-	2003	-	-	5.5	Farmers' fields, fertilization unknown	5
pH	-	2003	-	-	5.5	Farmers' fields with fertilization	3
CEC	[meq/100g]	before 1986	-	-	2	Bambey	6
exchangeable bases	[meq/100g]	before 1986	-	-	0.95	Bambey	6
Base Saturation	[%]	2003	-	-	55	Farmers' fields, fertilization unknown	5
sand	[%]	before 1986	-	-	91	Bambey	6
silt	[%]	before 1986	-	-	6	Bambey	6
clay	[%]	before 1986	-	-	3	Bambey	6
Bulk density	[g cm3]	before 1986	1.48(0.01)	1.54(0.01)	-	Farmers' fields with fertilization	4
Total C	[g/kg]	2003	3.35(1.44)	2.51(0.54)	-	Farmers' fields with fertilization	3
Total C	[g/kg]	2012	3.96(0.45)	3.04(0.40)	-	Keur Matar experimental plot (planting)	1
Total C	[g/kg]	2012	3.61(0.58)	2.70(0.22)	-	Keur Matar experimental plot (harvest)	1
Total C	[g/kg]	2013	2.07(0.18)	1.47(0.14)	-	Keur Matar experimental plot (planting)	1
Total C	[g/kg]	2013	3.44(0.48)	2.12(0.14)	-	Keur Matar experimental plot (harvest)	1
Nioro							
pH	-	2003	6.4	5.8	-	Farmers' fields with fertilization	3
CEC	[meq/100g]	before 1986	-	-	4.6	Nioro du Rip (unspecified location)	6
exchangeable bases	[meq/100g]	before 1986	-	-	4.7	Nioro du Rip (unspecified location)	6
sand	[%]	before 1986	-	-	77	Nioro du Rip (unspecified location)	6
silt	[%]	before 1986	-	-	16	Nioro du Rip (unspecified location)	6
clay	[%]	before 1986	-	-	5	Nioro du Rip (unspecified location)	6
Total C	[g/kg]	2003	5.77(0.4)	3.23(0.70)	-	Farmers' fields with fertilization	3
Total C	[g/kg]	Aug 2011	3.2	3	-	Nioro experimental plot (mid-season)	2
Total C	[g/kg]	2012	3.46(0.22)	3.34(0.16)	-	Nioro experimental plot (planting)	1
Total C	[g/kg]	2012	3.14(0.20)	2.86(0.04)	-	Nioro experimental plot (harvest)	1
Total C	[g/kg]	2013	3.04(0.10)	2.59(0.05)	-	Nioro experimental plot (planting)	1
Total C	[g/kg]	2013	3.00(0.17)	2.52(0.02)	-	Nioro experimental plot (harvest)	1

References [1] Personal comm. M. Bright; [2]Diakhaté et al. (2013), [3]Dossa et al. (2009); [4]Dossa et al. (2010); [5] Kizito et al. (2006); [6]Nicou (1986).

TABLE 2.2. Unsaturated hydraulic conductivity and water content at 100 cm suction, field capacity (fc), and wilting point (wp). The UNSODA Dior data is from the Unsaturated Soils Database (UNSODA) for the local Dior soil in the Keur Matar region. Numbers followed by the same letter at one of the sites are not statistically different. Wilting point water content is n = 3, the other water content and hydraulic conductivity is n = 1.

Site	Depth	Treatment	K_{100}	K_{fc}	θ_{100}	θ_{fc}	θ_{wp}
	cm		cm hr^{-1}		$cm^3\ cm^{-3}$		
Keur Matar	10	Crop and shrub near	3.37×10^{-3}	9.06×10^{-6}	0.08	0.03	0.03(0.006)a
	10	Crop and shrub far	3.89×10^{-3}	3.44×10^{-5}	0.10	0.05	0.016(0.001)b
	10	Crop only	6.75×10^{-3}	4.85×10^{-5}	0.09	0.04	0.023(0.003)ab
	100	Soil pit	3.90×10^{-3}	2.75×10^{-5}	0.05	0.02	–
	30-100	UNSODA Dior	–	–	0.09	0.04	–
Nioro	10	Crop and shrub near	4.96×10^{-3}	8.88×10^{-5}	0.13	0.06	0.035(0.002)c
	10	Crop and shrub far	4.72×10^{-3}	1.14×10^{-4}	0.12	0.06	0.035(0.002)c
	10	Bare soil	5.88×10^{-3}	3.29×10^{-4}	0.18	0.10	0.031(0.001)c
	100	Soil pit	9.30×10^{-3}	2.70×10^{-4}	0.17	0.12	–

TABLE 2.3. Durner-Van Genuchten bi-modal water retention fit parameters (Eqs. 2.6-2.5) for 10 cm and 100 cm samples at Keur Matar and Nioro.

Site	Depth cm	Treatment	θ_r cm^3	θ_s cm^{-3}	α_1 cm^{-1}	n_1 -	α_2 cm^{-1}	n_2 -	w_1 -	w_2 -
Keur Matar	10	Crop+shrub near	0	0.320	0.001	1.18	0.022	3.55	0.10	0.90
	10	Crop+shrub far	0	0.362	0.003	1.40	0.020	4.10	0.17	0.83
	10	Crop only	0	0.336	0.010	1.15	0.023	3.30	0.10	0.90
	100	Soil pit	0	0.297	0.015	1.50	0.021	3.90	0.15	0.85
Nioro	10	Crop+shrub near	0	0.350	0.042	1.24	0.021	3.29	0.35	0.65
	10	Crop+shrub far	0	0.364	0.0006	1.20	0.026	2.75	0.15	0.85
	10	Bare soil	0	0.393	0.026	1.22	0.015	3.00	0.39	0.61
	100	Soil pit	0	0.357	0.08	1.13	0.024	2.66	0.50	0.50

TABLE 2.4. Bulk densities (ρ_b) at different depths at Keur Matar and Nioro measured in the shrub treatments in the experimental plots and in soil pits just outside of experimental plots. In crop only (CO) crop+shrub near the canopy (CSn), crop+shrub far from the canopy (CSf), and in soil pits just outside of both experimental plots. Values that are significantly different when compared within sites (Keur Matar, Nioro) ($P < 0.1$) are marked with different letters.

Site	Depth cm	Treatment	ρ_b g cm^{-3}
Keur Matar	10	Crop+shrub near	1.606(0.007)a
	10	Crop+shrub far	–
	10	Crop only	1.619(0.002)b
	20	Soil pit	1.587 (0.003)
	40	Soil pit	1.531 (0.002)
	60	Soil pit	1.549 (0.006)
	100	Soil pit	1.547 (0.008)
Nioro	10	Crop+shrub near	1.496(0.012)ns
	10	Crop+shrub far	1.485(0.025)ns
	10	Crop only	1.468(0.025)ns
	20	Soil pit	1.397 (0.005)
	40	Soil pit	1.429 (0.013)
	60	Soil pit	1.484 (0.005)
	100	Soil pit	1.520 (n=1)

Mean values with SEM in parentheses for n=4 (Keur Matar study plots) and n = 3 (Nioro study plots and both soil pits).

TABLE 2.5. Two-way analysis of variance (ANOVA) of soil surface evaporation measured with microlysimeters at two sites with shrub presence is a treatment factor and date is a blocking factor.

Site	Treatment	Df [1]	MS [2]	F [3]	P [4]
Keur Matar	Shrub presence	2	0.00049	1.83	0.18
	Date	3	0.00012	0.445	0.72
	Residuals	21	0.00027		
Nioro	Shrub presence	2	0.00033	0.733	0.49
	Date	2	0.087	193.3	< 0.001
	Residuals	21	0.00045		

[1] Df = degrees of freedom; [2] MS = mean squared variance,
[3] F =ANOVA F-statistic; [4] P = P-value

CHAPTER 3

Water Relations and Plant Physiology of Food Crops and Native Woody Shrubs in the Sahel

Prepared for submission to: Plant and Soil

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Abstract

Large differences in crop success have been observed even during drought stress when crops are interplanted with two native evergreen shrubs in Senegal. This study investigates how these two shrubs, *Piliostigma reticulatum* D.C. Hochst, and *Guiera senegalensis* J.F. Gmel can alter the moisture and temperature regimes in agricultural fields, and how they affect the growth and physiology of associated crops. Crops of peanut *Arachis hypogea* and pearl millet *Penisetum glaucum* were monitored in plots at Keur Matar Arame and Nioro du Rip with no added fertilizer and a treatment of crop+shrub (CS) and crop only (CO) from 2012-2013. At Keur Matar the presence of shrubs can increase plant available water in the shallow zones in the early season by up to 14%. Additionally, at Keur Matar the shrubs moderate the temperature in the early part of the season by keeping daily maximum temperature 5°C cooler in the CS treatment. At Nioro the results showed decreased moisture content in the CS compared to the CO plot at 10 cm depth, but an increase of moisture of 18-20% of plant available water at 20 cm depth in the CS plot compared to the CO. The temperature differences were less pronounced at Nioro with the daily maximums were 0-5°C cooler in the CS plot than in the CO. At both sites the presence of shrubs increased LAI, and NDVI, and significantly increased the water potential on multiple dates. Soil moisture was monitored with two sensor networks to a depth of 3 m. At the beginning of the dry season just after the crop harvest, maximum weekly transpirational water use by the shrubs descends from 100 to 300 cm over the course of one to two months. These results show that the majority of water use by shrubs comes from below 3 m depth within 100 days after the harvest in October. This builds on previous work at the site investigating growing season water balance, and the alteration of soil physical properties by shrubs and their aboveground biomass that is spread over the surface of the fields.

3.1. Introduction

Subsistence farmers in the Peanut Basin of Senegal, as in most of the Sahel region, routinely face low crop yields as a result of moisture, nutrient, and heat stress. The vast majority of farming is rain-fed and involves minimal input of organic matter, fertilizers, or pesticides. Farmers mostly grow drought resistant crops such as millet, peanut, sorghum, and cowpea that have escape and avoidance mechanisms for combatting abiotic stress. The region suffers from erratic rainfall patterns, excessive heat stress, poor soil fertility, and low economic status of farmers (United Nations, 2014). As a result, staple crop productivity has remained nearly flat for over fifty years, while acreage of cultivated land has tripled in many areas to match the population growth (FAO, 2015).

Mean annual precipitation ranges from 100-200 mm in the Northern Sahel, on the border of the Sahara desert, to 500-600 mm in the Southern Sahel, where it meets the Sudan (Nicholson, 2013). The rains last one to two months in the north and four to five months in the south, with a maximum rainfall quantity in August or September (Fig. 3.1). As a result, the Northern part of the basin is prone to more precipitation shortfalls and drought spells, especially during the early stages of crop growth. Crop yield is highly impacted when annual precipitation falls below 500 mm (Mahul et al., 2009).

Crops are most vulnerable at the early growth stage before their roots are well developed in the soil profile (Garcia-Huidobro et al., 1982a), and at flowering and early grain filling stages (Winkel et al., 1997, 2001; Emendack et al., 2011). Both of these development phases happen at the margins of the rainy season when the timing and quantity of rainfall are the most uncertain (Fig. 3.1). The problem is exacerbated by limited moisture storage in the shallow root-zone. The soils of the region are highly permeable and have little water holding capacity. Drought effects are further compounded by poor soil fertility. Crops facing low nutrient availability often increase their stomatal conductance, at the expense of severe drop in water use efficiency. The opening of stomata leads to increased moisture use, which depletes the root zone of water and can accelerate the onset of drought stress (Lipiec et al., 2013). Moreover, stressed crops are also vulnerable to pests and diseases (Dordas, 2009). All of these challenges are likely to increase with climate change and further growth of population in the region.

Farming techniques that create a lasting solution to the above problems are clearly needed. Any practices adopted in the region must be well-suited not only to the environmental stresses, but to the cultural practices of the farmers in the Sahel. This means using agricultural approaches that can boost crop productivity and build soil quality without large amounts of external inputs.

The technique of intercropping with native woody shrubs is practiced by many farmers, and has shown clear benefits to crop production in a limited number of studies (Fig. 3.2) (Dossa et al., 2012; Wezel and Böcker, 1999). Islands of soil fertility surrounding shrubs, tress, and termite mounds have been observed throughout the arid and semi-arid regions of the Sahel, Sudano-Sahel, and Savannah (Belsky et al., 1989; Wezel et al., 2000; Lahmar et al., 2011; Bonachela et al., 2015; Hernandez et al., 2015). Several mechanisms by which the shrubs can increase the viability of the agricultural system have been proposed. Tap-roots of the shrubs over 3 m deep have been shown to help recharge deep soil layers during the rainy season and to help retain soil moisture during periods of water stress compared to soils outside of the shrub canopy (Burgess et al., 1998; Kizito et al., 2007). Soil water transfer from deep, moist soil layers to shallow and dry layers by hydraulic lift is another mechanism thought to provide increased soil moisture (Kizito et al., 2012). Increase in abundance and diversity of potentially beneficial microbes around the shrub rhizosphere may also contribute to the observed yield increases (Debenport et al., 2015; Diakhate et al., 2016). A number of projects have been carried out in the region to study the soil water balance (Kizito et al., 2007; Gaze et al., 1998), shrubs and their potential to increase nutrient availability (Lufafa et al., 2008; Diedhiou-Sall et al., 2013) , crop productivity (Dossa et al., 2012) and soil nutrient cycling (Dossa et al., 2009, 2010).

The physiological response of pearl millet (*Penisetum glaucum*) or peanut (*Arachis hypogea*) to intercropping with shrubs during the rainy season is not fully understood. Additionally, Kizito et al., (2006,2007) established higher moisture levels near the shrubs, and a likely spatial and temporal separation of water use by crops and associated shrubs. The overall goal of this study is to investigate the response of peanut and millet to intercropping with native woody shrubs *Guiera senegalensis* and *Piliostigma reticulatum*. Specifically, this study aims to elucidate (a) further possible mechanisms for increased vigor of shrub-associated crops during the season, (b) how shrubs can alter soil moisture and temperature at different times during the season, and (c) the dynamics of shrub moisture use below the crop rooting zone at the end of the rainy season.

3.2. Materials and Methods

3.2.1. Site description. The study was conducted at two research areas located in the Peanut Basin of Senegal. The first site is located in the village of Keur Matar Arame (14° 46’N, 16°51’W) in the Northern part of the basin. Rainfall is unimodal with mean annual precipitation of 450 mm. Mean annual temperature is 26°C and minimum and maximum temperatures are 11°C and 43°C, respectively. Relative humidity ranges from 50-100% during the rainy season. The soil is classified as a Rubic Arenosol (USDA Psamments), locally known as Dior soil, and its texture is 3% clay 6% silt and 91% sand and consists mostly of aeolian deposits emplaced by the Harmattan winds (Renaud, 1961; Nicou, 1986; USDA, 2015). The chemical composition of the soil includes 0.3% total C and 0.02% total N with a P content of 95 mg kg^{-1}(Nicou, 1986; Michéli et al., 2006). The water table is 11 m below the ground surface as measured by authors in 2013, and the site is 54 m above sea level (Google Inc., 2016). *Guiera senegalensis* J.F. Gmel. (Combretaceae) is a native evergreen woody shrub that is the dominant vegetation in the area and it is often found in farmers’ fields.

The second site is located at Nioro du Rip (13°45N 15°47’W) in the Southern part of the Peanut Basin. Rainfall is also unimodal but the mean annual precipitation is 750 mm and is higher than the rainfall at Keur Matar. Mean annual temperature is 28 °C and yearly minimum and maximum temperatures are 9 °C, and 44 °C, respectively. Relative humidity ranges from 50-100% during the rainy season. The site is predominantly occupied by *Piliostigma reticulatum* (DC.) Hochst (Caesalpinioideae), a native evergreen woody shrub that is commonly found in the fields of farmers. The soil is sandy, highly weathered, lateritic in areas, and is classified as Haplic Ferric Lixisol (USDA Alfisol) (FAO, 2006, USDA 2015). The soil texture is 5% clay 16% silt and 77% sand, and total C and total N are 0.35% and 0.04%, respectively (Nicou, 1986). The study plot lies at 18 m above sea level and the water table is approximately 18 m below ground surface,

3.2.2. Design and management of experimental plots. The research plots at both sites have been in existence since 2003. Prior to that, for at least 50 years, both sites were in a yearly crop rotation between peanuts and millet under local farmer management.

G. senegalensis and *P. reticulatum* existed at their native densities of 239±74.6 and 185 shrubs ha^{-1} at the sites of Keur Matar, and Nioro, respectively, and the majority of the shrub plots had their shrubs at native density prior to 2003. In 2003 additional shrubs were planted in crop and shrub plots to bring their density to 1500 to 1833 shrubs ha^{-1} at Keur Matar and 1000-1300 shrubs ha^{-1} at Nioro as counted by the authors and reported by Dossa et al. (2012). The plots were divided into four randomized complete blocks with 8 subplots in each block (6 m $\times$ 10 m at Keur Matar, 4.5 m $\times$ 10 m at Nioro) randomly assigned two levels of shrub treatments (crop only (CO) and crop+shrub (CS)) and four levels of fertilizer treatments ($0\times, 0.5\times, 1.0\times, 1.5\times$ recommended rate). All of the plants and soils studied here are from the 0 fertilizer CO and CS plots, additional soil moisture measurements were made in the un cultivated space between two blocks and is referred to here as the bare soil (BS) treatment.

The fields were prepared by cutting shrub material at the ground surface before the arrival of the rains in late May. The coppiced shoots and leaves were cut into approximately 5 cm pieces and spread over the shrub plots manually. After the spreading of biomass, a horse and plow passed over the area turning the soil to a depth of 6 cm and incorporating some of the shrub material into the soil. Subsequent weeding and cutting occurred after crop emergence and near the time of flowering. The surface coverage of the shrub mulch in the CS plots after the first cutting and tilling was estimated visually in a range from 40-60%, depending on the plot. Subsequent cuttings produced less biomass and less coverage of the soil surface. The shrubs were cut one last time around harvest in October or November and the biomass returned to the field before the dry season. The practices described here, except chopping and spreading of biomass, are standard procedures employed by the local farmers. The management technique of the local farmers involves burning shrub biomass in the fields at the beginning of the growing season and leaving the ashes in the field. The farmers burn the biomass mainly to avoid large sticks from the field that can interfere with ploughing and because of lack of adequate labor and equipment to chop and spread the biomass.

The traditional farming practice of the region, and the practice employed in this study is to plant a rotation of peanut *Arachis hypogea* var. Fleur-11, and pearl millet *Penisetum glaucum* var. Souna-III. At Keur Matar peanuts were sown every 15 cm with 50 cm between rows, millet was sown with 1 m spacing between plants and 1 m spacing between rows. Millet was planted with 5-6 seeds per hole at 3-5 cm depth and thinned to 1-2 plants per hole after emergence. In 2012 peanut was sown on July 1 at Nioro and July 9 at Keur Matar. In 2013 at Keur Matar millet was sown on June 22 before the rains came, following the practice of many local farmers. This planting in June 2013, however, desiccated post-emergence due to heat and drought stress and was fully re-seeded on July 22. Millet was sown on June 28, 2013 at Nioro. In 2012 peanuts were harvested at Nioro on October 20, and at Keur Matar on October 16. In 2013 millet was harvested at Nioro on October 8 and at Keur Matar on October 21.

3.2.3. Meterological data. All meteorological and soil measurements were recorded every 15 minutes and logged on a datalogger (CR1000, Campbell Scientific, Logan, UT). Rainfall was measured using a tipping bucket rain gauge at 2 m elevation above the soil surface and totalized every 15 minutes (TE-525m, Campbell Scientific, Logan, UT). Rainfall data for Keur Matar in 2012 was taken from a tipping bucket rain gauge at an agricultural station 3.6 km from the experimental site (Decagon Devices, Pullman, WA) . Temperature and relative humidity were recorded with a probe (HMP 60 Vaisala/Campbell Scientific). Net radiation was measured with a net radiometer (Kipp & Zonen NRLite 2, Bohemia, NY). Wind speed and direction were measured with an anemometer (03002 Young, Campbell Scientific, Logan, UT). Rainfall data for (Fig. 3.1) was extracted from the GPCC monthly Version 7 dataset by finding the latitude and longitude of the closest pixels to the two field sites, extracting monthly rainfall data from the rasters, and calculating cumulative sums for the years 2009-2013 (Schneider et al., 2014). On September 16, 2013 a rain event of approximately 18 mm was missed due to a power failure.

3.2.4. Soil temperature and water status. Soil capacitance and temperature sensors were used which measured measured the dielectric permittivity, temperature, and electrical conductivity of the soil in the zone surrounding the sensor (5TM and 5TE, Decagon Devices, Pullman, WA). In 2012, sensors were installed at 20,40,60, 100, 200 cm in the CO plot with duplicate sensors at 20 cm in the CO plot. A similar network was installed in CS plots with 20 cm depth sensors at radial distances of 50 and 100 cm from the center of the shrub, a single sensor at 300 cm, and a duplicate 60 cm depth sensor at a radial distance of 50 cm from shrub (Appendix C, Fig. C.1). In 2013 additional sensors were installed at 10 cm in all three treatments, and at 300 cm under the CO and BS plots. Sensors were calibrated in the field by measuring soil moisture content gravimetrically at multiple times throughout the year at both sites and converting gravimetric values to volumetric water content using the bulk density (Chapter 2). The following regression equation was obtained: $y = 0 + 0.45x + 0.92x^2$ where x is volumetric water content calculated from sensor output using the Topp equation and y is the true volumetric water content (Topp et al., 1980). A second-order polynomial fit represented the data better than a linear fit, and the y-intercept was set at zero to avoid physically impossible values below zero. The accuracy of the regression equation is ± 0.046 m^3 m^{-3}. This calibration is comparable to recently published papers Kinzli et al. (2011); Sharma et al. (2016). Gaps in the data stream are due to erroneous records and/or datalogger malfunctions, and were particularly acute in any sensors that had ever been read in SDI-12 mode.

Data was read through a multiplexer (AM 16/32, Campbell Scientific, Logan, UT) and recorded every 15 minutes on the datalogger described above. All data was checked for out of range values, a median filter was then applied to soil moisture and temperature values, and then it was manually checked for any erroneous values, or false negatives from the median filter. Hourly means of soil moisture data were calculated from the cleaned datasets.

Deep moisture data was plotted as hourly data with any gaps interpolated linearly, and then daily change in moisture was found by subtracting daily minimum from daily maximum and contour heat map by depth, daily moisture reduction, and time using R was created (Fig. 3.10-3.11) (R Core Team, 2016). Where reported, plant available water (PAW), is taken as the difference between water content at 100 cm of suction and water content at wilting point (15 000 cm suction).

3.2.4.1. *Estimation of seed-bed temperature.* The seeds were placed at approximately 5 cm below soil surface. Therefore, germination and seedling emergence were likely impacted by high soil temperatures. The soil sensors at 20 cm (in 2012) and 10 cm (in 2013) were partially insulated by the overlying soil and do not reflect the actual range of temperature experienced by the seeds and emerging roots. Therefore data from the deeper soil sensors was used and one dimensional (vertical) heat transfer model to infer the seed-bed temperature was applied. Combination of heat conservation and heat diffusion gives rise to a mathematical description of heat transfer as

$$c\frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left(\lambda\frac{\partial T}{\partial z}\right) \tag{3.1}$$

where T is soil temperature, which varies with depth (z) and time (t); c is volumetric heat capacity [MJ m^{-3} °C^{-1}] and λ is apparent thermal conductivity [J m^{-1} s^{-1} °C^{-1}]. By neglecting the dependence of c and λ on water content under dry conditions (hence, depth) Eq. (3.1) can be linearized as

$$\frac{\partial T}{\partial t} = D_H\frac{\partial^2 T}{\partial z^2} \tag{3.2}$$

Where $D_H = \lambda/c$ is apparent thermal diffusivity. The soil surface boundary condition can be described using a sinusoidal fluctuation,

$$T(0,t) = \overline{T} + T_0\ \sin(\omega t) \tag{3.3}$$

where $\overline{T}$ is the average temperature of the soil, T_0 is the amplitude of the soil surface temperature fluctuation, and $\omega = 2\pi/P$ is the angular frequency with a daily periodicity of $P = 24$hr. The temperature at very large depth is assumed to remain constant,

$$T(\infty,t) = \overline{T} \tag{3.4}$$

The solution to Eq. (3.2) subject to the boundary conditions Eqs. (3.3) and (3.4) is given by (Horton et al., 1983),

$$T(z,t) = \overline{T} + T_0\ \exp(-z/d)\ \sin(\omega(t-8) - z/d) \tag{3.5}$$

where d is the characteristic damping depth, at which the temperature fluctuation is reduced to the fraction $1/e$, is given by

$$d = \sqrt{2D_H/\omega} = \sqrt{PD_H/\pi} \tag{3.6}$$

From Eq. (3.5), the amplitude of temperature fluctuations at depths z_1 and z_2 can be deduced as,

$$A_1 = T_0\ \exp(z_1/d) \text{ and } A_2 = T_0\ \exp(z_2/d) \tag{3.7}$$

By combining Eqs. (3.6) and (3.7), the thermal diffusivity can be expressed a function of the amplitudes by

$$D_H = \frac{\pi(z_1 - z_2)^2}{P\,(ln\,[A_1/A_2[])^2} \tag{3.8}$$

Therefore, by plugging measured daily temperature fluctuations A_1 and A_2 at two depths z_1 and z_2 in Eq. (3.8) it is possible to deduce the effective thermal diffusivity D_H (Jackson and Kirkham, 1958). For this purpose, 2013 data from the 10 cm and 20 cm sensors were used. The mean soil temperature $\overline{T}$ and amplitude of the surface temperature T_0 can be estimated by fitting Eq. (3.5) to a time-series of soil temperature at any depth. For this purpose, 15-minute temperature data collected at 10 cm depth was used. Then, the fully parameterized Eq. (3.5) can be used to predict soil temperature dynamics at any arbitrary depth. This solution was used to estimate the temperature at 5 cm depth during the early stages of germination.

3.2.5. Crop physiology.

3.2.5.1. *Leaf water potential.* Leaf water potential of peanut and millet plants was measured with a Scholander-type pressure bomb (PMS Instruments, Albany, OR). Samples were read before dawn, between 1330h and 1930h and in the evening just before the sun went down, around 1800h. In each of 3 subplots 2-3 readings were made for a total of 8-12 measurements per treatment and time. Before each day of measurement the chamber was pressure tested to 20 bar to make sure there were no leaks. Additionally a small amount of clay or putty was added to the underside of the gland where the leaf was inserted to help avoid leakage during measure. For millet the youngest fully expanded upper canopy leaf fully exposed to sun/sky was chosen, for peanut the third tri-foliate leaf was chosen. A plastic bag was then placed around leaf and seal around stem. The stem was cut evenly with a sharp razor as close to the base of the leaf as possible. For millet leaves the leaf material was cut away from the central vein, and the central vein was inserted into the apparatus for measurement. Each sample was read within 3 minutes of being cut. This was accomplished by having one person in the field cutting, and one person making readings with the pressure bomb. To read the water potential the pressure was increased 0.2 bars at a time water was seen leaving the xylem with a magnifying glass.

3.2.5.2. *Greenness.* Water and nutrient status was measured using a handheld normalized differential vegetation index (NDVI) sensor (Greenseeker, Trimble, Sunnyvale, CA). NDVI was first developed using remote sensing data to measure the photosynthetic status of plants (Rouse Jr et al., 1974). The NDVI is a ratio calculated based on (Eq. 3.9).

$$NDVI = \frac{NIR + VIS}{NIR - VIS} \tag{3.9}$$

Where NIR (near infrared) and VIS (visible) are reflectances in the 550-700 nm and 700-1300 nm wavelengths, respectively. In order to make consistent readings, a 60 cm string was attached to the handle of the handheld unit with a weight hanging down at each reading the device was placed 60 cm above the flag leaf of a millet plant, or in the case of plants lacking tillers, it was placed 60 cm above the highest leaf. In order to eliminate the interference of green shrub material in shrub plots when it was present, shrub material was either pruned, or a piece of brown cardboard was placed over any shrub material when readings were taken. Five measurements were taken in each plot one near each corner, and one in the center for a minimum of n = 15 per treatment. NDVI was not measured in 2012 on peanut plants.

3.2.5.3. *Leaf Area Index.* Leaf area index (LAI) was modeled using a ceptometer that measured photosynthetically active radiation (PAR) above and below the canopy (AccuPAR LP80, Decagon Devices, Pullman, WA). The ceptometer was calibrated according to instructions in manual using external PAR sensor. Readings were taken around 1030 h for all sites. Five readings per subplot were made in CO and CS plots in 3 of 4 blocks (blocks 2-4 Keur Matar, blocks 1-3 Nioro) for a minimum of n = 15 per treatment. The readings were taken with the ceptometer wand with all of the sensors on and parallel with the lines of crops for millet, and perpendicular to crop rows spanning two rows for peanut. Readings were made along the central rows of crops within each plot to avoid edge effects.

3.2.6. Hydraulic redistribution potential. Hydraulic gradient was calculated between between depths as follows: 10-200 cm, 10-300 cm, 20-200 cm and 20-300 cm for the 2013 growing season by using converting sensor-measured volumetric water content to water potential using water retention curve parameters from the site (Chapter 2) (Zurmühl and Durner, 1998) and using the soil surface as a reference depth, measuring depth negative downwards. This is used to infer when a hydraulic gradient between deep and shallow soil layers would indicate flow in the upward direction:

$$\frac{\Delta\, H}{\Delta\, z} = \frac{(z_2 + h_2) - (z_1 + h_1)}{(z_2 - z_1)} \tag{3.10}$$

Where z is the elevation of the measurement using soil surface as the reference elevation [cm], and h is the matric potential measured measured in cm water of suction [cm] at depths 1 and 2.

3.2.7. Statistics. Welch's two sample t-tests were used for comparing means for both leaf water potential, LAI and NDVI (R Core Team, 2016). Significant differences were considered to be $P < 0.10$.

3.3. Results

3.3.1. Soil moisture and temperature. Hourly volumetric soil water content and temperature records at 5 depths in the top 100 cm are reported in Figures 3.3 - 3.4. In addition, daily precipitation and hourly air temperature are shown. The data spans from the onset of the rainy season until several days after harvest. At depths where multiple sensors were installed mean values are reported.

Before the start of the rains at Keur Matar (in both years), the water content at 20 cm in the CO treatment was comparable with that of the CS treatment (Fig. 3.3). Similarly, at 10 cm in 2013, the soil moisture in both treatments were nearly identical before the rains commenced. The moisture at 10 and 20 cm depths after most major rain events were higher in the CS treatment than the CO treatment. The top 20 cm soil also stayed wetter in CS treatment for most of the growing season. The range of plant available water (PAW) is 0.07 $m^3\ m^{-3}$. At 10 cm, there was a difference 0.01 $m^3\ m^{-3}$ which represents 14% of PAW. At 20 cm the differences at Keur Matar were on the order of 0-0.01 $m^3\ m^{-3}$ for the first week after sowing representing 0-14% of PAW. At 60 cm and 100 cm depths, the wetting front arrives 1 - 5 days sooner in the CO treatment in 2012, though the difference is minimal in 2013. The moisture at 100 cm was consistently higher, by up to 0.035 m^3 m^{-3}, in the CO treatment.

At 10 cm at Nioro CO stayed wetter than CS by 0.03-0.05 m^3 m^{-3} throughout the season, representing an increase of 27-46% of PAW. The water content at 20 cm for the first thirty days of the growing season, did not show discernible difference between the treatments (Fig. 3.4). By August of 2013, however, there was 0.01-0.02 m^3 m^{-3} more moisture at 20 cm in the CS plots, representing 9-18% more PAW in the CS plots. Similarly, the soil at 20 cm and 40 cm in the Crop Only treatment was wetter than the Crop and Shrub treatment. As in Keur Matar, the wetting front at Nioro reached the 100 cm depth earlier in the CO treatment while the CS treatment remained consistently wetter after the mid-season.

The precipitation was overall higher and more evenly distributed at Nioro than at Keur Matar. As a result of the rainfall distribution and the soil texture, the soil at Nioro was wetter than at Keur Matar at all depths. While the shrubs in Keur Matar appeared to have helped in keeping the moisture in the shallow layers, they had the opposite effect in Nioro. However, the delay in the wetting front arrival at 60 cm and 100 cm depths in the presence of shrubs was consistently observed in both sites.

The temperature record shows that shrubs had a cooling effect during both years at both sites. The highest differences were observed in the shallowest layers but differences as high as 0.5-2° C persisted down to 100 cm as well. The diurnal range of fluctuation was wider in the CO treatments. Diurnal fluctuation was observed down to 60 cm in both years at both sites.

At Keur Matar, during the 2012 growing season, the highest daily maximum occurred in late September. The median difference between the treatments in daily maximum temperature at 20 cm was 1.5° C and the largest difference was 4.0° C. During the 2013 growing season the 10 cm sensors were consistently warmer in the CO treatments with a median difference in daily maximum of temperature of 4.0° C and a maximum difference of 9.0° C.

At Nioro, the 20 cm soil temperature during early parts of the 2012 growing season was comparable at in both treatments. But following planting, and regrowth of the shrubs, the

CS treatment remained cooler, with differences in daily maximum temperature of 1 to 3°C. The soil temperature at 10 cm during early July of 2013 were also comparable between the treatments. After mid July the CS treatments were cooler by an average of 6 °C than the CS treatment. During both years, the range of daily temperature fluctuations were higher in the CO treatment, particularly at the 10 cm depth.

3.3.2. Germination temperature. Soil temperature dynamics at 5 cm depth during the early stages of germination of 2013, which were estimated using Eqs. 3.5 to 3.8, are shown in Figure 3.5. For reference, percentage of successful germination of two pearl millet varieties at wide range of temperatures reported by Garcia-Huidobro et al. (1982b) is also shown.

At Keur Matar, the daily maximum temperature in the CO treatment was warmer by approximately 5° C for over a week. The mid-day temperatures in the CO plots were within the range that resulted in significant reduction in germination success in the study by Garcia-Huidobro et al., (Garcia-Huidobro et al., 1982b). In contrast, in Nioro the treatments exhibited nearly identical temperature patterns during the early stages of growth.

3.3.3. Profile hydraulic gradient. The hydraulic gradient was calculated for the differences between the 10 and 20 cm and the 200 and 300 cm depths under the CS treatment (Figs. 3.6 and 3.7). At Keur Matar The hydraulic gradient between 10 cm and the 200 and 300 cm depths stays positive (upward flux) until late July when the first infiltration happens (Fig 3.3) and millet is sown, then the gradient goes strongly downwards as the moisture is redistributed throughout the profile by gravity. At Nioro the trend is similar but the gradients are much lower, on the order of 20 cm cm^{-1}. Most profile moisture redistribution happens at the gravitational gradient which is ± 1, so the gradients shown here, both upwards and downwards sustain a high absolute magnitude over a long period of time.

3.3.4. Plant physiology. The LAI and NDVI values of the crops measured at multiple stages of the crop growth are reported in Tables 3.1 and 3.2 . At Keur Matar there were significant differences in LAI of peanuts (2012) only on the last measurement (63 days after sowing), where CS had an LAI that was 45% higher than CO. In 2013, LAI of millet was measured once (52 DAS) and significant difference were reported, with the LAI in CS

166% higher than CO. At Nioro on day 33 days after sowing the LAI in the CS plot was significantly higher than in the CO plot by 23%, but this was the only date with significant differences. In 2013 at Nioro millet had a significantly higher LAI in CS plots compared to CO by 47% and 71% on days 68 and 83 after sowing, respectively. Overall, the differences between treatments were larger in millet than in peanut at both locations.

Figures 3.8 and 3.9 show crop leaf water potential measured at three dates during the growing seasons 2012 (millet) and 2013 (peanut) at Keur Matar and Nioro. As a note *suction* here refers to water potential and *high suction*, for the purposes of this paper means a highly negative water potential.

In 2012 at Keur Matar at 45 DAS the only significant difference was the evening measure with a difference of 0.15 MPa this measurement was taken as peanuts sending gymnophores into the soil. For the 63 DAS measures there were significant differences in the predawn value and the evening, but not the midday value. When the 63 DAS measures were taken, the CS plots were already in full flowering phase (50% of individuals), whereas the CO plots had far fewer flowering plants (unpublished data). The 72 DAS measures showed that CS plots had significantly higher predawn suction. Midday the crop only had higher suction, and in the evening there was no significant difference between the two.

In 2013 at Keur Matar the millet crop had much smaller differences in leaf water potential and there was only significant differences between treatments on two dates (Fig. 3.8). At the first measurement 52 days after sowing CS had higher suction in the evening, and 74 days after sowing CS had higher suction in the evening. Throughout the measurement period CS plots were much further along in their developmental cycle (Diedhiou et al., in prep).

At Nioro in 2012 at 46 DAS there were significant predawn differences in peanut leaf water potential, but no significant difference at the other times of day (Fig. 3.9). On 60 DAS there were highly significant midday water potential differences in the midday measurement ($P < 0.001$). Part of this may be due to the fact that the shrub canopy was growing up around some of the peanut plants and partially shading them. There were also significant differences in the evening measurement, but the differences were not as large. On 74 DAS in 2012 there were significant differences in the predawn and midday suction. Both of the highly significant differences in suctions occurred when the soil was beginning to dry and it had been a few days (at 60 DAS) to more than a week (at 74 DAS) since the last rainfall event.

At Nioro in 2013 There were fewer significant differences in millet water potential with the only one coming at a late measurement date, 83 DAS. At Nioro there was a strong millet crop in 2013 3.2 and ample rainfall (Fig. 3.4).

3.3.5. Deep moisture use. The spatial and temporal dynamics of soil water content after the harvest of 2013, at both sites, are shown as rasterized two-dimensional heat-maps in Figures 3.10 and 3.11. Data from all functioning sensors between 100 cm and 300 cm were spatially interpolated to populate the grid space. The color range indicates net daily (noon to noon) change in volumetric water content. Positive values indicate water use and negative values indicate an increase in soil moisture. The raw data that this was calculated from is presented in (Appendix C).

At both sites in 2013 the weeks after harvest the highest daily reduction in moisture content occurred near 100 cm (Figs. 3.10 and 3.11). At Keur Matar, the 100 cm soil layer began to lose moisture in mid to late November in BS and CO plots. The moisture depletion occurred as diurnal fluctuations of 0.002-0.006 m^3 m^{-3}, which is below the accuracy range but within the measurable precision of the sensors. In the CS plots the diurnal fluctuations occurred only sporadically and for short periods, and large reduction in moisture content did not occur until late December. At 200 cm the CO and bare soil (BS) sensors went through a similar decrease in moisture content with diurnal fluctuations in early and mid-December, respectively. Both of these were accompanied by diel fluctuations in moisture content. At 300 cm depth the largest moisture reductions came in early January in the BS plots. There are distinct diurnal fluctuations at this depth and these have the largest measured magnitude of 0.006-0.008 m^3 m^{-3} day^{-1}. The CS sensor goes through a steady decline in moisture content during this same time, and the crop only sensor stopped working in late December.

At Nioro the largest reduction occurred in the 100 cm sensors with an overall reduction of 0.06 m^3 m^{-3} over a period of 2.5 months. The fastest reductions occurred with diel fluctuations of 0.006 to 0.008 m^3 m^{-3} day^{-1} in November. In the BS and CS plots the highest moisture reductions occurred in late November and early December. The moisture declined steadily in until march then leveled off around 0.11 m^3 m^{-3} but just before it levelled off it underwent a slight increase of 0.01 $m^3\ m^{-3}$. At 300 cm the declines occurred steadily for all treatments with some of the largest diel fluctuations occurring after February 1 in the BS plot with fluctuations of 0.004 $m^3\ m^{-3}\ day^{-1}$. The 100 cm bare soil sensor only functioned intermittently throughout this period.

3.4. Discussion

3.4.1. Crop physiology and water stress. Some of the largest differences in soil moisture and temperature occur at the time of planting when rainfall is the most erratic (Fig. 3.1). This is when crop roots are not well established, and a period of soil desiccation can severely limit the development of roots. Crops that do not quickly establish root systems during this early and highly variable moisture and temperature regime run the risk of developing more slowly or not at all. Furthermore, when plants are not well established in the coarse-grained soils at Keur Matar and Nioro the onset of drought stress can occur very quickly, within a matter of days due to the low water holding capacity of the soil (Chapter 2). It is also during this time at Keur Matar that there are significant differences in soil temperature at the sowing depth of the seeds (Fig. 3.5). High temperatures occurring in the days after sowing can quickly lead to a reduction in germination (Fig. 3.5). Ong (1983) suggests that a single event when soil temperature exceeded 39° C under well watered conditions for 5 hours caused a large reduction in crop emergence of one of the experimental plots. When the temperature rises above 35°, the activity of ribulose 1-5-biphosphate carboxylase/oxygenase (Rubisco) is reduced, which can cause a significant reduction in photosynthesis in cotton and tobacco (Crafts-Brandner and Law, 2000; Griffin et al., 2004). Single events of high temperature have a strong effect since the physiological effect of heat stress on plants involves the mis-folding or denaturation of some plant proteins which can occur quickly (Barnabás et al., 2008). Elevated temperatures at shallow soil depths can can strongly affect growth in millet and peanut during the vegetative stage (GS1 for millet, VE to V-1 for peanut) (Maiti and Bidinger, 1981; Boote, 1982). Studies on sorghum (Peacock, 1982) and maize (Watts, 1972) suggest that leaf extension rates show a sharp decline between 35 and 40° C. (Huda et al., 1984). Ong and Monteith (1985) propose optimum temperature for leaf extension in millet to be 32-34° C under optimal moisture conditions. Data from Keur Matar clearly shows that soil temperature at 5 cm in the crop only plots goes well above 35° C and shrub-associated plots stay below the 35° C and within the optimal range of 32-34° C more often. This likely is part of what leads to such large differences in early growth and plant vigor observed in the fields at Keur Matar.

During the first 20-30 DAS, the shrubs have recently been cut and there is little apparent transpiration occurring in the upper 60 cm of the profile where the crops develop their roots (Fig. 3.3). The soil temperature trends are consistent with the findings in Kizito et al. (2006), with increases of 2-5° C at Keur Matar in the CS plots during planting time. The magnitude of the difference in this study, however, was lower than the 5-9° C differences observed by Kizito et al. (2006). At Nioro there were no differences in shallow soil temperature during planting and germination in 2013, this is likely due to more sparse shrub canopies of *P. reticulatum* that appeared to shade the soil surface less than *G. senegalensis* at Keur Matar. In the later part of the season at Nioro, however, there are large differences in shallow temperatures as high as 5° C in 2013 when the shrub canopies have grown back, the weather is extremely hot, and there is more leaf area in the CS plots than in the CO plots (Table 3.1).

There was slightly higher moisture in the 0-60 cm depth range in the CS plots at Keur Matar (Fig. 3.3). Higher moisture content near *G. senegalensis* is consistent with the findings of Kizito et al. (2007). The higher moisture content near shrubs is likely a result of lower hydraulic conductivity and slightly higher water retention, as well as the incidence of hydraulic redistribution that adds a small amount of water to the shallow soils during the driest parts of the season (Fig. 3.6) (Kizito et al., 2012). At Nioro, however, there is consistently higher moisture content throughout the season in CO plots. This is inconsistent with the results of Kizito et al. (2007), and may be due to the fact that some of the *P. reticulatum* shrubs have grown larger since they were first transplanted in 2003 and may use significantly more soil moisture than when they were young without well developed root systems. Furthermore, the early rain events flow through and evaporate from the shallow depths more quickly showing a higher apparent hydraulic conductivity in the crop only plots (Fig. 3.4).

Large differences between CS and CO in the first measurements of LAI each year, particularly in millet, indicate that processes in the vegetative growth stage were strongly affected by the presence of shrubs as compared to crops planted alone. Furthermore, a consequence of early season stress can be slower development, which was observed in the field. Although there was no strong drought stress in the early season in 2012, there was elevated temperature and reduced moisture availability in the CO plots compared to the CS. It was likely a combination of improved conditions of moisture, temperature, and nutrient environment that improved the early-stage growth at Keur Matar.

In 2012 at both sites the differences between treatments were smaller across all measurements, including crop yield (Dossa et al., 2012). This may be due to the fact that peanuts, grown in 2012, can fix nitrogen in these nutrient-poor soils, also, in 2012 the rainfall regime was well-distributed and the annual total was high (Fig. 3.1). At Keur Matar in the 63 DAS measurements of leaf water potential there were significant differences between the CO and CS treatment. It is during this phase that the peanuts were passing from flowering into grain filling (stage R3-R6) (Boote, 1982). The difference likely reflects differential access to soil nutrients between the plots, since there was ample water in both treatments. Findings from (Dossa et al., 2009, 2010) show increased availability of C, N, and P beneath both *G. senegalensis*, and *P. reticulatum*. Increased nutrient availability likely played a large role in the differences seen in the 2012 peanut crop. Despite differences in peanut yield, the LAI shows that peanut canopies compared between treatments were similar in size at Keur Matar. At Nioro there is much more full canopy closure as evidenced by higher LAI values than at Keur Matar (Table 3.1). .

In millet crops in 2013 the large differences in NDVI and LAI reflect increased access to moisture and nutrients in *G. senegalensis* associated millet. Kizito et al. (2006) found that millet planted alone had more extensive root systems than millet planted in association with *G. senegalensis* this would further support the assertion that millet in CO plots allocated more below-ground resources in order to access a more moisture and nutrient resource pool than in the *G. senegalensis* associate plots where the resources may be more available in the vicinity of shrub roots. NDVI as been correlated with both moisture and nitrogen availability in a field where both covaried (Barnes et al., 2000). At Nioro the large and highly significant differences in NDVI are likely a result of only nutrient availability, as there was ample rainfall in 2013. The *P. reticulatum* associated millet plants in higher NDVI, but lower soil moisture (Table 3.2, Fig. 3.4). Therefore, the differences in vigor between the two must be a result of increased nutrient availability, since moisture availability did not appear to limit plant growth or development.

Measurements of leaf water potential in millet and peanut tended to show that crop and shrub plots underwent lower levels of suction overall, especially in peanut in 2012. Leaf water potential is an aggregate measure of many plant functional traits. It can vary widely in time and space within a field, and responds quickly to environmental changes, on the order of seconds to minutes. None of the measures on either year showed any level of drought stress according to the literature, which shows significant transpiration reduction in millet below 0.5 MPa of predawn suction, and significant increase of stomatal resistance below 1.4 MPa of suction in midday measurements in peanut (Petrie and Hall, 1992; Bennett et al., 1984). The statistically significant differences in midday peanut water potential at Nioro likely reflect a response to high temperatures. Soil temperatures in the shallow depths at Nioro in both years were significantly lower in the CS plots associated with *P. reticulatum* than in the crop only plots (Fig. 3.4). Despite the lack of stress based on the literature, some signs of stress were observed at both Nioro and Keur Matar. In the field the authors observed significant amounts of leaf closure midday in peanuts as well as leaf curling in millet, which can be a response to extreme heat or drought (Black et al., 1985). When peanuts were finishing grain filling during the late season the shrub canopies were large enough to cast shade onto the plots. This may have helped regulate the canopy temperature and aid the peanuts in avoiding heat damage. Overall the presence of the shrub tended to lower the leaf water potential, which correlates to more availability to moisture and nutrients.

These results indicate that the effect of shrubs in farming plots may be to greatly alleviate the stress experienced by intercrops through temperature reduction, increase of moisture, and the shading effect of the shrub canopy. To the best of the authors' knowledge, the combined effects of multiple abiotic stresses are not well understood in any crops (Barnabás et al., 2008; Mahalingam, 2014). The limited amount of research into the topic suggests that the effects of multiple stresses cannot be extrapolated from studies that focus on a single stressor at a time (Barnabás et al., 2008). Additionally, it is very common for multiple stresses to occur at once, particularly heat, light, and moisture under hot, dry conditions. In millet the effects drought stress combined with high irradiance can severely limit photosynthetic activity (Masojídek et al., 1991). Stress at any time during the season can delay growth stages, and delayed flowering shows strong correlation with yield (Mahalakshmi and Bidinger, 1985). In the early season, the shrubs appear to have a cooling effect during the day and a slight warming effect at night which reduces the extreme temperature exposure of shrub-associated crops. The time during the season when these combined stresses are likely the most acute are at the beginning of the season when the full extent of the rooting system is exposed to high soil temperatures in the upper 20 cm. At the end of the season when the crops are better developed, their extensive rooting system allows them to buffer more effectively against drought and head stress by maintaining the ability to draw water and nutrients from a larger volume of soil.

Comparing rainfall events between sites, Keur Matar has overall lower rainfall (Fig. 3.1), but has larger rain events, events of 40-50 mm can sometimes account for 20 percent of seasonal rainfall. These kinds of large rain events can episodes of high infiltration. At Nioro the amount of rain is more consistent and the rainfall events are smaller individually. This, along with somewhat higher clay content at Nioro leads leads to a system that is slightly less susceptible to rapid onset of drought conditions.

3.4.2. Hydraulic lift and the importance of the shrub rhizosphere. Hydraulic lift is a process that occurs in both *G. senegalensis* and *P. reticulatum* (Kizito et al., 2007). Although the results presented here do not explicitly show HL occurring, the physical potential for its occurrence is shown in Figs. 3.6 and 3.7. The soil moisture data presented here show that the times when HL can occur are during the times when crops are the most vulnerable to frequent early and late-season drought stress. There is considerable evidence as to when hydraulic lift occurs in many species and environments, which is when roots span a strong gradient of soil suction (Cardon et al., 2013; Dawson and Ehleringer, 1993; Warren et al., 2007; Wan et al., 2000). The reasons proposed as to why it occurs include to maintain root contact (Carminati et al., 2009), facilitate the uptake of nutrients, and to facilitate the uptake of water (Volk, 1947; Breazeale, 1930).

Additionally, the water that is released through HL is released directly into the rhizosphere which can harbor increased population and activity of microbes which Cardon et al.

(2013) demonstrated led to increased nitrogen cycling compared with bare soil. Increases in microbial activity have also been found at both sites in this study (Diedhiou-Sall et al., 2013). The differential effects of mulch additions and hydraulic lift on microbial abundance and activity have not been shown separately, but the existence of less negative water potential has been shown to increase microbial activity (Adebayo and Harris, 1971). Therefore, in this study it is reasonable to conclude HL aids in microbial survival and activity at these sites. Furthermore, shrub biomass additions on the order of 5 Mg ha^{-1} (Dossa et al., 2012) decompose in the *G. senegalensis* and *P. reticulatum* sites annually (Diedhiou-Sall et al., 2013), and it may be the cycling and mineralization of these additions that HL facilitates, which can help explain the large differences in crop vigor observed.

It is known that the rhizosphere can undergo water potential dynamics that are significantly different from the bulk soil (Kroener et al., 2014). The dynamics in the rhizosphere are such that plants may have more access to water as soil dries, but less access to water as the re-wets rhizodeposits (Ghezzehei and Albalasmeh, 2015). Even without the occurrence of hydraulic redistribution, the increased volume of rhizosphere-influenced soil could serve as a benefit to crops. The authors observed in the field that millet roots grew around lateral roots of *G. senegalensis*, which would further support the idea that the rhizosphere harbors increased levels of nutrients and moisture and that crops would concentrate their roots nearby. The fact that the shrub associated crops had higher yield at all fertilizer levels at both sites indicates that it is water availability, not mineral nutrients, that is the limiting factor between treatments (Dossa et al., 2012). In a study at this site in 2014 hydraulically lifted water from shrubs was found in crops under drought stress (Chapter 4.5). The data presented here and the observations in the field support the assertion that hydraulic lift aids in both water availability, as well as nutrient availability.

3.4.3. Shrub water use and hydraulic redistribution. The *G. senegalensis* and *P. reticulatum* are both very hearty shrubs that survive across the Sahel. They have evolved to make use of the resources in a way that is sustainable for their survival on the landscape. It takes at least three months after the cessation of rain for *G. senegalensis* and four to five months for *P. reticulatum* to deplete water in the deep rooting zone below between 1 and 3 m (Figs. 3.10-3.11). The shrubs have the ability to send roots down this far, though it is unknown whether they reach the water table or not. A study in Niger showed that *G. senegalensis* roots used a significant amount of moisture below the 4.5 m depth (Gaze et al., 1998). These data show that in the weeks after harvest at both sites shrubs still obtain a significant amount of their moisture from above 60 cm depth (Fig. 3.3-3.3). As the rains end and the dry season progresses, the shrub moisture use moves downward with water availability. One way that the shrubs may be able to capitalize on this deep moisture is through their root architecture. Since these roots travel down into soil zones that have plant available moisture on all but the most stressed years, it makes sense for them invest resources in order to send roots down this far. Furthermore, in other species highly significant differences can be seen between the hydraulic properties of the shallow and deep roots. In *Juniperus ashei*, *Bumelia lanuginosa* and *Quercus fusiformis*, the xylem of deep roots had much higher conductivities, and were more susceptible to cavitation and disturbance (McElrone et al., 2004). This shows an accounting that all plants do to balance available resources with available energy. As a result of differing conductivities in the deep and shallow roots, the root flow can be restricted in the upper zones, and allow water to be taken up from deep while maintaining the same suction at the soil surface. The regulation of root architecture and properties is what allows *G. senegalensis* and *P. reticulatum* to use this deep reserve of soil moisture and survive through the long dry season.

Another reason that shrubs may have deep roots is to take advantage of available nutrient reserves that have drained below the crop rooting zone. Some arid and semi-arid environments in the Western USA have increased concentration of P, Ca^{2+}, Mg^{2+} at depth (McCulley et al., 2004). In the aforementioned article the authors also show that there is uptake by deep rooted (> 1 m) shrubs. In the Sahel there is evidence of increased chloride and nitrate at depths below 6 m as a result of their high mobility due to their negative charge and the high permeability of the soil (Edmunds and Gaye, 1997). Although there is no data shown here for nutrient profiles at depth, there may be deep reserves of nutrients that shrubs are exploiting with their roots that extend past 3 m depth.

There are definitely shrub roots throughout the entire measurement zone, as evidenced by diel fluctuations in moisture content at all depths below 100 cm in all treatments (Appendix C). The diel fluctuations indicate that the reduction in moisture content is as a result of plant transpiration, not gravity driven moisture redistribution. These daily differences in soil moisture represent daily water depletion and capillary flow back to the roots to replenish moisture.

3.4.4. Perspectives. Overall the processes that improve the performance of shrub-associated crops vary with the time of the season and the crop growth stage. Reduction in temperature extremes and an increased availability of soil moisture near the surface surface can help the seeds planted near shrubs with germination success and early growth. Once the seeds sprout, there is indirect evidence that mulch at the surface can help retain moisture in near-surface soils where the young roots of peanut and millet crops develop. As the season progresses and the shrubs grow back post-coppicing, their water use is increasingly in competition for soil water resources with the crop roots in the upper 60 cm of the soil profile. But by this time, the crop roots are developed enough to sustain themselves through some drought periods. As the season ends, depending on the drought regime for that year, hydraulic lift may provide added benefit to crop survival in the late season as well, helping maintain root-soil contact to allow for root survival. Further research is needed as to the exact quantity of hydraulically lifted water that can be taken up by crops and at what time of the year. In addition, the ability to measure presence of hydraulic redistribution, even at relatively high soil water contents, will be important in assessing the true dynamics of redistribution within the shrub rooting zone. It is possible that the presence of shrub roots, in their increased water holding capacity and their ability to perform hydraulic redistribution, creates a situation where crop roots do not have to explore as far and wide for a resource zone and can thus allocate more of their energy toward above-ground vegetation and grain production. Further research on the rooting patterns of crops in the presence of, and away from shrubs is needed. Lastly, this experiment was designed with mulch and shrub effects as a single effect. The large amount of biomass addition, both through surface mulch and shrub root respiration, does not manifest in significant aggradation of carbon in the soil, which means that much of the added biomass is mineralized and either respired, lost to deep drainage, or taken up by plants. Further research is needed to determine the extent to which this added biomass is being used by nearby crops and shrubs, or whether it is respired to the atmosphere after it is applied.

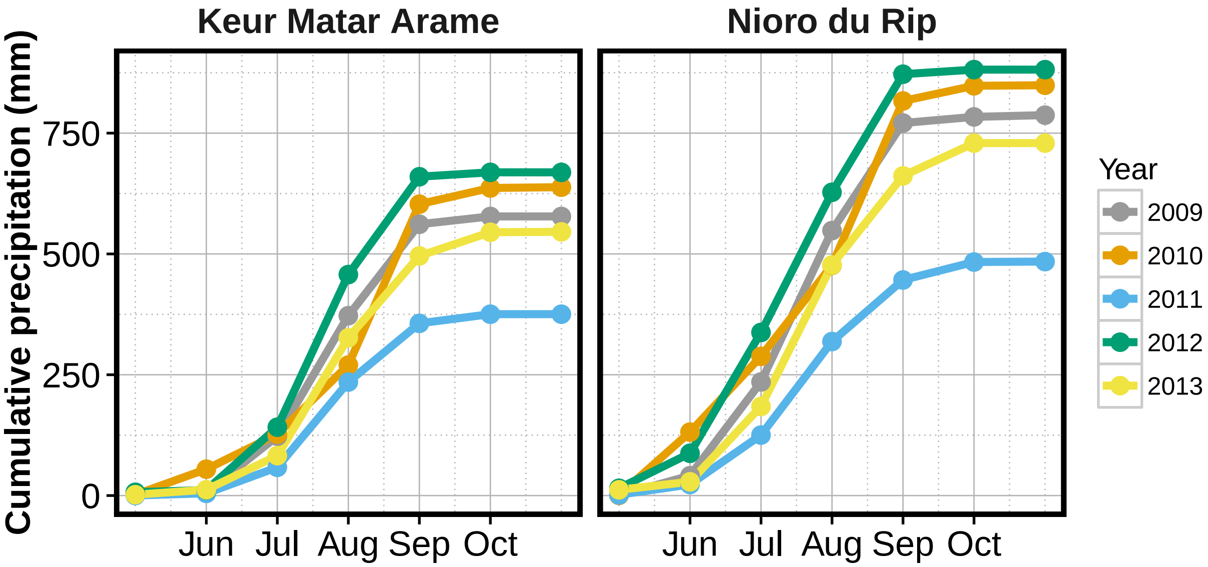

FIGURE 3.1. Cumulative rainfall during rainy season for five years in the regions of Keur Matar and Nioro from GPCC.

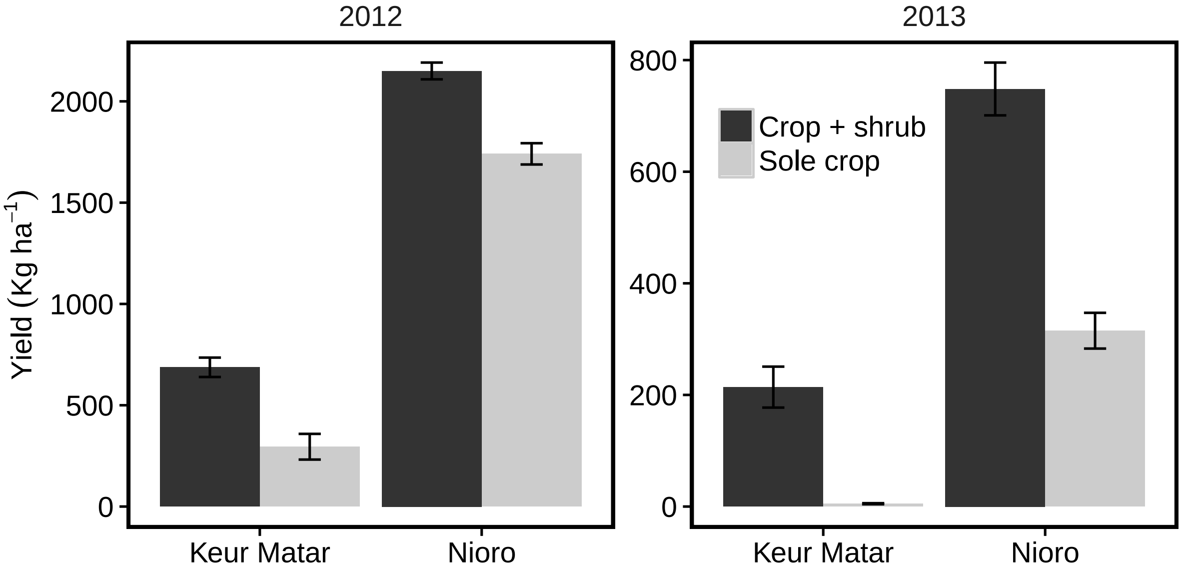

FIGURE 3.2. Crop yield for two years in zero fertilizer plots with and without *G. senegalensis* and *P. reticulatum* at Keur Matar and Nioro, respectively. Peanuts were grown in 2012 and millet in 2013.

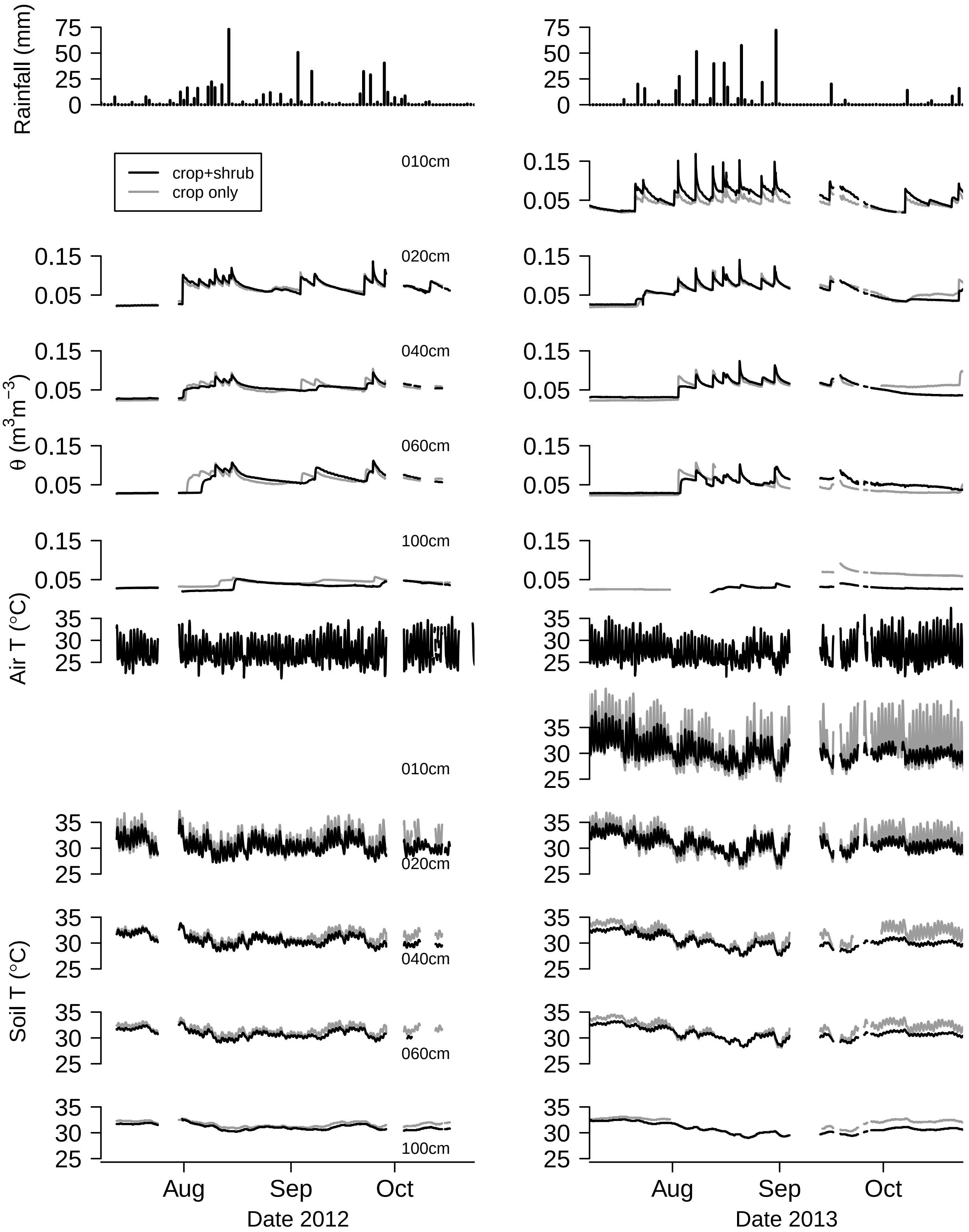

FIGURE 3.3. Precipitation, air temperature and root zone soil moisture and temperature for years 2012 and 2013 at Keur Matar, Senegal.

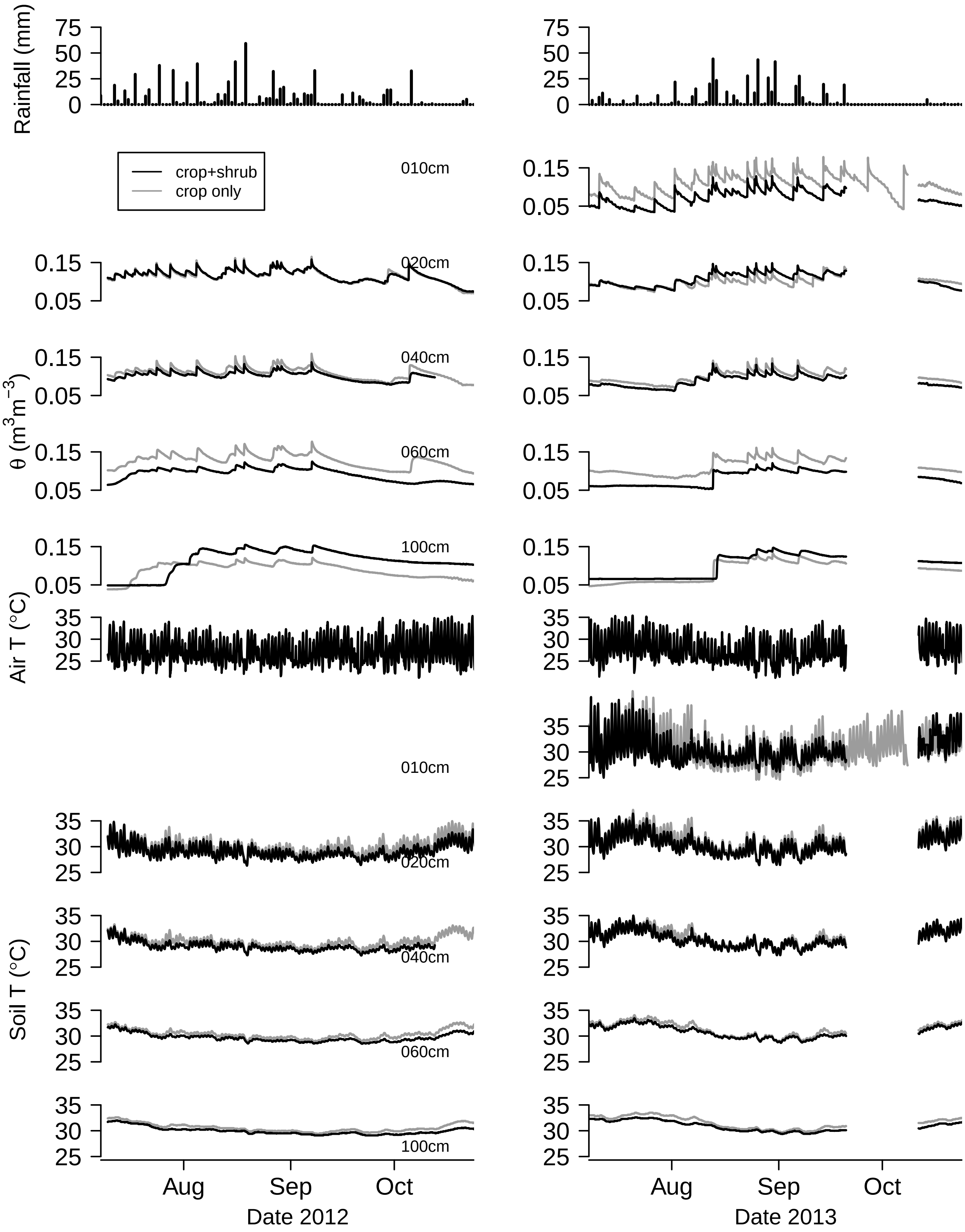

FIGURE 3.4. Precipitation, air temperature and root zone soil moisture and temperature for years 2012 and 2013 at Nioro, Senegal.

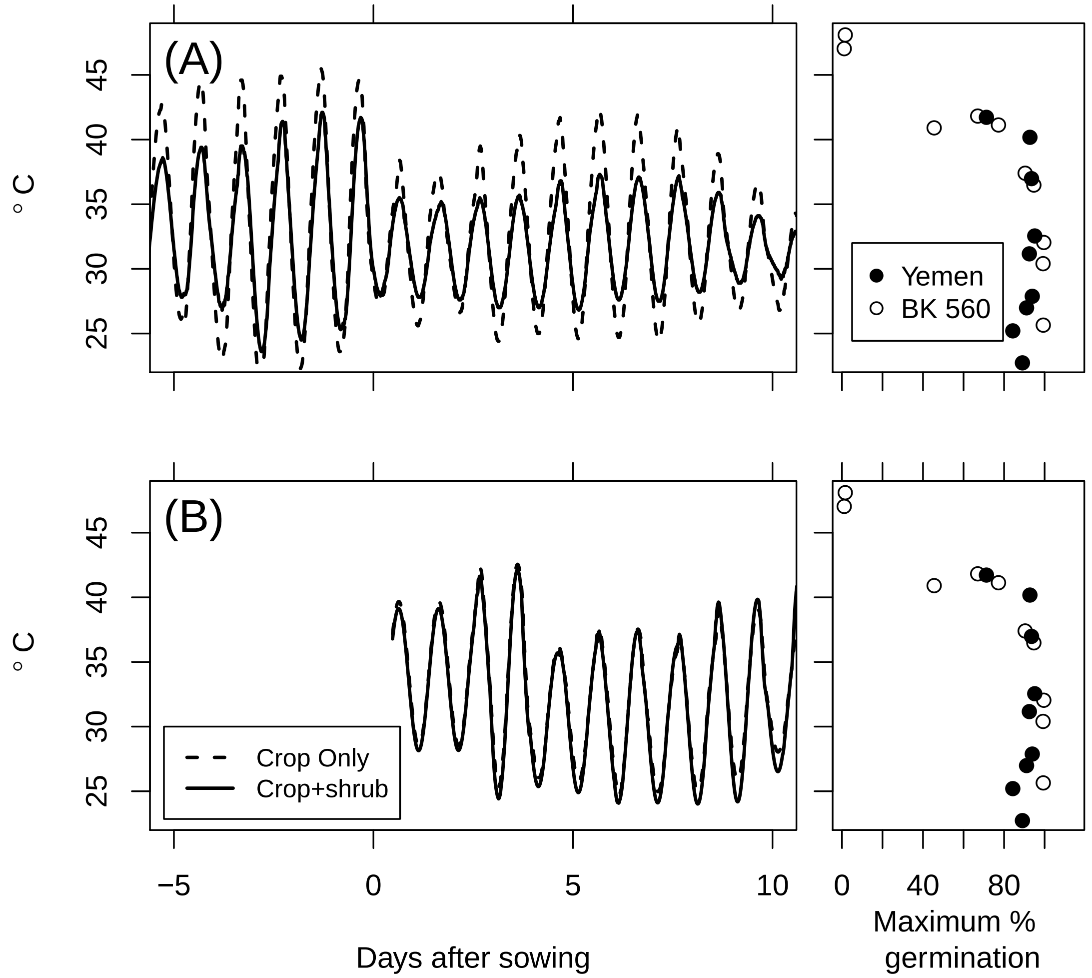

FIGURE 3.5. Comparing germination rates at different temperatures from a lab study (Garcia-Huidobro et al., 1982a) with modeled 5 cm temperatures based on 10 cm and 20 cm sensor temperatures at (A) Keur Matar and (B) Nioro.

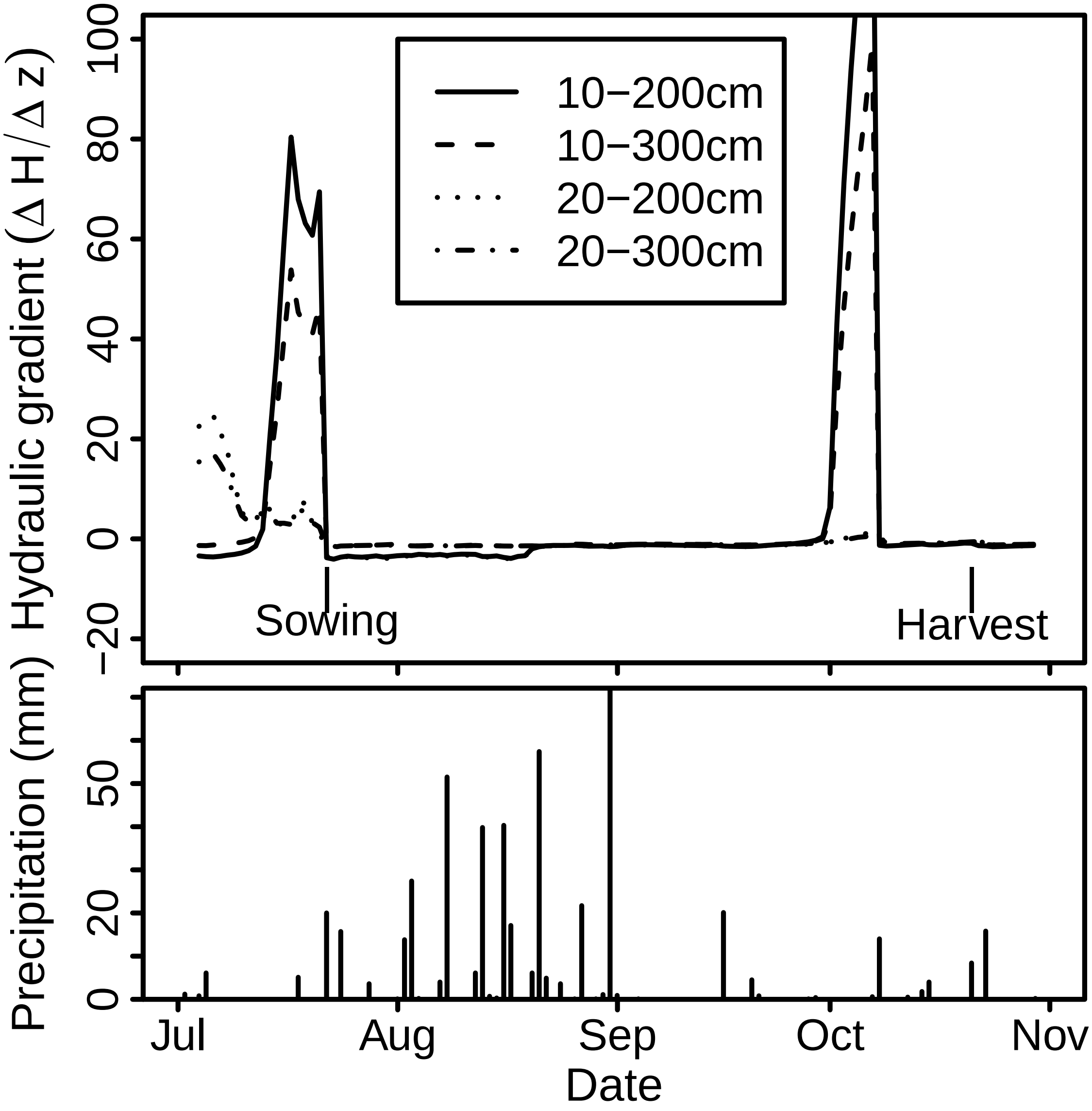

FIGURE 3.6. Physical potential for hydraulic redistribution represented as the gradient calculated between the 10 and 200 cm, 10 and 300 cm, 20 and 200 cm, and 20 and 300 cm soil moisture sensors for growing season 2013 at Keur Matar under the crop+shrub plot. Sowing and harvest dates of millet in 2013 are included.

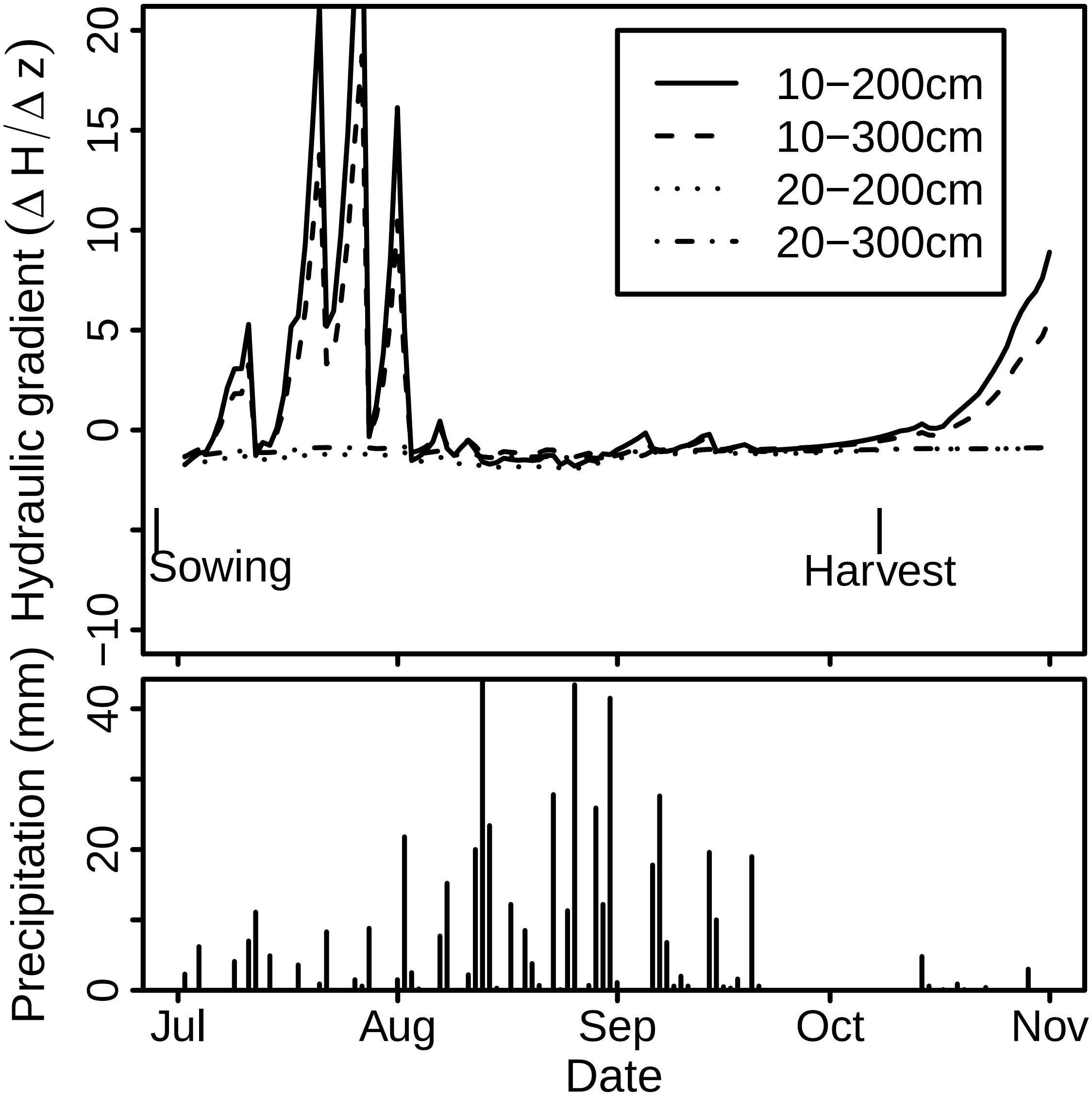

FIGURE 3.7. Physical potential for hydraulic redistribution represented as the gradient calculated between the 10 and 200 cm, 10 and 300 cm, 20 and 200 cm, and 20 and 300 cm soil moisture sensors for growing season 2013 at Nioro under the crop+shrub plot. Sowing and harvest dates of millet in 2013 are included.

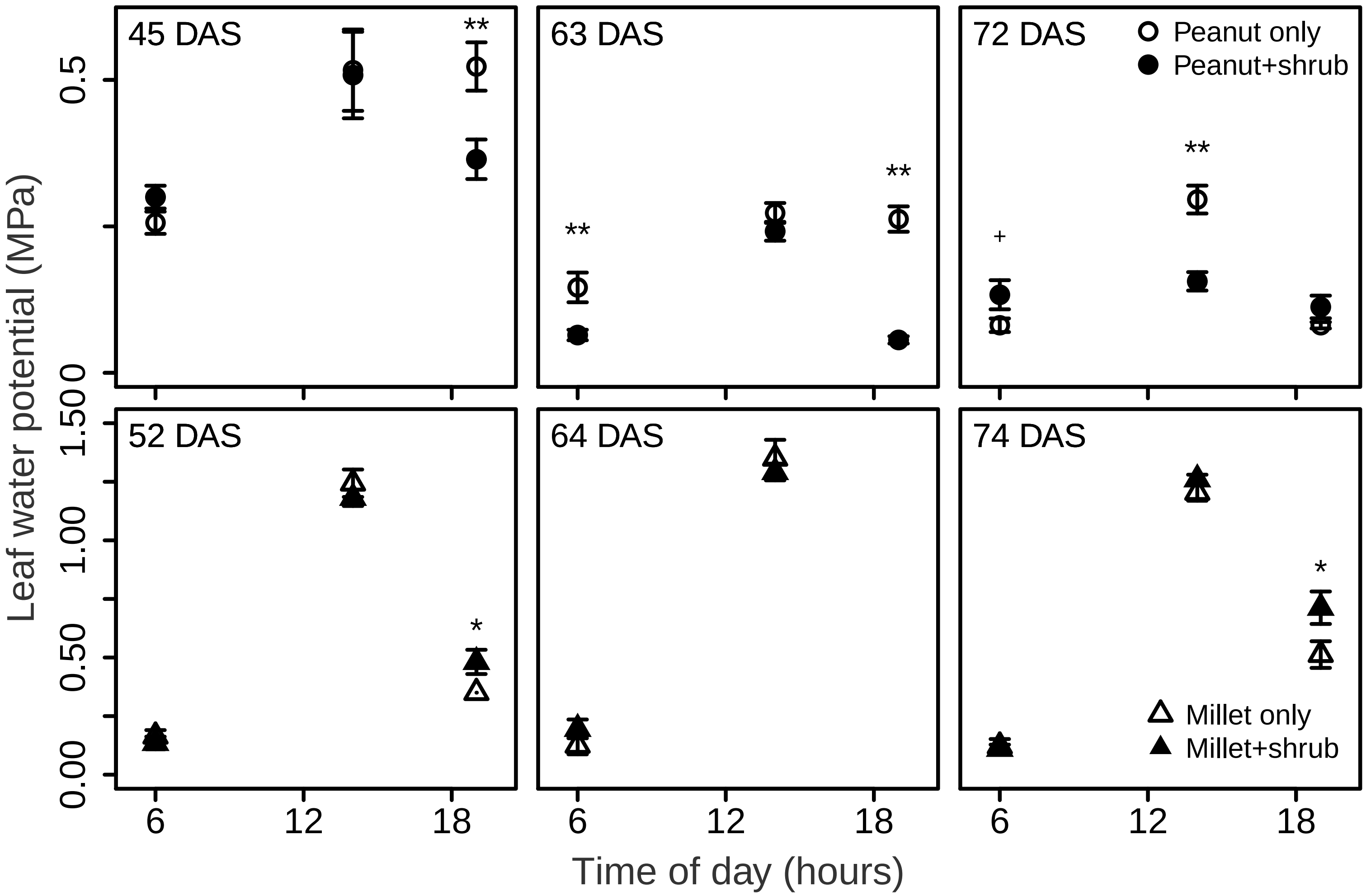

FIGURE 3.8. Leaf water potential at Keur Matar measured in intercropped *G. senegalensis* (closed symbols) and crop only (open symbols) plots with peanut in 2012 (top) and millet in 2013 (bottom). Measurements performed three times during season, DAS stands for days after sowing. *** significant at $p<0.001$, ** significant at $p< 0.01$, * significant at $p<0.05$, + significant at $p<0.10$

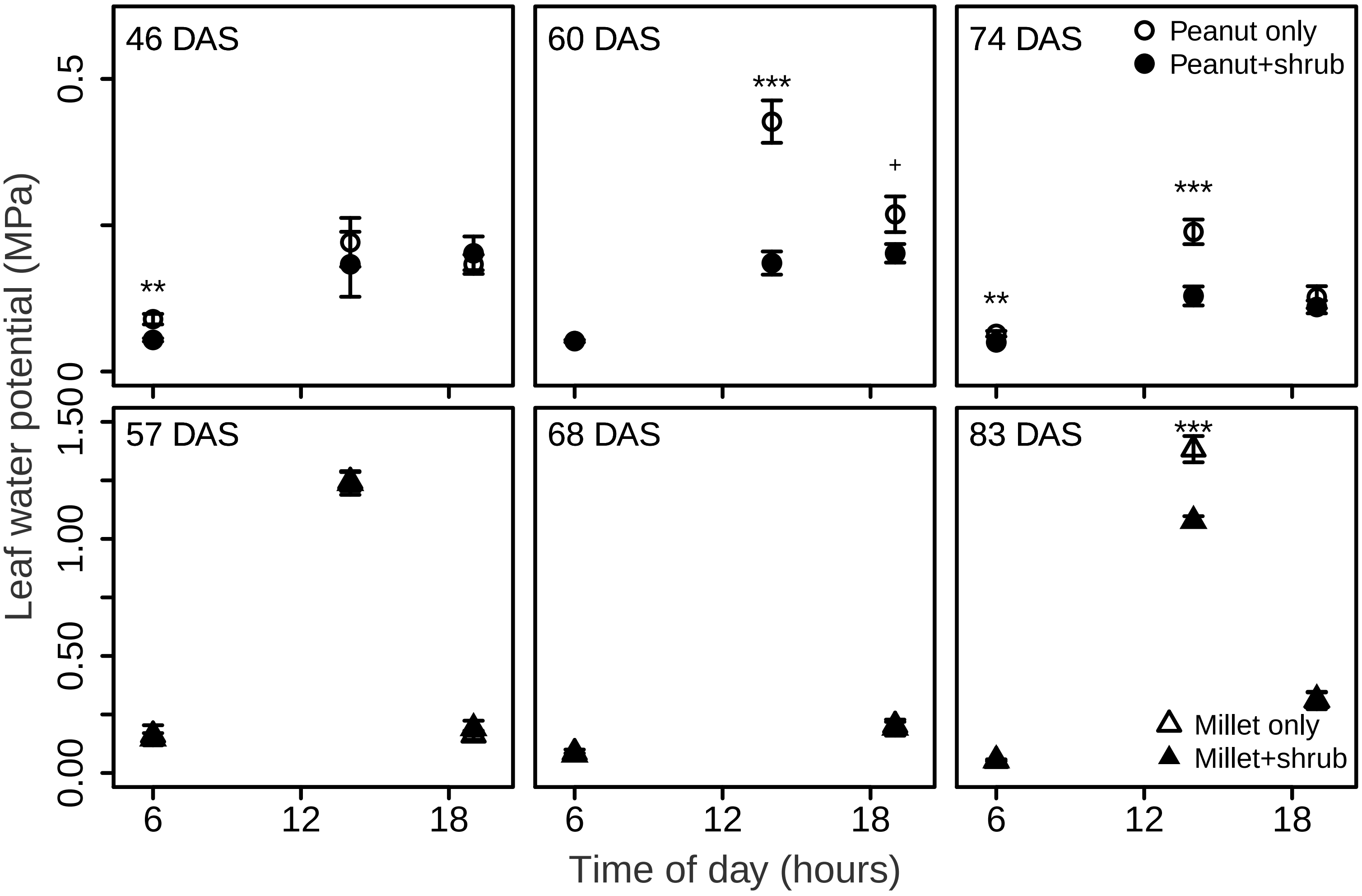

FIGURE 3.9. Leaf water potential at Nioro measured in intercropped *P. reticulatum* (closed symbols) and crop only (open symbols) plots with peanut in 2012 (top) and millet in 2013 (bottom). Measurements performed three times during season, DAS stands for days after sowing. *** significant at $p<0.001$, ** significant at $p< 0.01$, * significant at $p<0.05$, + significant at $p<0.10$

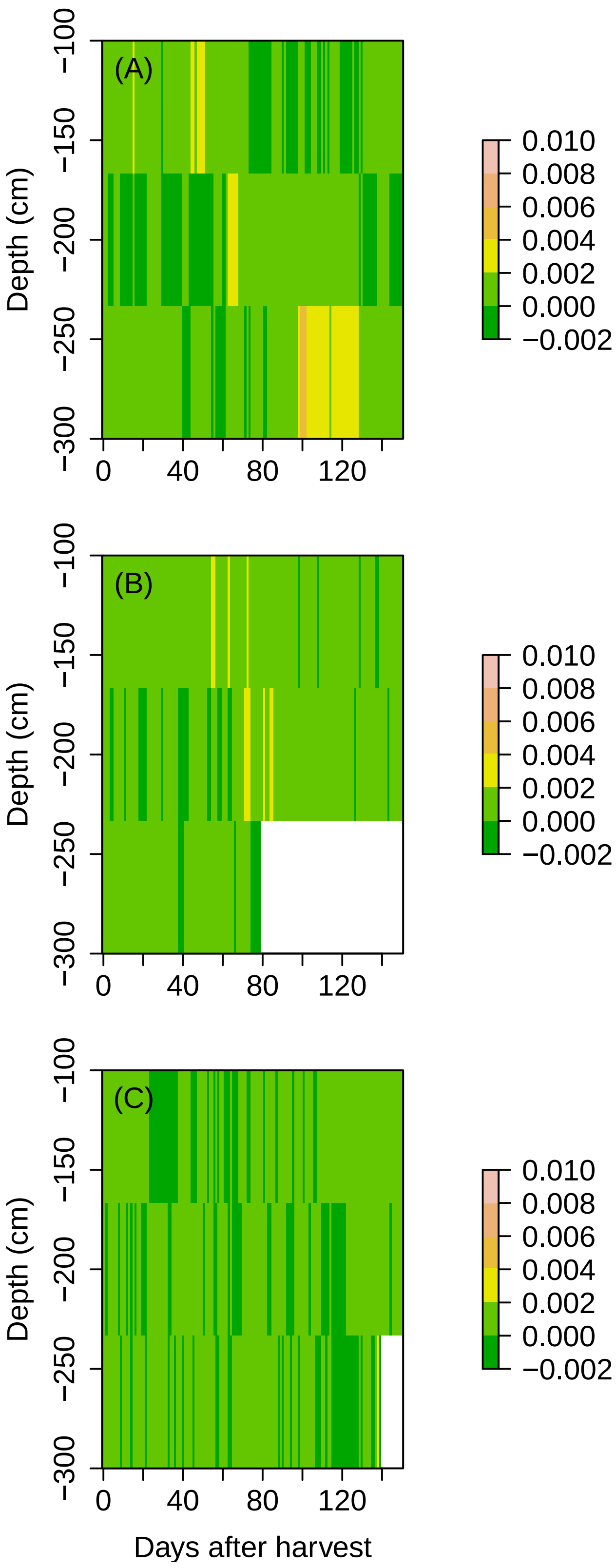

FIGURE 3.10. Rasterized soil moisture reduction late in the season in 2013 and into early 2014 at Keur Matar. A, B, and C are bare soil, crop only, and crop+shrub, respectively. A total of 20 mm of rain fell during the period shown here and each individual storm totaled less than 5 mm. Harvest was on October 21. White areas represent missing sensor data due to power failure.

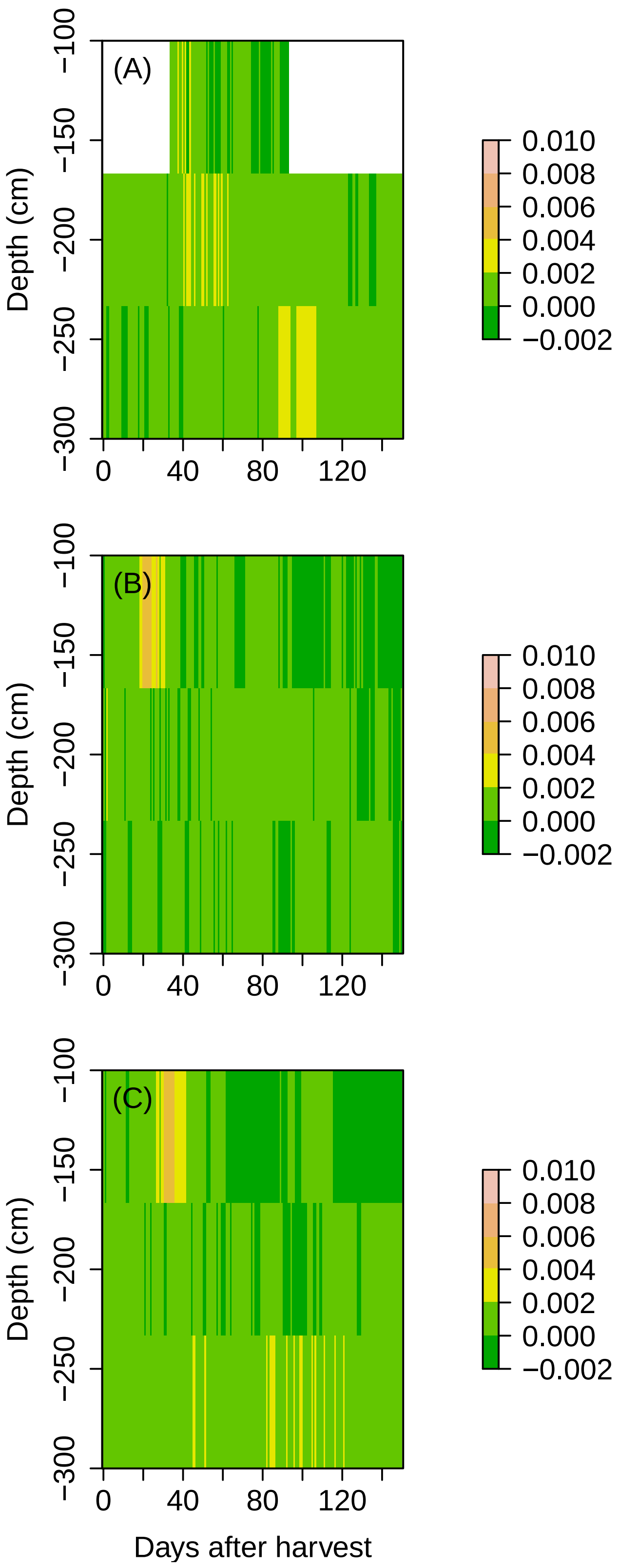

FIGURE 3.11. Rasterized soil moisture reduction late in the season in 2013 and into early 2014 at Nioro. A, B, and C are bare soil, crop only, and crop+shrub, respectively. Harvest occurred on October 8. During the period shown only 10 mm of rain fell. White areas represent missing sensor data due to power failure.

TABLE 3.1. Table of LAI mean (SEM) with t-test statistics for years 2012 (peanut) and 2013 (millet) from Keur Matar and Nioro, shrubs at Keur Matar are *G. senegalensis* and at Nioro are *P. reticulatum*.

LAI							
Site	Year (Crop)	Days after sowing	Crop+shrub	Crop only	Df [1]	t [2]	P [3]
Keur Matar	2012 (peanut)	32	0.37(0.02)	0.32(0.02)	55	1.61	0.11
		45	0.41(0.06)	0.39(0.04)	52	0.34	0.69
		63	2.00(0.09)	1.37(0.06)	55	5.94	2.0×10^{-7}
	2013 (millet)	52	1.41(0.14)	0.53(0.07)	30	5.60	4.0×10^{-6}
Nioro	2012 (peanut)	33	0.49(0.04)	0.49(0.04)	90	-0.04	0.96
		46	1.43(0.08)	1.16(0.06)	52	2.84	0.006
		60	1.96(0.13)	1.97(0.13)	51	-0.06	0.94
	2013 (millet)	68	1.15(0.05)	0.78(0.05)	35	5.21	8.6×10^{-6}
		83	4.04(0.22)	2.36(0.08)	39	7.22	1.1×10^{-8}

[1] Df = degrees of freedom; [2] t = t-statistic, [3] P = P-value

TABLE 3.2. Table of NDVI statistics mean(±SEM) from Keur Matar and Nioro, shrubs at Keur Matar are *G. senegalensis* and at Nioro is *P. reticulatum*, 2013 (millet).

NDVI							
Site	Year	Days after sowing	Crop+shrub	Crop only	Df [1]	t [2]	P [3]
Keur Matar	2013	52	0.50(0.01)	0.23(0.03)	26	9.6	5×10^{-10}
		64	0.46(0.01)	0.26(0.02)	32	8.1	3×10^{-10}
Nioro	2013	55	0.59(0.02)	0.50(0.03)	75	2.9	0.005
		83	0.54(0.02)	0.48(0.03)	25	1.8	0.08

[1] Df = degrees of freedom; [2] t = t-statistic, [3] P = P-value

CHAPTER 4

Hydraulic Redistribution by Native Shrubs of the Sahel can Mitigate Drought Induced Crop Failure

Prepared for submission to: Science

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Abstract

Drought periods during the growing season are common in the Sahel, causing chronic low yields, crop failures, and long-term food insecurity. Recently, intercropped native shrubs have been shown to significantly increase yields and stabilize productivity in limited rainfall years in West Africa. However, the mechanisms of this beneficial shrub-crop association are not well understood, particularly water relations. One effect of the shrub-crop association is increased root-zone moisture content during times of drought stress, but the exact mechanism for this effect is not fully understood. Therefore, the objective of this study was to conduct a controlled simulated drought experiment to determine whether hydraulic lift (HL) by shrub roots (a night time release of water by shrubs into the shallow dry soil) could explain this benefit. Pearl Millet (*Penisetum glaucum*) was grown in the presence or absence of a well established perennial woody shrub *Guiera senegalensis* in Senegal, West Africa. After imposing drought stress that caused a root zone water potential of $<$ -1.5 MPa; shrub roots located $>$ 1 m beneath the surface were inserted into sealed vials of deuterium (D) enriched water. A strong deuterium signal (more than 300‰ above the background) was detected in millet plants located near shrubs at the ground surface within 12 to 96 hours after introduction of the tracer. The only viable path for the tracer to enter millet tissues was via HL by the shrubs. This finding demonstrates, for the first time, sharing of scarce, HL soil water between drought adapted shrub and an agricultural crop during an extreme drought period. There was a corresponding strong crop growth response with intercropped millet producing an order of magnitude more biomass than monoculture millet. This unique agroforestry practice capitalizes on the evolutionary adaptation of native shrubs to mitigate the frequent in-season drought events in Senegal and throughout the semi-arid Sahel. The result presented here provides evidence for HL as an important mechanism for the previously observed stability of millet yield in the presence of *G. senegalensis* in low rainfall years. Furthermore, this intercrop system is an avenue of research that should be investigated in semi-arid regions world wide. As global climate change brings a warmer and more erratic climate to many areas, adoption of this strategy can help improve food security in semi-arid regions.

4.1. Introduction

A third of the inhabitants of the Sahel (20.2 million) annually face food and economic insecurity (United Nations, 2014). The majority populations of semi-arid West Africa are directly employed in agriculture; 97% of which is rain-fed and carried out with limited or no inputs on low-fertility soils. In addition, unsustainable land management practices have severely degraded an estimated 1.1 million km^2 of agricultural land (approximately 7%) and 3.5 million km^2 in Sub-Saharan Africa (Lal, 2008; Vågen et al., 2005). Decades of agricultural projects and governmental interventions have had little impact on regenerating degraded landscapes (Foley et al., 2011) while the yield rate of staple cereals such as millet *Pennisetum glaucum)* have remained flat for more than five decades (Appendix D, Fig. D.1). As a result, the demand to feed the exponentially growing population of this region has been met so far by expansion to new arable land (Appendix D, Fig. D.1). Fallow lands have been reduced, which can lead to overgrazing and further degradation (United Nations, 2014). Hence to meet future food demands it is necessary to increase yield per hectare.

Another important agronomic challenge for the Sahel is unpredictable rainfall with long dry periods during critical growth stages of crops, which often lead to low yield or complete failure of harvests (Terrasson et al., 2009). This precarious situation will only be exacerbated by a changing climate. The parkland agroforestry system, which involves planting crops among scattered trees, is practiced to varying degrees by African farmers and can provide ecological benefits to soils and landscapes. Trees provide rural populations in the Sahel with animal fodder, medicinal treatments, fuel, and building materials (Sinare and Gordon, 2015). Of the Parkland tree species, néré (*Parkia biglobosa* Jacq. Benth) and karité (*Vitellaria paradoxa* C.F. Gaertn) are the dominant species in the Sahel (Hopkins and White, 1984; Oni, 1997). Karité is highly valued as a cash crop for its shea butter and other uses (Hall et al., 1996; Boffa et al., 2000). The seeds of néré are fermented to produce a condiment used throughout West Africa in the preparation of local dishes (Tomlinson et al., 1998; Hall et al., 1997). Unfortunately, for sorghum (*Sorghum bicolor*) and millet which are the major food crops of the Sahel, néré and karité typically cause excessive shading that substantially reduces yields under the crowns of these trees, compared with crops in the open (Kessler, 1992; Kater et al., 1992; Boffa et al., 2000; Jonsson et al., 1999). Crown pruning can reduce the negative shading effect of néré and karité on crop production (Kessler, 1992; Jones et al., 1998; Jonsson et al., 1999; Bayala et al., 2002). However, farmers are unwilling to prune because it would reduce the fruit production of these two tree species that have significant cash value for rural subsistence families throughout the Sahel (Personal comm, A. Bationo, 2016). Although *F. albida* with its reverse season phenology, does not compete with crops for light and has been shown to have positive effects on yields of cereals in the Sahel (Bayala et al., 2012), there is less incentive to promote this species as it has limited economic value. Although trees should be promoted for long-term benefits to landscape protection, stabilization of soils, and to resist desertification, other local resource strategies are needed that can directly improve yields of rainfed cereals in the Sahel.

Fortunately, there are local shrubs found in the Sahel to varying degrees in farmers fields that improve soil quality (Dossa et al., 2009, 2010; Diedhiou-Sall et al., 2013) and do not compete with crops (Wezel and Böcker, 1999). *Guiera senegalensis* has been shown to dramatically increase yields (Dossa et al., 2012) and is found throughout the Sahel between the 500 and 800 mm isohyets (Le Houerou, 1980). In part this yield response can be attributed to improved soil structure and organic matter levels from the presence of roots and litter inputs that increases nutrient availability and water storage (Dossa et al., 2009, 2010). Crops and shrubs both have extensive roots in the upper 1 m of the soil profile, but *G. senegalensis* also has tap roots that descend greater than 3 m (Kizito et al., 2006; Gaze et al., 1998). However, the timing of water use by the shrubs in the crop root zone is such that the crops and shrubs don't compete for soil moisture at the most critical phases of crop growth or during drought (Kizito et al., 2007).

Another intriguing characteristic discovered by Kizito et al. (2012) is that these shrubs perform hydraulic lift (HL) which is the passive movement of water via roots from wet subsoil to dry surface soil via roots (Caldwell and Richards, 1989). This raises the possibility of HL from woody species providing water to adjacent crops. Limited research has been performed to investigate this mechanism by tracking deuterium (D) enriched tracer water through the intercropped system (Sekiya and Yano, 2004; Sun et al., 2013). For *G. senegalensis*, HL may contribute to the yield response noted by Dossa et al. (2012) in low and adequate rainfall years in Senegal, West Africa. However, an important question that has not been addressed is whether HL performed by woody species can assist crops through drought periods. If so, this would be a valuable asset that should be exploited for the Sahel, where drought periods often occur during the cropping season reducing yields or even causing crop failure. Therefore, a field experiment was undertaken with the objective to determine the impact of a late season severe water stress on millet growth and yield in the presence or absence of *G. senegalensis* and whether labeled water (deuterium) injected in the tap roots of *G. senegalensis* could be taken up by adjacent millet plants.

4.2. Materials and Methods

4.2.1. Site Description. This research was performed in the Peanut Basin, Senegal in the village of Keur Matar Arame (14°45'N, 1620°51'W and 54 m above sea level) the mean annual precipitation is 450 mm yr^{-1}. The farming system is a yearly rotation of millet and peanut crops. Daily mean temperatures at the site range from 20°C in December-January to over 33°C from April-June. The soil is a Rubic Arenosol and it is locally described as Dior. It has minimal structure except for a periodic crust layer at a depth of approximately 5 cm that disappears once the soil is wet. This crust layer was not reported in previous studies at the site (Kizito et al., 2006; Dossa et al., 2009; Badiane et al., 2000). There is little horizonation in the top 1 m of soil. The texture of the soil is over 95% sand.

The study was performed in a research plot that has been in existence since 2003. Prior to that, for at least 50 years the area was in a crop rotation between peanuts and millet under local farmer management. Prior to 2003 *G. senegalensis* existed at the site in their native density of 240 shrubs ha^{-1}. In 2003 the plots were planted with an increased shrub density of 1500 to 1833 shrubs ha^{-1} (Dossa et al., 2012). The research plots have been in constant rotation of peanut and millet since 2003. The management strategy involves preparing the field by cutting shrub material at the ground surface before the rains come in late May. Once the aboveground material is cut, the cut shoots and leaves are chopped into approximately 5 cm pieces and spread over the shrub plots manually. After the spreading of biomass a horse and plow pass over the area and plow to a depth of 6 cm, turning some of the shrub material in with the soil.

For the purposes of the isotope tracer study, millet plants were grown under irrigation from March to June of 2014. The shrub management mimicked that of the rainy season with the shrubs cut and spread on the plots before planting, and again mid-season. All shrubs used for the tracer study were the oldest shrubs at the site with extensive root systems, present before the addition of new shrubs in 2003.

4.2.2. Plot layout and irrigation. In the region of the study crops are typically grown by rainfall only. Due to the erratic nature of rainfall in the region, this study was carried out under drip irrigation so that the timing of drought stress could be controlled. Subplots measuring 10 m × 6 m normally cultivated at the site were split to 5 m × 6 m. In these smaller plots a drip system was installed. Drip tubes were positioned with 1 m between tubes and along these tubes drip emitters were inserted every 0.5 m. The plots were then sown with pearl millet (*Penisetum glaucum* var. Souna III) at a 1 m × 1 m spacing. Crops were irrigated beginning on March 5 with 3-30 mm of water every 1-2 days with groundwater piped from a local water system. For two weeks in the early part of the season, plots were irrigated with a sprayer by hand with the amount of water delivered to each plot quantified by a volume counter on the hose, as well as checks in each plot using five buckets to measure water quantity. This was done to avoid excessive surface temperatures since there were no clouds and the climate stayed dry and hot. On days when water was not available, and irrigation had to be increased at the following event. Beginning on May 9, irrigation was cut off to the plots where the isotope tracer was carried out. Plants were harvested on June 19, 2014, six plants in each of three blocks were harvested from a 6 m^2 area and the total per block (n = 3) was used to scale the mass of the six plants to per hectare yield. It was not possible to accurately determine grain yield from this particular experiment because the panicles of some plants were damaged by birds that managed to pass through protective cloth shields that were placed over the panicles.

4.2.3. Isotope tracer. In order to deliver labelled water to the deep roots of the shrub, glass vials with approximately 4 cm diameter rubber septa and screw caps were drilled with holes from 2 to 5 mm in order for them to stretch and create a tight seal around roots that ranged in diameter from 3 to 9 mm. In three different plots a hole was dug to approximately one meter and two roots were chosen from a shrub for each plot. The shrubs were the only other plants visible within the study site, and the shrubs had large woody roots compared to the softer roots of the millet found at depths above 60 cm. Previously sealed vials with approximately 70 mL of 46 atom % D_2O (Sigma Aldrich, St. Louis, MO) were attached to two roots for each of three shrubs cut below 1 m depth. δ D values are reported here relative to VSMOW using the following equation:

$$\delta D = \left(\frac{R_{sample}}{R_{standard}} - 1\right) * 1000 \tag{4.1}$$

Where R_{sample} is the ratio of D/H of the sample, and $R_{standard}$ is the ratio of D/H of the Vienna Standard Mean Ocean Water (VSMOW) standard. Background δD signals were determined from millet plants grown in shrub-free plots separated by more than 30 m from the nearest tracer source. Shrub control samples were collected from a shrub 100 m away from the nearest tracer source. The latter long distance was chosen to eliminate potential shrub-to-shrub connection via rhizomes. Tracer δD exceeding two standard deviations above the control mean is considered as a statistically significant signature of the applied tracer, and is denoted in red in Fig. 4.3.

Crops and shrubs were sampled separately in the following order: prior to any sampling in tracer plots, shrubs chosen 100 m away from the site were sampled, then crops 30 m from the nearest tracer application location were sampled as a control, then the crops in the sample plots were sampled, and following this, the labelled shrubs themselves were sampled. Sampling was carried out by cutting of approximately 4 pieces of stem at the ground surface, removing the young bark, and placing it into a glass vial with a polycone cap, sealed, and wrapped with parafilm. The shoots of the shrub that were sampled were all new growth since the beginning of the study, and were approximately 40 cm long. For the crop sampling, tillers were cut within 5 cm of the ground surface, the first 2 layers of material were removed, then pieces were transferred into glass vials. Glass sample vials sealed with parafilm were immediately put into sealed polyethylene bags separated by sampling time and plant type and placed into a cooler full of ice and transported to a -20° C freezer within two hours where they were stored frozen until analysis. Extreme caution was taken to avoid contamination. Baseline samples were collected before the deuterium solution was ever removed from the lab, and a separate pair of rubber gloves was used to sample each replicate of each type of plant. On the evening of May 27 the roots attached to the vials were severed above the bottle, and both cut ends covered in electrical putty to stop the flow of tracer. The bottles were then removed from the holes on May 29 after the last sampling was complete.

Samples were extracted by cryogenic vacuum distillation with protocol similar to that of West and colleagues (West et al., 2006). The one way this cryogenic vacuum distillation protocol differed from that of West et al. is that samples were removed from the freezer 12 hours before extraction to thaw and equilibrate, usually overnight. Once samples were thawed, they were placed into the extraction vial with clean dry tweezers and sealed immediately onto a previously evacuated vacuum extraction apparatus. Once sealed on the vacuum line, samples were frozen in liquid nitrogen. Once frozen, the samples were drawn down to 30 mTorr using a rotary vane vacuum pump (Max 8C, Fisher Scientific, Pittsburgh, PA). The sample was then isolated from the manifold and monitored for leaks. If no leaks occurred, then the nitrogen was replaced with boiling water over the extraction tube and maintained at boiling throughout the extraction. The nitrogen was placed on the collection tube to catch the distillate. After 70 minutes the glass lines were inspected for any condensation and heated with a heat gun to make sure no condensation occurred inside the lines. Once it was established that there was no condensation anywhere in the system, the frozen collection tube was removed from the manifold and sealed with parafilm to thaw, then pipetted into 2 mL storage vials with screwcaps and PTFE septa. These vials were sealed with parafilm and brought back to the Fogel Lab at UC Merced for analysis on the mass spectrometer.

4.2.4. Isotope analysis. Samples were run through a Thermo Scientific Temperature Conversion Elemental Analyzer (TCEA) coupled to a Conflo-IV then analyzed by an isotope ratio mass spectrometer (IRMS) (Delta V- Plus, Thermo Scientific) in continuous flow mode. One micro-liter aliquots of water samples were injected manually into the TCEA with a 10 μL syringe. The TCEA furnace was maintained at 1430°C with a constant stream of helium carrier gas. The TCEA reactor column consisted of a graphite crucible housed in a glassy carbon rod where H_2O was converted to H_2 and CO. Hydrogen and carbon monoxide were separated on a molecular sieve column before entering the Conflo. Samples were run in triplicate with H_2 gas standard injected twice before and twice after the sample injections with a mean standard deviation of $1.5‰$ among peaks for a given sample. In order to correct for $H3^+$ that is produced during ionization in the ion source, the $H3^+$ factor was measured with a typical value of 4.71 ppm nV^{-1}. This is introduced because $H3^+$ has the same mass/charge (m/z) value as HD+ and is read by the Faraday detector for m/z = 3 (Sessions et al., 2001). The voltage signal from the IRMS was processed using ISODAT and calibration regressions were performed using R (R Core Team, 2016). For a sample reading δD -23‰ the 95% confidence interval was $\pm 1.4‰$. A series of Los Gatos Research working standards were used across the range of -150$\pm$1.0 to -40 $\pm$1.0 ‰, as well as VSMOW standard, UC Merced distilled water, and SMOW-GL, an internal water standard with a δ D close to VSMOW.

4.2.5. Soil Moisture and Water Potential. Soil water potential was measured using screen-cage thermocouple psychrometers individually calibrated in a range of KCl solutions (Brown and Bartos, 1982). Psychrometers used a cooling time of 30 s and were logged hourly with a datalogger (PST-55/PSYPRO, Wescor, Logan, UT). Soil moisture was measured with a multi-depth profile capacitance probe in access tubes that were installed according to the manufacturer's recommendations with great care taken to avoid air gaps along the tube (PR 2/6, Delta-T Devices, Cambridge, UK). The profile probe measured moisture at depths of 10, 20, 40, 60, and 100 cm. The factory calibration of profile probe was used with an accuracy of ± 0.04 m^3m^{-3}. Soil moisture measurements were taken just prior to turning on irrigation every 1-3 days.

4.3. Results

Comparison of crop performance between millet monoculture and millet-shrub intercropping, from crops that were subjected to drought stress, are reported in Fig. 4.1. The photo of neighboring plots taken 60-days after planting (May 3, 2014), shows that intercropped millet outperformed the monoculture substantially in terms of visible aboveground biomass and growth stage. Similar differences were observed during the regular growing season both in the research plots and plots of farmers who use this approach. The difference persisted throughout the experiment and is also reflected in final crop yields. There was a highly significant difference in yields (t(4.7), df = 2, p = 0.04) with 235 kg ha^{-1} and 2138 kg ha^{-1} for crop only and crop+shrub, respectively. This ten-fold increase in biomass productivity is comparable to the grain yield differences observed during the regular growing season (Dossa et al., 2012).

Water potential dynamics in one intercropped plot (plot C) during the drought-stress period are also shown in Fig. 4.2. The period shown in the plot starts 12 days after the last irrigation day (May 9) and shows rapid decline in water potential recorded by the shallowest sensor. As the drought period progressed, the 20 cm soil became more dry than the 60 cm and 100 cm depths decreasing to 3.0 MPa at the end of the tracer experiment on May 29. All three sensors recorded the typical signature of HL, indicated by night-time partial recovery of water potential. Recovery of water potential starts just before sunset and lasts until just after sunrise the following day. The fluctuations in water potential are synchronized, and there is no time lag of the daily maximum and minimum water potential with depth. This is strong evidence that these fluctuations are not caused by diurnal temperature changes, which typically exhibit a depth-wise phase shift. During the study the largest overnight increase in water potential occurred in the 20 cm sensor on the night of May 25 with an increase of 0.57 MPa over a period of 12 hours (Fig. 4.2).

The results reported here provide conclusive evidence that *G. senegalensis* performs HL. Soil moisture tended to be comparable in the presence of shrubs to that in their absence until the extreme drought period. This follows Kizito et al. (2012) who found elevated near-surface moisture in CS plots as compared to CO plots as well as movement of moisture upwards toward the shrub and laterally away from the shrub at night indicating the presence of hydraulic lift (Kizito et al., 2012). Based on these findings Kizito et al. (2012) concluded that HL occurred in *G. senegalensis* as well as another native woody shrub, *Piliostigma reticulatum*.

Soil water content dynamics in all the stressed plots were measured using handheld multi-depth profile probe (at 10, 20, 30, 40, 60, and 100 cm) every one to three days. Measurements were made in each crop+shrub plot at a distance of < 1 m from the shrub canopy, in the crop+shrub plots > 1 m from the nearest shrub canopy but still including biomass additions, and in crop only plots with no shrubs and no biomass additions. Cumulative profile soil moisture depths between 10 cm and 100 cm, reported in Appendix D Fig. D.3, show continuous decline in soil moisture after the irrigation was interrupted. Declines in the crop+shrub $>$ 1 m and crop only plots of replicate A and B were less pronounced than the crop+shrub $<$ 1 m plots. By the end of the stress period the moisture in crop+shrub $<$1 m became as dry as the plots at the beginning of the experiment before full wetting of the soil profile. In plot C the crop only moisture content stayed higher than the two measurements near the shrubs during drought stress.

The δD in millet plants growing adjacent to the source shrub are reported in Fig. 4.3. In plot C additional millet tissue samples were sampled 4.5 m away from the source shrub (labeled as 'far'). Concurrently measured tracer δD in the shrubs are reported in Fig. 4.4. Signature of the stable isotope tracer was detected in the millet tissues at all three replicate plots, including at the 'far' sampling site in plot C. The strongest signal of the tracer was recorded in plots A and B, which exhibited above-background δD at all but one sampling time each. Whereas in plot C above-background signatures were detected only once at the 'near' sampling site and 'twice' at the 'far' sampling site. The highest δD recorded in plots A-C were $335.3,‰$ $208.7‰$, and $-17.4‰$ respectively. Above-background tracer δD was detected in shrub tissues only in plots A and C. Plot A showed the strongest signal with a maximum δD of $5000‰$ and and above-background signal in all but one of the sampling times. There was only one sampling time with significant signature of δD of $-17.6‰$ in plot C. All of the bottles except one in plot C lost between 33 and 65 mL of the tracer water as a result of root uptake. When the bottles were retrieved the water level had dropped to just below the root in each bottle when they were dug up, the authors assume uptake ceased when the root was no longer submerged in liquid.

4.4. Discussion

The finding that the tracer moved from shrub roots 1 m below the surface into the adjacent crops is very significant. The detection of tracer in millet plants adjacent to the shrubs one day after shrubs received the tracer, indicates that adjacent crops take advantage of some of the HL water. Although it was not possible to quantify the amount of water transferred, the crop growth response in crop+shrub plots compared to crop only plots indicates that the amount of water transferred is significant. Using the assumptions of no water loss in the soil, and complete mixing in the plants and a modified technique of Calder et al. (1992), an estimate of the amount of water transferred from shrubs to millet could be 7% of daily transpiration (Appendix D). Other indications for significant transfer are that with the cessation of irrigation there was no other available water other than that stored in the rooting zone or HL water. An indirect water-balance model predicted the HL at this site to be 25 mm during the six driest months of the year (Kizito et al., 2012). If the 25 mm reported in Kizito et al. (2012) is available at the margins of the season when the shallow soil is extremely dry and the deep soil is moist, then 7% of crop transpiration is a plausible amount of moisture transfer under drought stress, when the soil is near wilting point and millet transpiration is likely lower than 1 mm day^{-1} (Allen et al., 1998).

The tracer signal was not strongly detected in the shrub tissues in two of three replications. This was somewhat unexpected, since the tracer was applied directly to shrub tap roots. *G. senegalensis*, however, has an extensive vertical and horizontal rooting system and many aboveground stems (Kizito et al., 2006). Furthermore, a preliminary study using a dye tracer showed stained vascular pathways indicating that individual roots shoots aboveground (Appendix D , Fig. D.4). It is therefore conceivable that some of the sampled shrub tissue was not directly connected to the tracer-source roots. This phenomenon does not, however, explain why all HL water wasn't reabsorbed by the shrubs themselves. A plausible explanation for this counterintuitive explanation is that a plant may not use its own HL water, as deep water may be easier to obtain due to wetter conditions at depth. Another possible explanation is that the crop roots are able to quickly take advantage of the extra moisture in the rhizosphere due to their ability to react quickly to available moisture in the soil near their roots.

Besides release of water into the soil that is taken up by the millet plant directly, it is possible that mycorrhizal hyphae connecting between shrub and millet roots could serve as a water transfer pathway. The data presented above are not adequate to ascertain whether the water was transferred through the soil or through mycorrhizal pathways. However, the strong HL signal in the soil water potential (Fig. 4.2) would suggest release of moisture into the soil, but does not rule out the mycorrhizal pathway.

In soils undergoing large fluctuations of temperature at the surface such as those in the Sahel, there can be significant driving force for vapor flux in the soil. Vapor flux has been investigated in the context of a hydraulic lift conditions and was found to represent 20% of the daily water potential recovery in a ponderosa pine *Pinus ponderosa* forest (Warren et al., 2011). Calculations of vapor flux in the soil were also made for the Keur Matar site by Kizito et al. (2012) and found to be approximately an order of magnitude lower at 20 cm depth than the apparent quantity of hydraulic redistribution. Based on this information, for this study calculation of the vapor flux contribution to HL was neglected.

Additionally there is a strong possibility based on recent research that the rhizosphere near the shrubs is able to retain more moisture than the soil in the crop only plots. The ways that it may differ may include increased aggregation and the presence of extracellular polymers which may exhibit high water retention than bulk soil under drying conditions (Ghezzehei and Albalasmeh, 2015; Carminati and Vetterlein, 2013). If the rhizosphere does, in fact, hold more water than the bulk soil then HL water released into the rhizosphere could help maintain hydraulic connection between pores, thus facilitating increased water availability to plants.

An interesting observation is that during the entire tracer test period the matric potential of the top 100 cm soil in plot C was below the wilting point of -1.50 MPa, a critical stage at which many plants undergo irreversible damage (Richards and Weaver, 1943). In areas with less than 800 mm of average annual precipitation, which is the case in this study, agroforestry systems will lead trees to outcompete crops for limited water resources, unless the deep rooted species have access to groundwater (van Noordwijk and Ong, 1999). However, in the presence of shrubs millet continued to grow and clearly was not as stressed as the crop only plots. This supports Kizito et al. (2007) who provided water balance evidence that *G. senegalensis* does not compete with crops for soil water and that of Dossa et al. (2012) where intercropping with shrubs consistently outperformed mono cropping by several folds over a number of low and adequate rainfall years.

So how does such a relatively small volume of water, in an environment of very high potential evaporation contribute to significant increases in crop performance? Two possible mechanistic explanations follow.

First of all, as demonstrated by the soil water potential data (Fig. 4.2) and other similar studies (Cardon et al., 2013; Richards and Caldwell, 1987; Caldwell and Richards, 1989), HL is particularly strong during times of extreme drought. It has been suggested that HL helps with the longevity of shrub roots (Horton and Hart, 1998) by maintaining contact between the root and the rhizosphere. This mechanism could be extended to include the maintenance of root health and vigor of the shrub-associated millet as well. During the rainy season nearby farmers' fields the authors observed millet roots growing closely around *G. senegalensis* roots, which support the hypothesis that HL water helped maintain the function of the roots of both species.

Secondly, in many arid and semi-arid regions, islands of elevated soil fertility exist surrounding shrubs (Schlesinger et al., 1996; Dossa et al., 2012; Hernandez et al., 2015; Diakhate et al., 2016) and termite mounds (Bonachela et al., 2015). The rhizosphere soil often contains much higher biomass and diversity of microbes and represents a hotspot of microbial activity due to the supply of rich carbon sources such as fine roots and exudates (Foster, 1988; Kuzyakov and Blagodatskaya, 2015). Improved crop yields as a result of intercropping with shrubs at our study site was also correlated with significantly higher microbial activity and abundance in the rhizosphere (Debenport et al., 2015; Diedhiou-Sall et al., 2013). Therefore, shrubs besides providing water during periods of drought stress also provide higher quality soils and beneficial microorganisms that improves crop nutrient and health status, all of which can contribute to drought resistance.

The results presented here show that shrubs can assist crops through within-season drought periods. This is extremely important for semi-arid farming. It is common to have such drought periods in the Sahel, particularly at the critical early and late crop development stages. It is likely that these type of erratic rainfall events will increase as the climate warms and weather patterns change. It is predicted that many arid and semi-arid regions including the West African Sahel will experience an increase in drought severity and a decrease in soil moisture (Dai, 2013).

4.5. Conclusion

The findings confirmed two very significant outcomes about root hydrology and crop water relations of *G. senegalensis* as a companion plant in farmers' fields of the Sahel. Previous research measuring diurnal water potential and directional flow of sap in *G. senegalensis* Kizito et al. (2007, 2012) only provided indirect evidence for HL by *G. senegalensis*. The second major finding is that these results demonstrated is that millet plants intercropped with *G. senegalensis* are able to utilize a small but critical quantity of water lifted by this shrub. The continued growth and significantly higher biomass production in the presence as compared to the absence of shrubs during the imposed water stress shows that HL can assist crops through in-season drought periods. This has implications for all semi-arid regions where drought-resistant crops are grown to buffer against increasingly erratic climate patterns due to global climate change. For highly mechanized semi-arid agroecosystems, engineering shrub intercropped systems offers a whole new avenue to improve crop water relations.

Feeding the rapidly growing and large populations in the socioeconomically and environmentally precarious region of the Sahel is an important challenge. For the Sahel, where the majority of rural populations depend on rainfed crops for their main food supply such as millet, sorghum (*Sorghum bicolor*), and cowpea (*Vigna unguiculata*); shrub intercropping is a logical and locally available solution for increasing yields and stabilizing productivity in low rainfall years. Previous research by Dossa et al. (2012) has shown that even in the absence of external inputs, *G. senegalensis* dramatically increases crop yields of peanut and millet compared to crops in the absence of shrubs. Thus, this is a technology that farmers can take advantage of. The results provide a sound justification to launch major research campaigns to develop optimized shrub intercrop systems for the Sahel through crop and shrub breeding and selection, spatial plant patterns and density, and other agronomic factors.

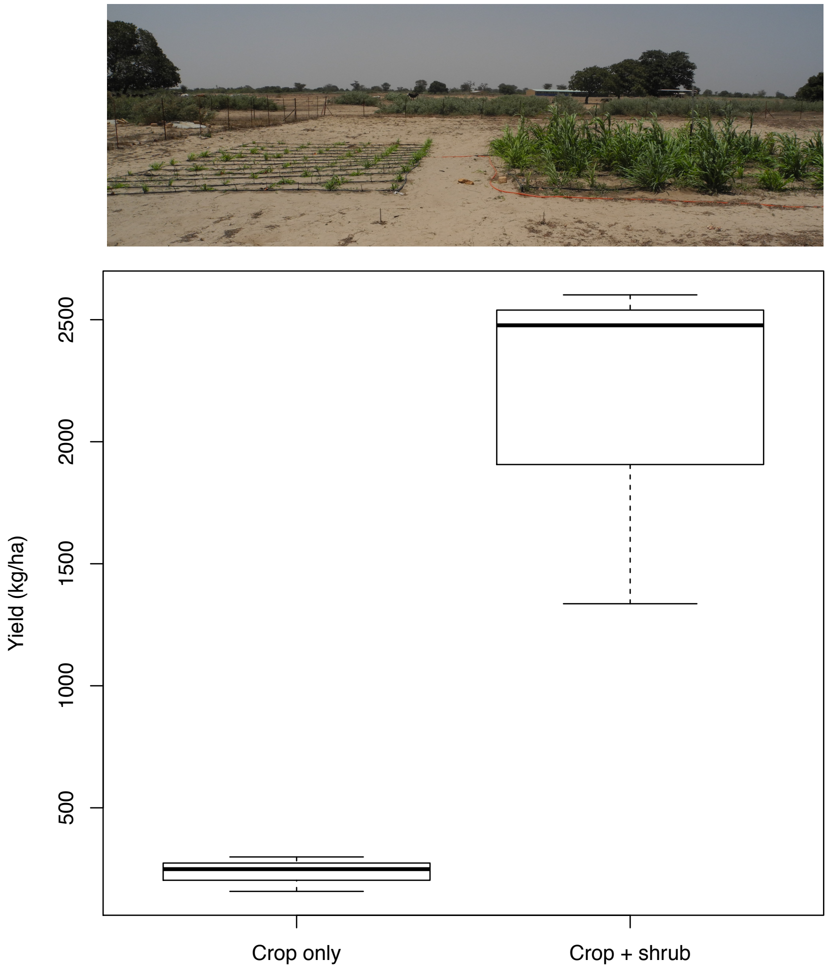


Figure 4.1. Comparison of biomass yield of millet crop grown alone and in association with *G. senegalensis* (n=3 for crop-only and n=6 for crop+shrub). Photo is of plots 60 days after sowing. Welch's two-sample t-test t(4.7021), df = 2.0421, P = 0.04.

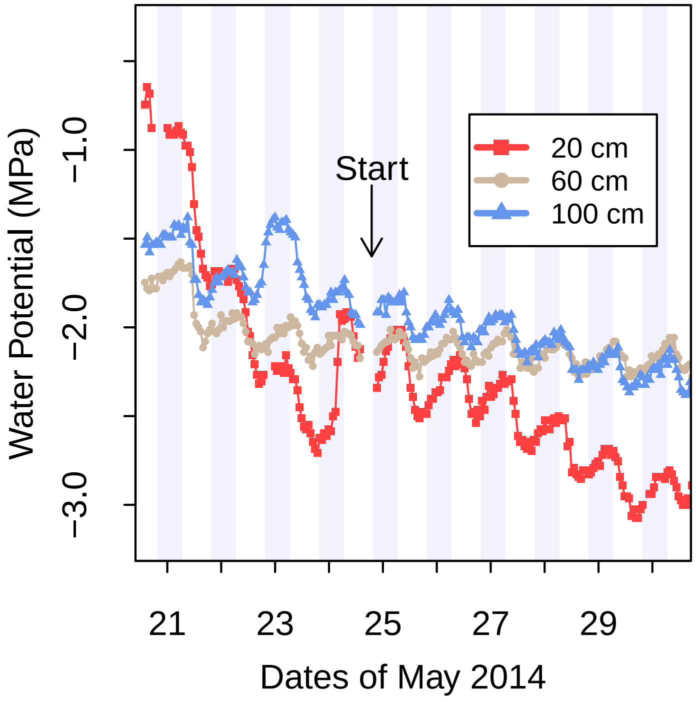


FIGURE 4.2. Soil water potential measured by thermocouple psychrometers at three depths in plot C. Tracer study began in the evening of May 24. Grey shading represents nighttime hours. The start arrow represents the beginning of the isotope tracer study.

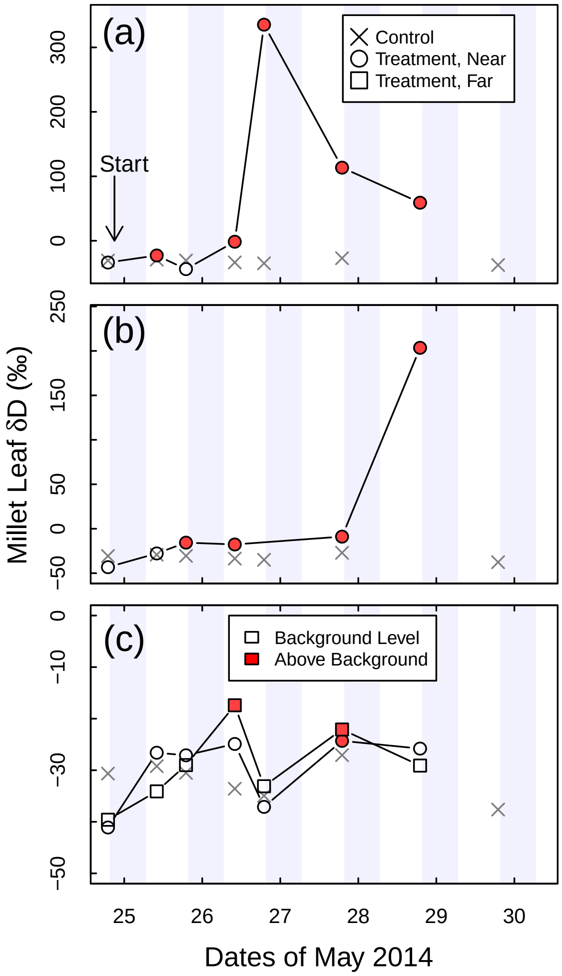


FIGURE 4.3. Time evolution in $\delta\ ^2$H showing crop signals in each of three repetitions. The control data are the same for each plot using a control crop that was 30m from closest deuterium injection. (a) Plot A (b) Plot B (c) Plot C. In plot C two different crop sampling locations were used; one in the same location as the shrub where labelled water was applied, and one 4.5 meters East of the labelled shrub. This sampling was undertaken to determine if there was lateral transfer of water. Scales on x-axis are the same, note different y-axis scales. The start arrow represents the beginning of the isotope tracer study.

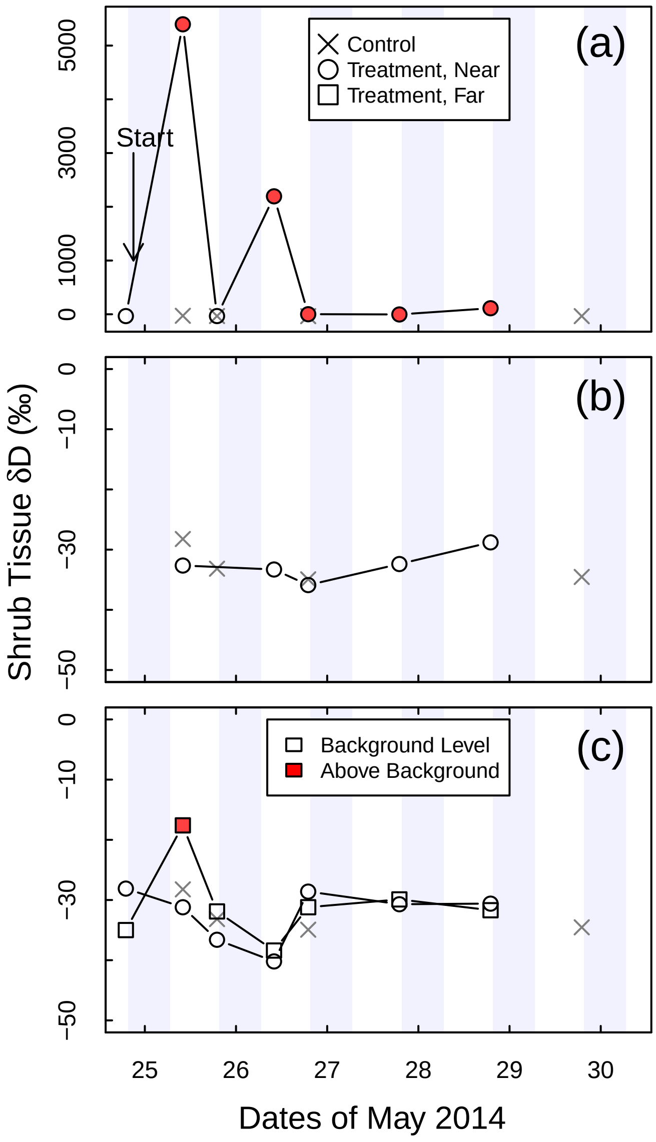


FIGURE 4.4. Time evolution in $\delta\,^2$H showing shrub signals in each of three replicates. The control data are the same for each plot using a control shrub that was 100 m from closest deuterium injection. (a) Plot A (b) Plot B (c) Plot C. In plot C two different shrub sampling locations were used; one in the same location as the shrub where labelled water was applied, and one 4.5 m East of the labelled shrub. This sampling was undertaken to determine if there was lateral transfer of water. Scales on x-axis are the same, note different y-axis scales.

CHAPTER 5

General Conclusion

Many soils throughout the world have been severely degraded due to the pressure of humans and a changing environment. The consequences of increased pressure on the land have been reduced time for land to lay fallow, and increased grazing pressure. This dissertation addresses the applied agronomic questions of when and how the presence of shrubs and shrub mulch affect the growth of interplanted crops. It also, however, probes two more basic mechanistic questions about how shrubs can alter the soil and crop growth environment:

(1) How have surface additions of shrub biomass over ten years affected the physical structure of the soil?
(2) Can hydraulic lift (HL) carried out by shrubs provide any water to crops growing nearby under moisture stress conditions?

The previous two questions address very important areas of agricultural research, particularly for low-input farming. As the climate warms and the population grows, taking advantage of the evolutionary adaptation of native vegetation can help buffer farmlands against degradation.

In chapter two the effects of shrub leaf and stem addition for ten years on soil physical properties was investigated. Increased moisture under shrubs was observed both by the author and by previous authors at the site. The water retention, saturated hydraulic conductivity, and surface infiltration were studied to investigate if the differences in moisture had to do with differences in soil texture and structure. Also studied was soil surface evaporation where there was no significant difference between treatments.

- There was lower surface infiltration in CS plots as compared to CO plots both sites, which helps to explain how higher moisture levels are maintained at shallow depths in the early growing season beneath the shrubs. The differences in water retention, measured in the lab, were less striking than those of surface infiltration and only showed a difference in water content at wilting point at Keur Matar. This shows that the soil at 10 cm depth is not heavily affected by the incorporation of shrub biomass into the shallow soil layers. Nonetheless, there were differences shown in unsaturated hydraulic conductivity where conductivity near the shrubs was slightly lower than that greater than conductivity measured 1 m from the shrubs in crop only plots. Soil surface evaporation data are evidence that surface moisture loss within 48 hours after rain is not strongly affected by the presence of a shrub canopy. This has to do with the coarse-grained soils acting as a self-mulch by breaking capillary contact with the soil below.

Chapter three built upon the work of F. Kizito in studying soil moisture and temperature dynamics throughout two growing seasons. Additionally, plant-level measurements of NDVI, LAI, and leaf water potential were measured. Lastly, deep moisture use by shrubs after harvest (November-February) were measured.

- Presence of shrubs increased the leaf area in associated crops, increased the nutrient and water status, as measured by NDVI, and improved crop plant water status throughout the day. It was established based on soil moisture dynamics at one, two, and three meters that shrubs have expanded into the zone below 1 m depth across all treatments (crop+shrub, crop only, bare soil). This is shown by diurnal fluctuations in soil moisture under moist conditions at depth (near field capacity) characteristic of plant water use at both sites. It is also shown that the shrubs use progressively deeper moisture reserves going to at least 3 m during the months of February. It is likely that plants are using moisture at 3 m during the harshest part of the dry season and into the early wet season when crops are growing in the upper horizons. It is this spatial and temporal separation of use of water resources that likely allows for crops to become established with no competition for water resources. Data from the sensor networks also showed that the hydraulic gradient, the driving force for water movement, favors hydraulic lift the most in the very early and late season. But it can also develop during periods of extreme drought during the growing season.

In chapter four the presence of HL in shrubs and the transfer of HL water from shrubs to crops under drought conditions during an irrigation experiment was investigated.

- Using an enriched D tracer water was tracked from shrub roots below one meter depth into millet crops growing in association with the shrubs. This finding is one of very few of its kind, particularly in a field situation, and the first in an agroforestry system that shows such large benefits with no evidence of negative interactions between crops and shrubs. These data showed that there is, in fact, water transfer between species. In order to change the water potential by 0.1-0.5 MPa in the soils at Keur Matar, extremely small fluctuations in moisture content are needed. This supports the idea that HL may not be supplying a large amount of the total water use to the crops, but it may help crops avert mortal dessication.

There remain considerable knowledge gaps with regards to how *G. senegalensis* and *P. reticulatum* function on the landscape. The water use of shrubs in the 0-3 m depth range are well understood based on this and other studies. What is less well understood is the true extent of shrub roots and if they may reach all the way to the water table in some places. Recent studies show an increase in the water table throughout the Sahel, and reasons given for this have to do with clearing land and changing of surface soil properties which lead to an increase of runoff Leduc et al. (2001). If the density of the native shrubs on the landscape is to be recommended to increase as a means of increasing crop production then the shrub water use will have to be carefully balanced with recharge. This is particularly important if these shrubs are, in fact, phreatophytes, because phreatophytes often have xylem with high porosity that are prone to cavitation if they are stressed. Therefore if a high density of shrubs was planted and caused a drop of water table it could quickly lead to a large-scale cavitation within the shrub roots and potentially a large die-off of shrubs. A second and related question for further research is to quantify exactly how much water is hydraulically lifted by the shrubs. This is difficult to measure and the most reliable method so far is to employ soil psychrometers to measure water potential fluctuations in the range near permanent wilting point. As technology evolves, however, devices are being developed that can measure soil water potential throughout the wet and dry ranges and this could be very useful to quantify when and where HL occurs.

The research in this dissertation, combined with the work that was previously conducted at the site by R.P. Dick, F. Kizito, E.L. Dossa and others shows that under a range of climate and soil nutrient conditions, the presence of the two shrubs serves as a benefit to crop growth. The fact that no negative interactions have been observed between the shrubs and crops grown nearby is unique. Typically when two species occupy the same space and are in need of the same resources competition arises, however in this case the benefits to crop growth strongly outweigh any competition between species. The research in this dissertation, as well as the previous research should provide a basis to launch larger-scale study and implementation of agroforestry sytems involving *G. senegalensis* and *P. reticulatum*. Capitalizing on the evolutionary adaptation of these two shrubs, and other species in similar environments, can be one of many powerful tools available to combat land degradation and increase food security throughout semi-arid regions worldwide.

APPENDIX A

Site Overview and Field Plot Map

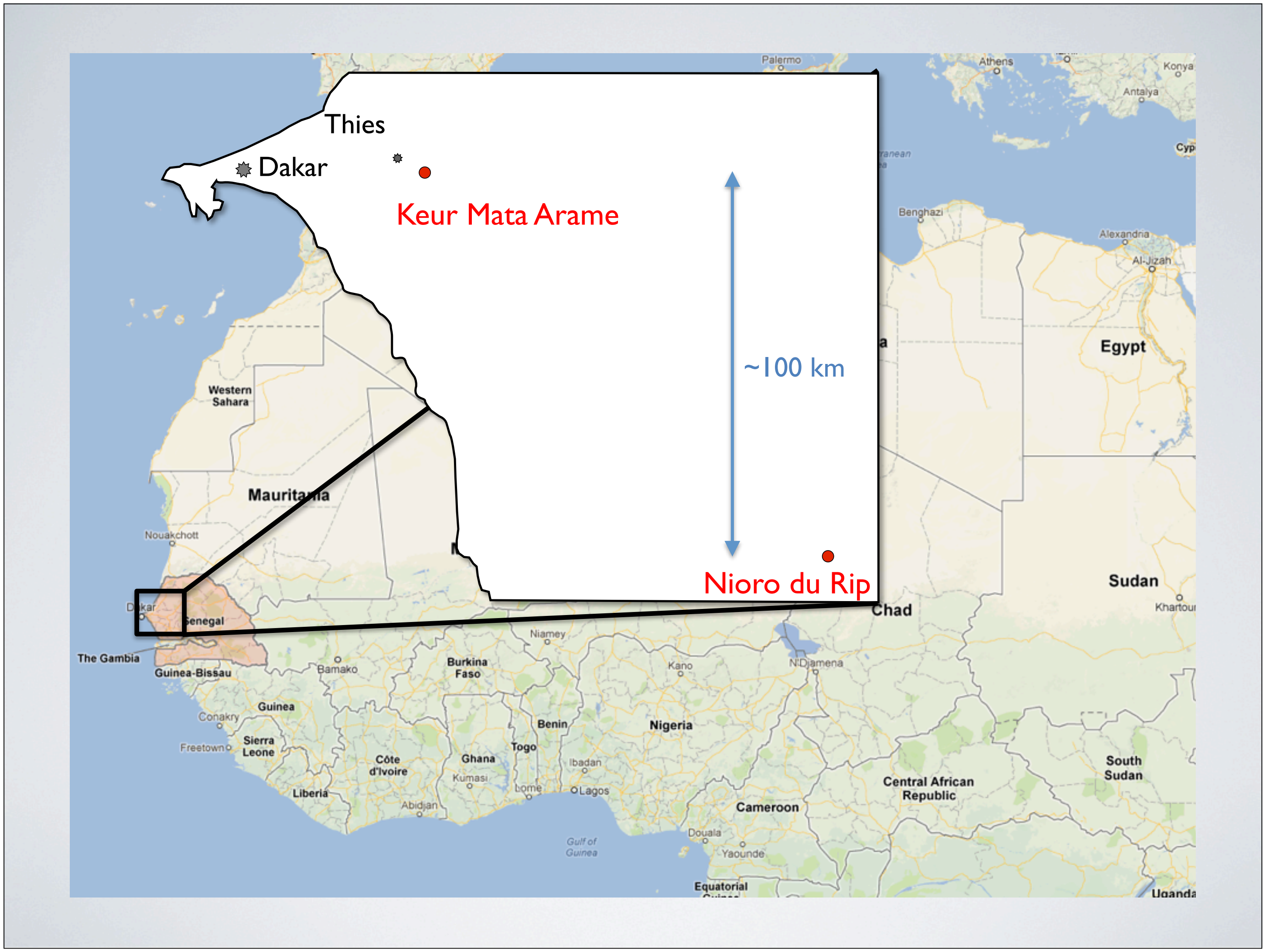


Figure A.1. Map of Senegal with two study sites marked (Google, 2016).

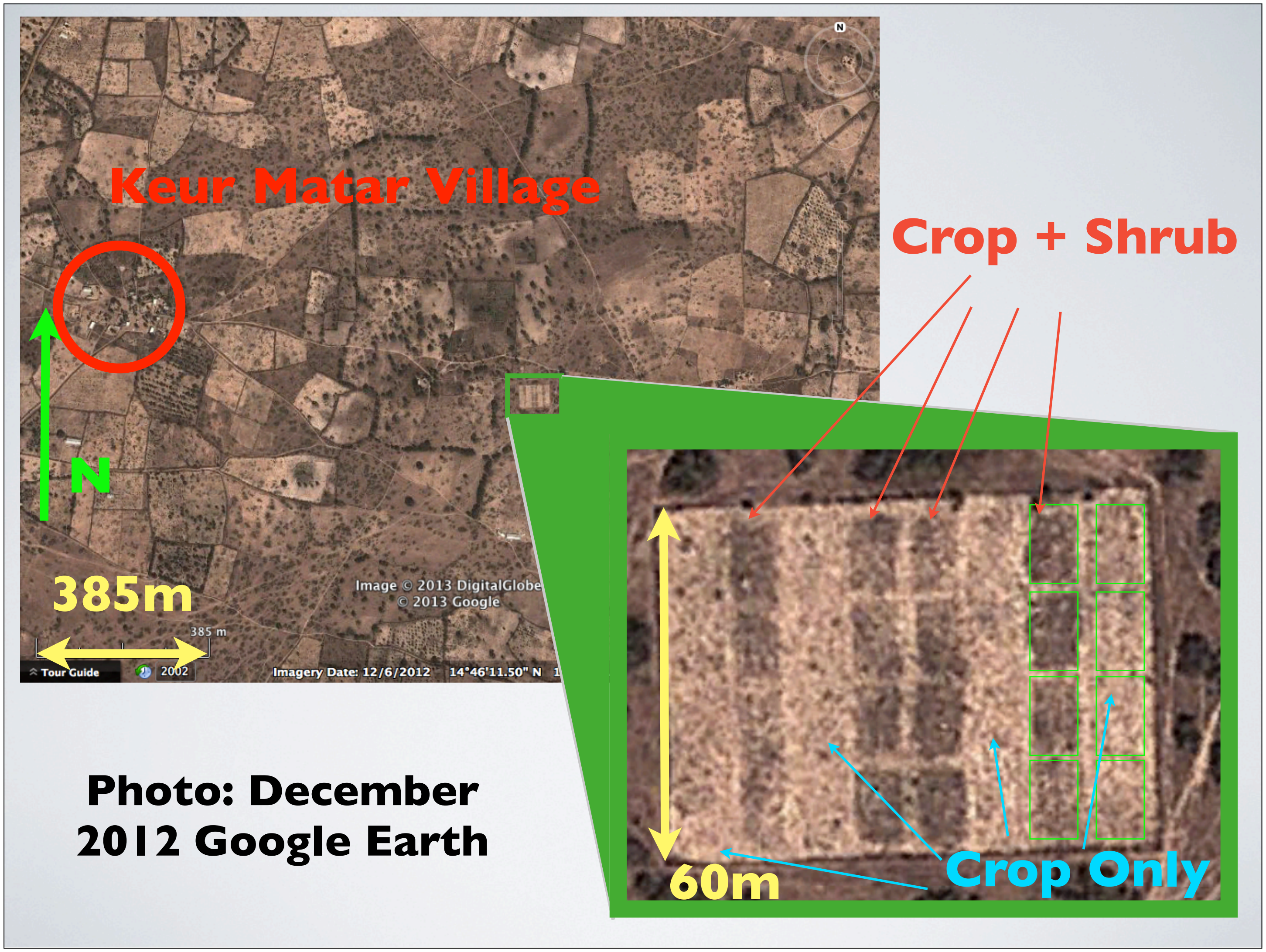


Figure A.2. Aerial photo of Keur Matar Arame site showing crop+shrub and crop only plots.

APPENDIX B

Supplemental Information for Lysimeter and Water Retention measurement

B.1. Dual tensiometer evaporation

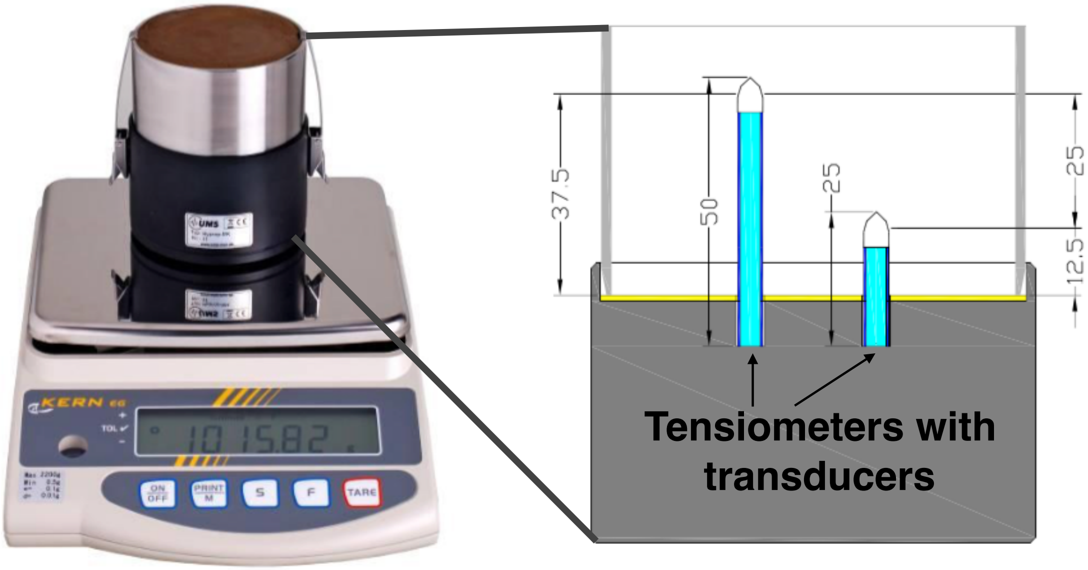


FIGURE B.1. Photo of sample in hyprop unit on balance (left) and diagram of HYPROP dual tensiometer evaporation apparatus (right) for measuring water retention and unsaturated hydraulic conductivity. Cable connections to balance and HYPROP unit for datalogging not shown.

B.2. Lysimeters

FIGURE B.2. Preparing the microlysimeter in the field. Heat conductive, waterproof tape being applied to the bottom side of lysimeter after trimming soil. Outer diameter of lysimeter is 10.7 cm

FIGURE B.3. Microlysimeter in field with green wind shield and pink flag next to it at Keur Matar. Outer diameter of lysimeter is 10.7 cm.

B.3. Non-linear fitting routine for Durner-Van Genuchten water retention in R

```r
rm(list=ls(all=TRUE))
library(plyr)
library(minpack.lm)

# Functions for Water Retention Curves and non-linear Data Fitting, code needs to be modified to fit specific data formats, it is written generically

# Fitting routine written by Teamrat Ghezzehei
# Edits to code and customization by Nate Bogie

#this fits only the durner bimodal model



# Reset all variables
rm(list=ls(all=TRUE))

# General Functions
SE      = function(theta,theta.s,theta.r){
    SE = (theta-theta.r)/(theta.s-theta.r)
    return(SE)
}

file = <insert file name>

# Water Retention Models --------------------------------
Durner = function(P,alpha.1,N.1,alpha.2,N.2,fine){
  #Fine Portion has index 1
  M.1 = 1-1/N.1
  Q1 = (1+(alpha.1*P)^N.1)^(-M.1)

  # Coarse Portion has index 2
```

```
  M.2 = 1-1/N.2
  Q2 = (1+(alpha.2*P)^N.2)^(-M.2)

  # Composite
  Q = Q1*fine + Q2*(1-fine)

   return(Q)
 }

vG = function(P,alpha,n){
      m =1-1/n
      vg=  (1+(alpha*P)^n)^(-m)
      return(vg)
}






# Predictions ------------------------------------------------------------
predict.vG = function(P,fit){
      theta.s = fit$theta.s[1]
      theta.r = fit$theta.r[1]
      alpha   = fit$alpha[1]
      n       = fit$n[1]


      theta = vG(P,alpha,n)*(theta.s-theta.r)+theta.r
      return(theta)
}
# stop('here')
predict.Du = function(P,fit){
      theta.s   = fit$theta.s[1]
```

```r
    theta.r   = fit$theta.r[1]
    alpha.1   = fit$alpha.1[1]
    N.1       = fit$N.1[1]
    alpha.2   = fit$alpha.2[1]
    N.2       = fit$N.2[1]
    fine      = fit$fine[1]

    theta = Durner(P, alpha.1, N.1 ,alpha.2, N.2, fine)*(theta.s-theta.r)+theta.r
    return(theta)
}

# Fitting Routines --------------------------------------------------------
fit.durner = function(theta,P,theta.s = -999, theta.r = -999, alpha.1 = -999,N.1= -999,alpha.2= -999,N.2= -999,fine= -999){
  # REQUIRES
  # - minpack.lm | Library
  # - vG | Function

  # Initialize starting guess and bounds of free parameters
  # s.par = c(theta.s=0.36,theta.r=0.01, alpha.1=0.01, N.1=6.00, alpha.2 = 0.0010,N.2 = 2.6, fine = 0.5)
  s.par= c( theta.s = 0.326,theta.r = 0.00, alpha.1 = 0.0001, N.1 = 1.3, alpha.2 = 0.018, N.2 = 3 , fine = 0.3) #outputs from commented s.par above fit with +-50% on the upper/lower. coarse portion has index2
  # l.par = s.par -5*s.par
  # u.par = s.par + 9*s.par
  l.par = c(theta.s=0.30,theta.r=0.0000, alpha.1=0.000001, N.1=1.1, alpha.2 = 0.0001,N.2 = 1.1, fine = 0.03)
  u.par = c(theta.s=0.50,theta.r=0.00001 , alpha.1=0.2,     N.1=6 , alpha.2 = 0.15 ,N.2 = 3.55   , fine = 0.9)

  # If parameter is supplied, assume it is known and remove from free parameters
```

```
  if(theta.s!=-999){
    s.par = s.par[-1]
    l.par = l.par[-1]
    u.par = u.par[-1]
  }
  if(theta.r!=-999){
    s.par = s.par[-2]
    l.par = l.par[-2]
    u.par = u.par[-2]
  }
  if(alpha.1 !=-999){
    s.par = s.par[-3]
    l.par = l.par[-3]
    u.par = u.par[-3]
  }
  if(N.1 !=-999){
    s.par = s.par[-5]
    l.par = l.par[-5]
    u.par = u.par[-5]
  }
  if(alpha.2 !=-999){
    s.par = s.par[-6]
    l.par = l.par[-6]
    u.par = u.par[-6]
  }
  if(N.2 !=-999){
    s.par = s.par[-7]
    l.par = l.par[-7]
    u.par = u.par[-7]
  }
  if(fine!=-999){
    s.par = s.par[-8]
    l.par = l.par[-8]
    u.par = u.par[-8]
  }
```

```

# Setup Objective Function
fit = nlsLM( theta ~ Durner(P,alpha.1,N.1,alpha.2,N.2,fine)*(theta.s-
    theta.r)+theta.r,  start=s.par,lower=l.par, upper=u.par,trace=F)

# Summarize fitted results. Out put a list of:
# 1. all parameters (so that predict function can use them all
    regardless of whether fitted or not)
# 2. Statistics of fitted parameters


param = coef(summary(fit))
param = data.frame(t(param))

ini_and_lims = data.frame()
ini_and_lims = rbind(s.par, l.par, u.par)

if(theta.s!=-999){
  param$theta.s = c(theta.s,NA,NA,NA)
}
if(theta.r!=-999){
  param$theta.r = c(theta.r,NA,NA,NA)
}
if(alpha.1!=-999){
  param$alpha.1 = c(alpha.1,NA,NA,NA)
}
if(N.1!=-999){
  param$N.1 = c(N.1,NA,NA,NA)
}
if(alpha.2!=-999){
  param$alpha.2 = c(alpha.2,NA,NA,NA)
}
if(N.2!=-999){
  param$N.2 = c(N.2,NA,NA,NA)
}
```

```
  if(fine!=-999){
    param$fine = c(fine,NA,NA,NA)
  }
  # 3. Number of iterations and SSE




  # return(param)
  myp = list(param = param, ini_and_lims = ini_and_lims)
}

fit.vG = function(theta,P,theta.s=-999,theta.r=-999,alpha=-999,n=-999){
      # REQUIRES
      # - minpack.lm | Library
      # - vG | Function

      # Initialize starting guess and bounds of free parameters
      s.par = c(theta.s=0.5,theta.r=0.1,alpha=0.1,n=2)
      l.par = c(theta.s=0.1,theta.r=0.01,alpha=0.000001,n=1.05)
      u.par = c(theta.s=0.9,theta.r=0.3,alpha=1,n=5)

      # If parameter is supplied, assume it is known and remove from free parameters
      if(theta.s!=-999){
            s.par = s.par[-1]
            l.par = l.par[-1]
            u.par = u.par[-1]
      }
      if(theta.r!=-999){
            s.par = s.par[-2]
            l.par = l.par[-2]
            u.par = u.par[-2]
      }
      if(alpha!=-999){
```

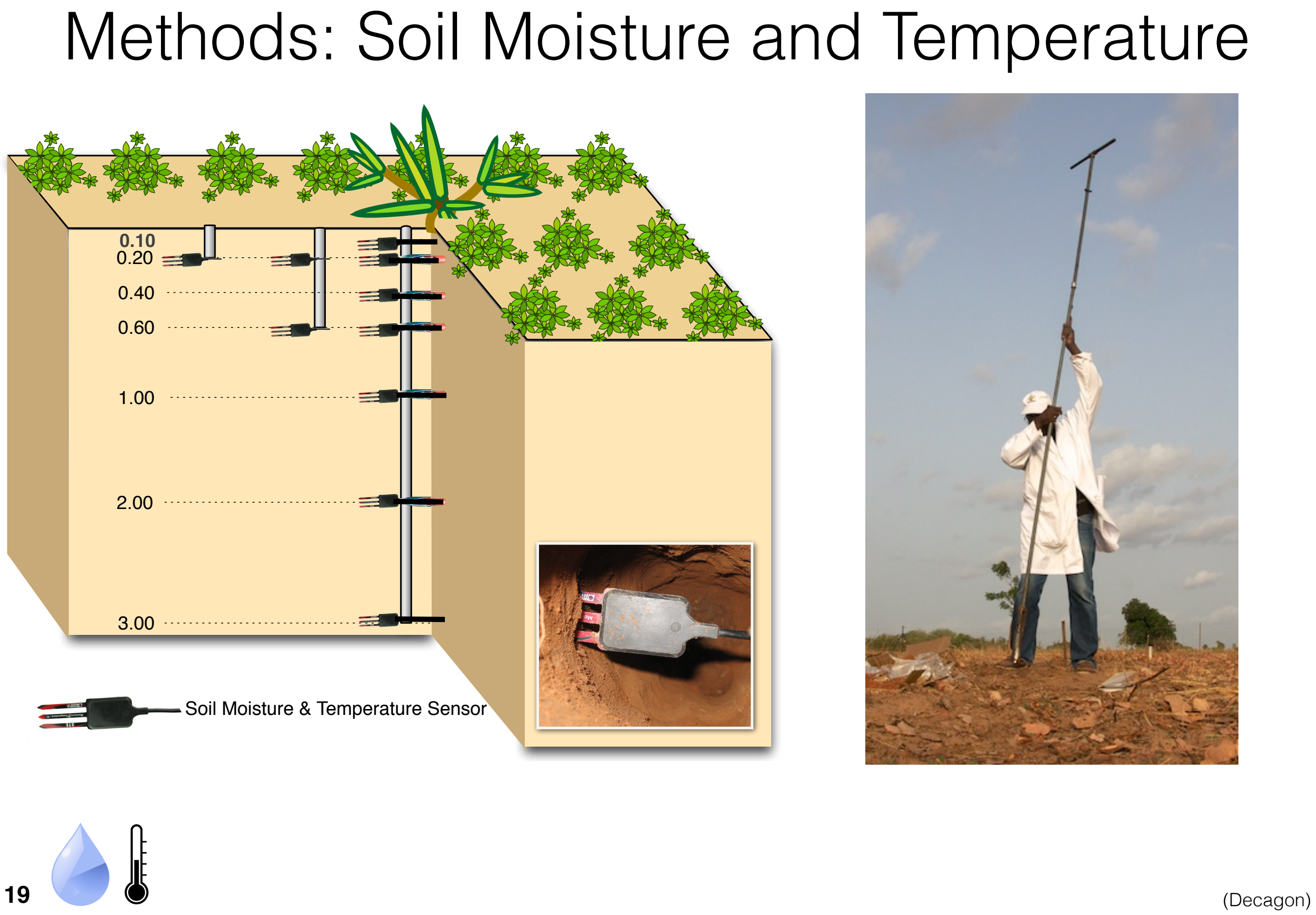
```
        s.par = s.par[-3]
        l.par = l.par[-3]
        u.par = u.par[-3]
    }
    if(n!=-999){
        s.par = s.par[-4]
        l.par = l.par[-4]
        u.par = u.par[-4]
    }

    # Setup Objective Function
    fit = nlsLM( theta ~ vG(P,alpha,n)*(theta.s-theta.r)+theta.r, start=s.par,lower=l.par, upper=u.par,trace=FALSE )

    # Summarize fitted results. Out put a list of:
    # 1. all parameters (so that predict function can use them all regardless of whether fitted or not)
    # 2. Statistics of fitted parameters
    param = coef(summary(fit))
    param = data.frame(t(param))

    if(theta.s!=-999){
        param$theta.s = c(theta.s,NA,NA,NA)
    }
    if(theta.r!=-999){
        param$theta.r = c(theta.r,NA,NA,NA)
    }
    if(alpha!=-999){
        param$alpha = c(alpha,NA,NA,NA)
    }
    if(n!=-999){
        param$n = c(n,NA,NA,NA)
    }
    # 3. Number of iterations and SSE

```

```



    return(param)
}

# TEST
# Example Data (ID 1281 from UNSODA)
# eg.P = c(10, 50, 100, 200, 316, 631, 1000, 2000, 6310, 15850)
# eg.theta = c(0.4069, 0.3652, 0.3462 ,0.3145 ,0.2789 ,0.1774 ,0.1518
    ,0.134 ,0.0931 ,0.0834)

eg.P = all_data$cm_h2o
eg.theta = all_data$vol


# Call fitting routine
# ff  =fit.vG(eg.theta,eg.P, theta.s=.326)         # Fixed theta.s (BLUE)
# ff1 =fit.vG(eg.theta,eg.P, theta.r=0.045707)     # Fixed theta.r (GREEN)
# ff2 =fit.vG(eg.theta,eg.P)                       # All four free (RED)
#

fd_all = fit.durner(eg.theta,eg.P) # All 7 free
fd1    = fit.durner(eg.theta,eg.P, theta.s = real_thetaS) # Fixed theta.
    s
fd2    = fit.durner(eg.theta,eg.P,theta.r=0.045707) # Fixed theta.r

# Print parameters
# print(fd_all)
print(fd1)
# print(fd2)


# Print data and fitted model
```

```r
pp=exp(log(10)*seq(log10(1),log10(1000000),by=0.01)) # finely log-spaced P values for smooth model curve
mydurn = data.frame(theta.s=0.36,theta.r=0.05, alpha.1=0.02, N.1=6.00, alpha.2 = 0.0010,N.2 = 2.6, fine = 0.5)

pdf(paste(file,'Durner_BiM_V2_fit.pdf', sep = ''))


plot(eg.theta,eg.P,log="y",xlim=c(0,0.5),ylim=c(1,100000), xlab = 'theta (v/v)', ylab = 'tension(cm H2O)')
# lines(predict.vG(pp,ff),pp,col="blue",lwd=2)
# lines(predict.vG(pp,ff1),pp,col="green")
# lines(predict.vG(pp,ff2),pp,col="green")
# lines(predict.Du(pp,fd_all),pp,col = 'blue', lty = 2)
lines(predict.Du(pp,fd1$param),pp,col = 'red', lty = 1)
myVg = data.frame(theta.s=0.36,theta.r=0.010, alpha=0.02, n=6.00) # zero means all weight goes to 2
dev.off()


plot(eg.theta,eg.P,log="y",xlim=c(0,0.5),ylim=c(1,100000), xlab = 'theta (v/v)', ylab = 'tension(cm H2O)')
# lines(predict.vG(pp,ff),pp,col="blue",lwd=2)
# lines(predict.vG(pp,ff1),pp,col="green")
# lines(predict.vG(pp,ff2),pp,col="green")
# lines(predict.Du(pp,fd_all),pp,col = 'blue', lty = 2)
lines(predict.Du(pp,fd1$param),pp,col = 'red', lty = 1)

# output of parameters table
write.table(fd1$param, paste(file, '_param.csv', sep = ''), sep = ',', row.names = F, col.names = T)

#output of initial estimates and bounds table
write.table(fd1$ini_and_lims, paste(file, '_ini_est.csv', sep = ''), sep = ',', row.names = F, col.names = T)
```

APPENDIX C

Supplemental Information: Calibration, Raw Data Plots, and Sensor Map



Methods: Soil Moisture and Temperature

FIGURE C.1. Schematic of soil moisture and temperature locations, depths in meters.

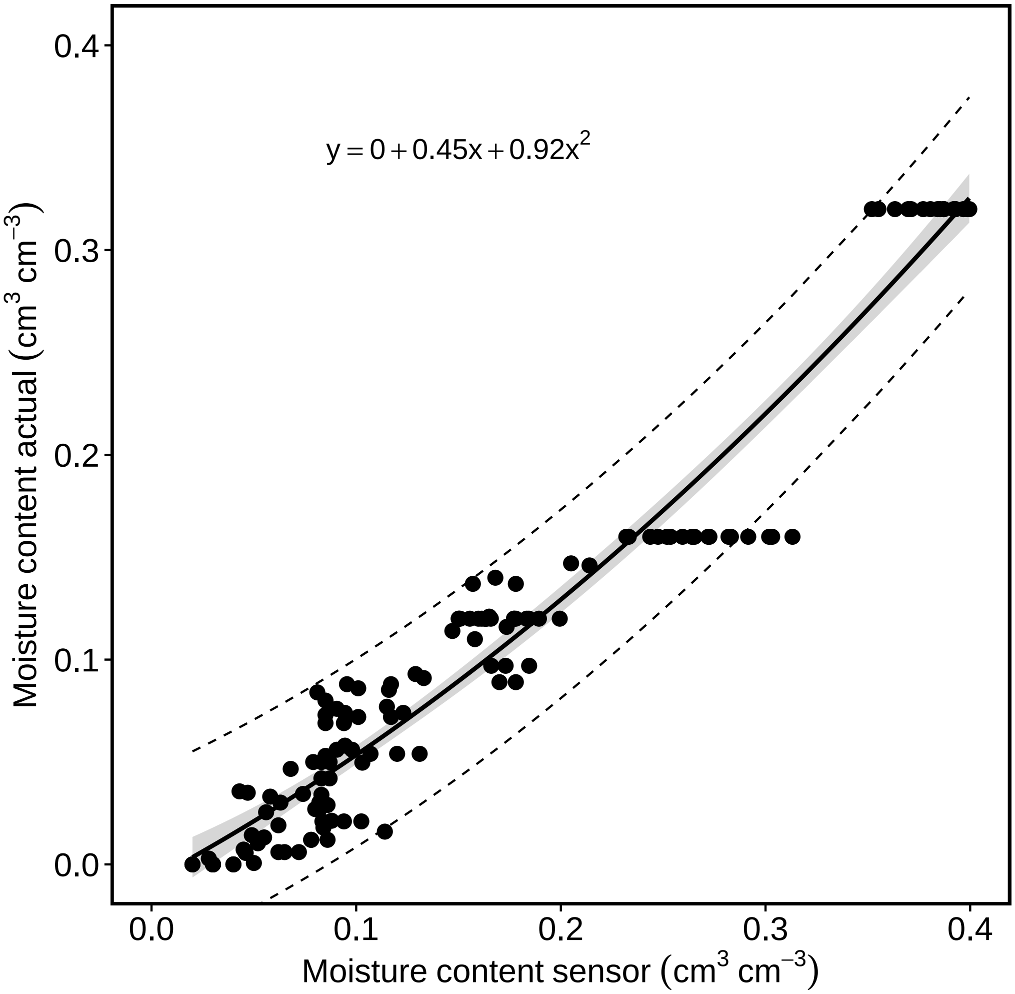


Figure C.2. Calibration of moisture sensors against true moisture content measured in the field and the lab. Data based on field-measured water content as well as lab-measured water content of oven dry soil at the dry end. Dotted lines represent 95% prediction interval, shading represents 95% confidence interval.

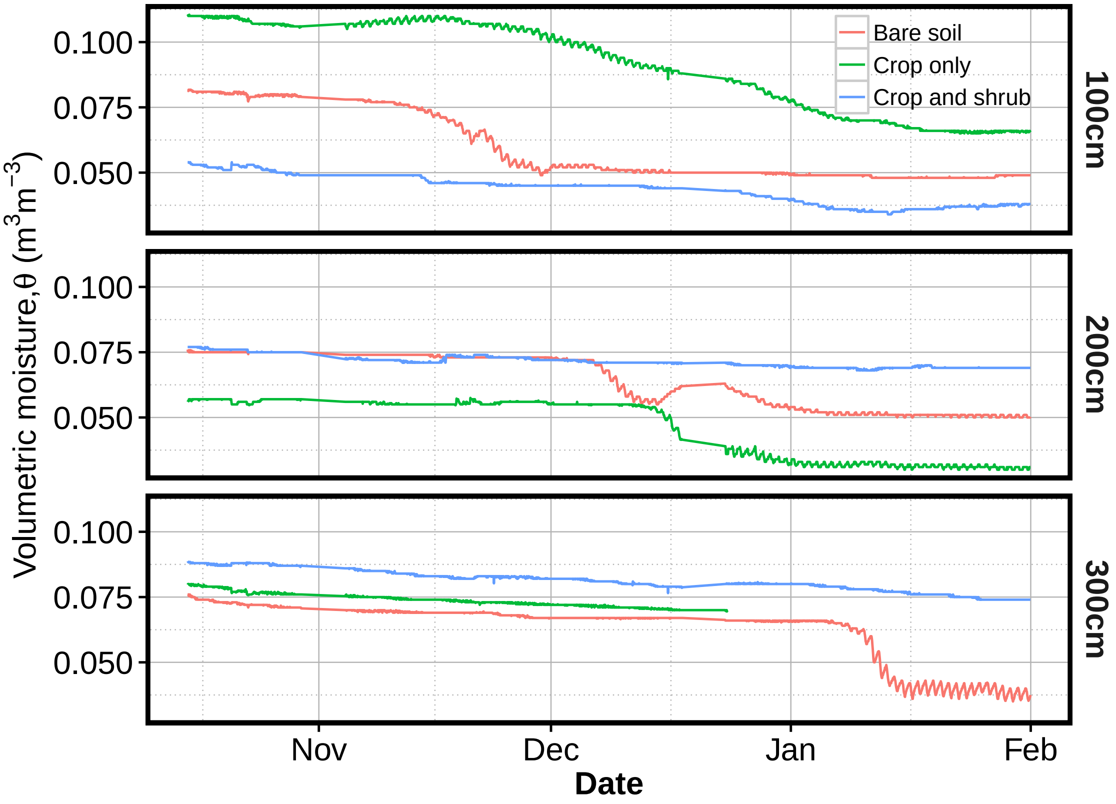


FIGURE C.3. Raw moisture content sensor data from Keur Matar. The measurement period begins at harvest in early October 2013 and goes into February, 2014. Sensor depths are 100,200, and 300cm.

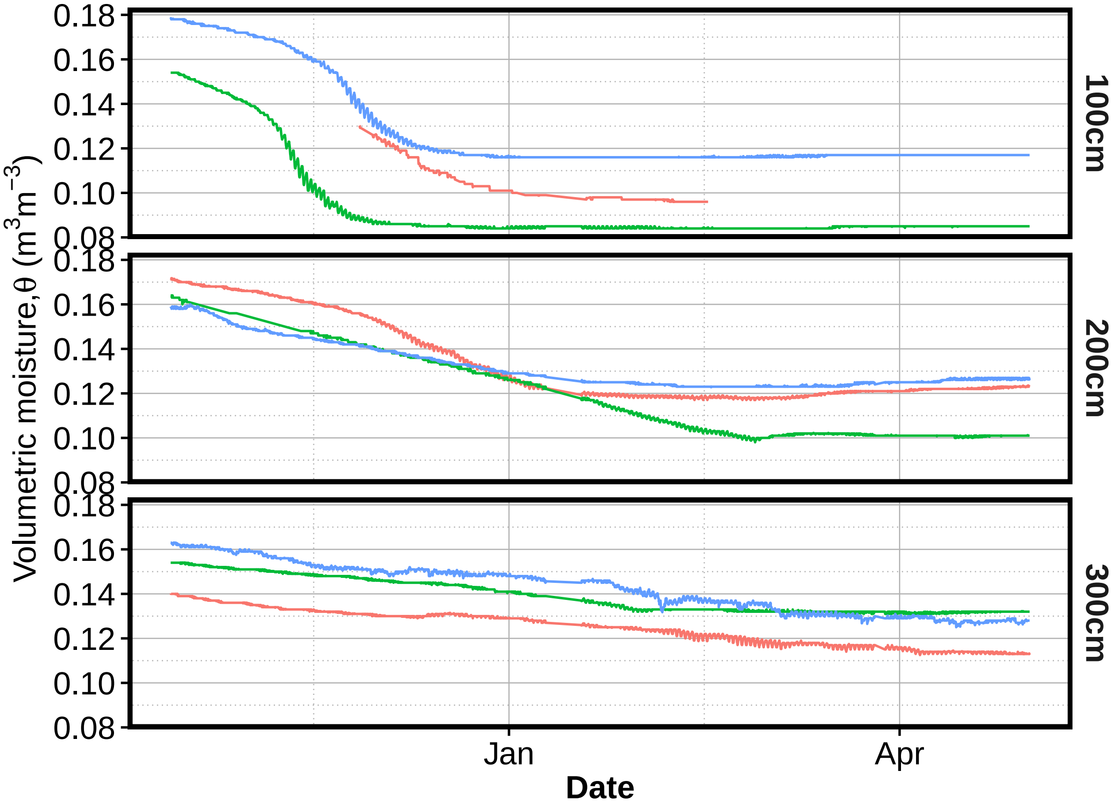


FIGURE C.4. Raw moisture content sensor data from Nioro. The measurement period begins at harvest in early October 2013 and goes into February, 2014. Sensor depths are 100,200, and 300cm.

APPENDIX D

Supplemental Information for Isotope Tracer Experiment

D.1. Supplemental plots

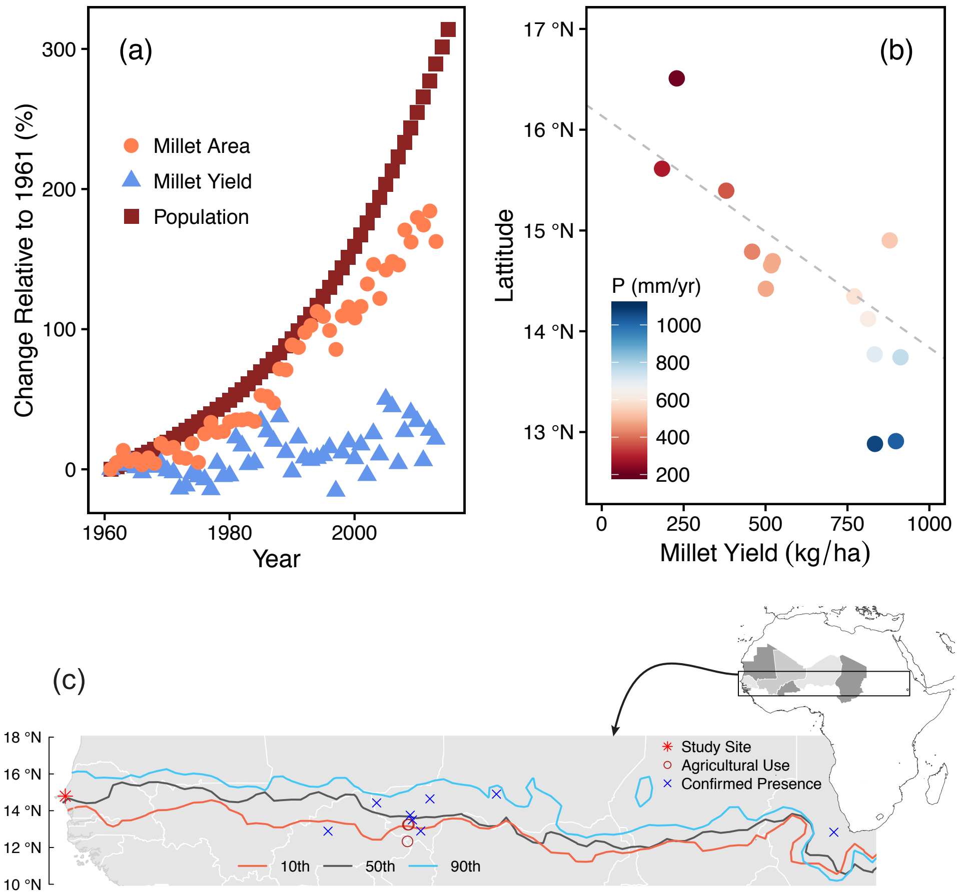


FIGURE D.1. The state of staple food production and agroforestry in the Sahel compiled from (FAO, 2015) (a) Changes relative to 1961 in population, millet yield per ha and area cropped with millet. (b) Mean annual millet yield across latitudinal transect in Senegal over the years 1987-2002. Mean annual precipitation for the same time period is indicated by color. Yield decline correlates with decrease in precipitation below 500 mm. Data compiled by (Mahul et al., 2009) based on reporting from regional experimental stations. (c) 500 mm isohyets for the median, 10th percentile, and 90th percentile years in terms of annual precipitation for the western and central Sahel since 1920 (Schneider et al., 2014). Known locations of Guiera are marked with triangles and site of known co-existence in cropland are shown with circles.

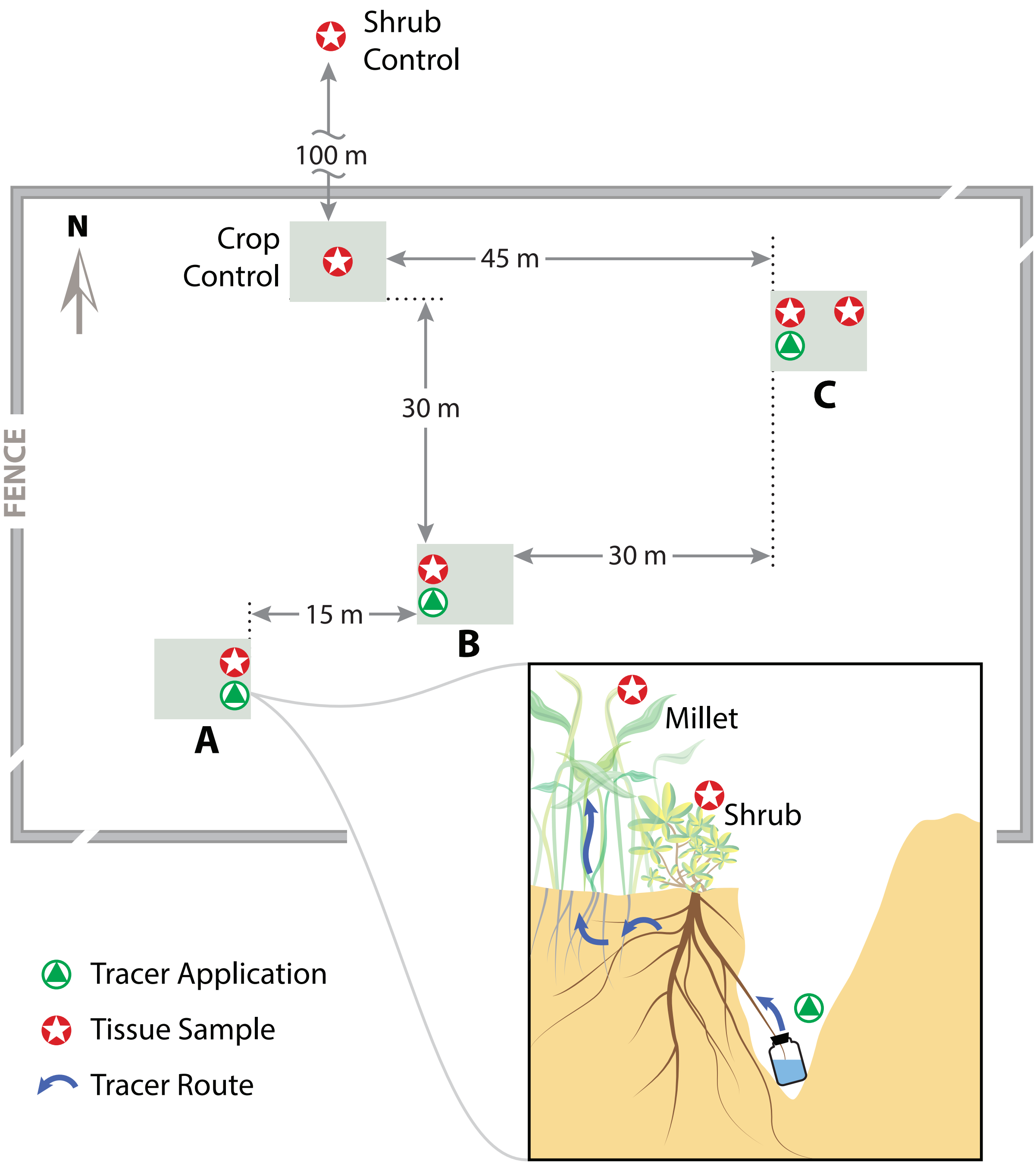


FIGURE D.2. Schematic of field layout at Keur Matar Arame, figure not drawn to scale.

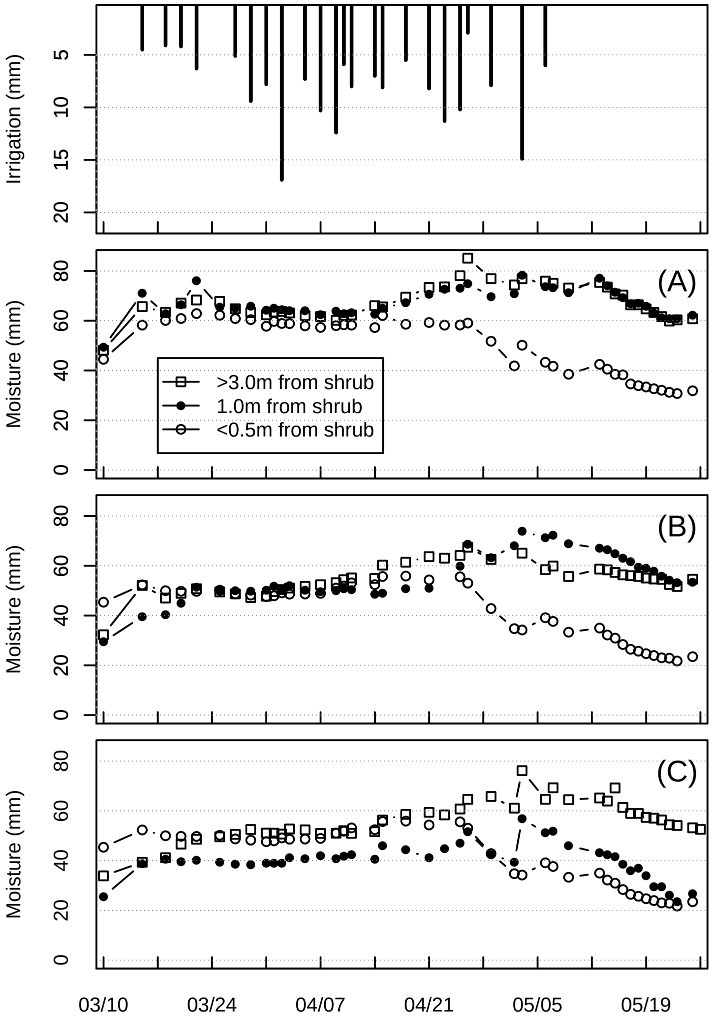


FIGURE D.3. Drip irrigation depth applied to field and soil moisture at three distances from the injection shrub for three reps (A)Plot A (B)Plot B (C)Plot C. Open squares represent crop-only (monoculture) plots that were at least 3m from the nearest shrub. Filled in circles represent measurements taken 1m from the center of shrubs in the crop+shrub plots, and open circles represent measurements taken directly within the shrub canopy.

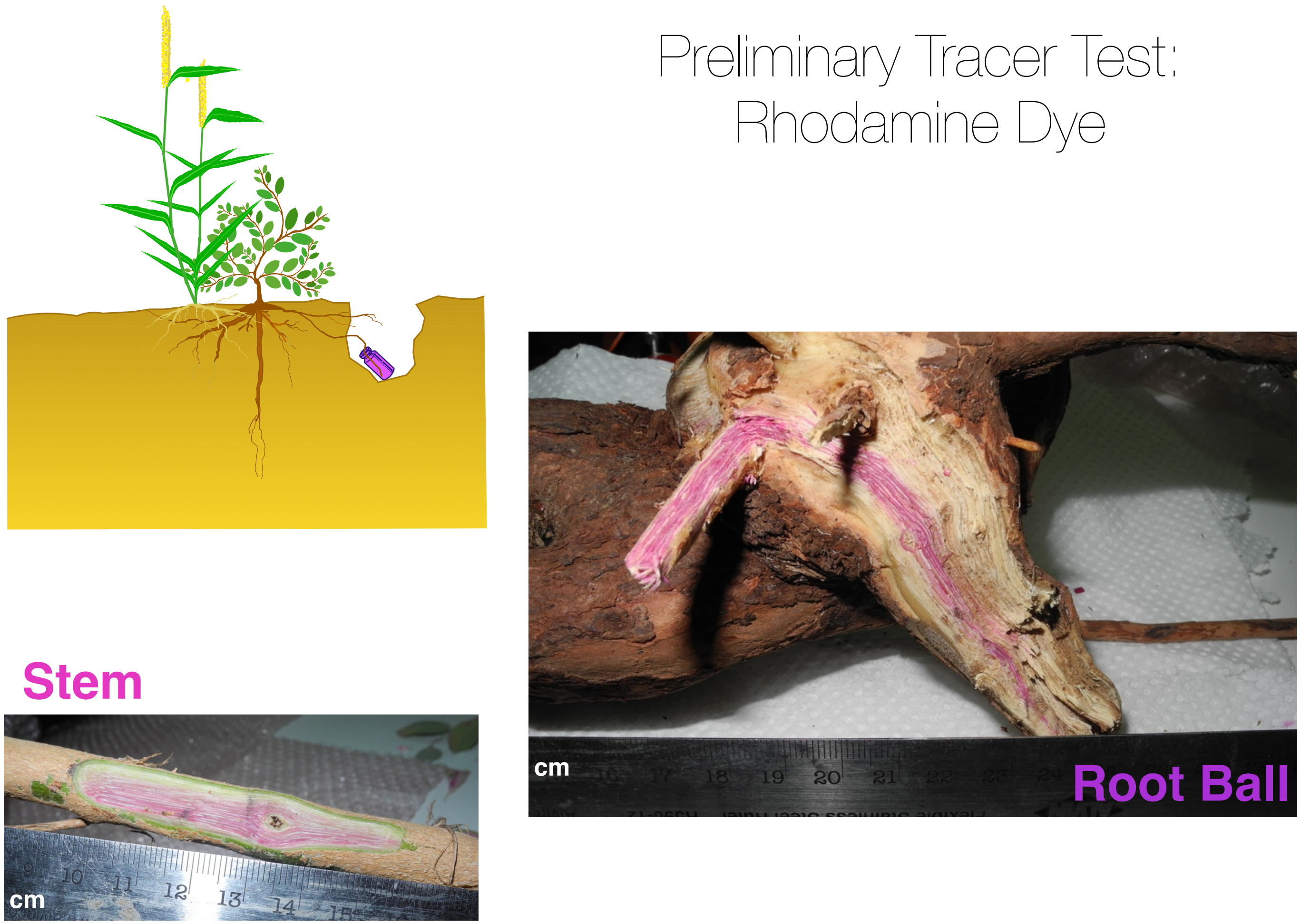


FIGURE D.4. Preliminary dye test with Rhodamine B showing water pathway in a *G. senegalensis* root and shoot.

D.2. Estimating quantity of water transferred to crops by hydraulic redistribution in shrubs

Using methods taken from tracer breakthrough studies, the total mass of tracer that flows through a system can be represented by the following equation from (Calder et al., 1992):

$$M = F \int_0^\infty C \, dt \tag{D.1}$$

Where M is the mass of tracer administered in the system, F is the flow rate [L^3 t^{-1}], C is the concentration of tracer in the plant [M L^{-3}] and t is time. For calculation of these parameters this Eq. D.1 is cast in finite-difference form:

$$F = \frac{M}{\sum_{i=1}^{i=T} C_i \Delta t_i} \tag{D.2}$$

Where C_i is the concentration in the system at the ith time step, and the duration of the ith time increment is denoted by Δt_i. To obtain values for C, isotopic ratios from the mass spectrometer were converted to atomic ratios (D:H) using baseline crop and shrub data at $-33.7‰$ and $-33.1‰$, respectively. These data were then converted to molar ratios of D_2O:H_2O and those ratios were then converted to mass concentrations of D_2O and H_2O using the atomic masses of D, H, and O.

The total mass M and the total transpiration flowrate F are a combination of the two different plants in the system:

and

$$F = F_{cr} + F_{sh} \tag{D.3}$$

and

$$M = M_{cr} + M_{sh} \tag{D.4}$$

Combining Eqns. D.3 and D.4 with (Eq. D.1) the following equations are obtained:

$$M_{sh} = F_{sh} \int_0^\infty C_{sh} \, dt \tag{D.5}$$

$$M_{cr} = F_{cr} \int_0^{\infty} C_{cr}\, dt \tag{D.6}$$

The ratio of crop transpiration to shrub transpiration can be given, and the following relationship can be used to calculate the ratio of F$_{cr}$:F$_{sh}$ by using the finite difference approximation of the integrals (Eq. D.2).

$$R = \frac{M_{cr}}{M_{sh}} = \frac{F_{cr} \int_0^{\infty} C_{cr}\, dt}{F_{sh} \int_0^{\infty} C_{sh}\, dt} \tag{D.7}$$

And F_{cr} is the amount of flux provided by HL.

The assumptions underlying this calculation are as follows:

1. Complete mixing of tracer within all tissues of the plant at all times.
2. Complete recovery of tracer from plant tissue.
3. No evaporative loss of hydraulic lift water before uptake by the crop.

References

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